Low-Floor Light Rail Vehicle Development in Europe

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Growing pressure by handicapped groups in recent years has induced European public transport systems to improve accessibility not only on buses but also on the numerous and important (as compared with the case on the American continent) light rail vehicles and streetcars. The installation of wheelchair lifts has been generally avoided in providing greater accessibility for wheelchairs and for some elderly and handicapped persons because of the high cost of their installation and maintenance. Instead, European cities have tried to lower the car floor, at least partially, so that boarding and alighting becomes easier for the handicapped with and without wheelchairs. Various basic low-floor car designs developed by the active European car builders are described and compared. It is evident that no standardization has yet been achieved and that there are still more designs on the drawing board. Some projects are likely not to go beyond the prototype stage. Another problem is the comparatively high prices of these cars; a reduction in such costs appears possible only when fewer designs are being built in greater series. The problems arising from the joint operation of routes upgraded to light rail transit operation with high and low platforms and of classic surface streetcar routes equipped with low-floor cars throughout are reviewed.

On the North American continent, especially in the United States, handicapped groups have been applying pressure on legislators, government, and the public transport systems for the last 20 to 25 years to make the facilities accessible to handicapped people in general and to wheelchairs in particular. As a consequence, public money for construction of new facilities and new rolling stock is only being provided if these facilities and vehicles are easily accessible for the handicapped and for wheelchairs. Although in subways the remedies have been concentrated on fixed facilities, accessibility for the handicapped and wheelchairs for buses could only be achieved by remedies within the vehicles themselves. Light rail transit (LRT) and streetcar systems have not been the object of this pressure because there were only a few systems in a few cities and they had small fleets.

In Europe the pressure by the handicapped associations gained importance only during the last few years. This led to the need for the public transport systems to deal directly with the problem. For the subways in Europe, the same need is valid as for those on the American continent, that is, the measures required are limited to fixed facilities. The surface transportation systems in Europe, however (i.e., the buses and the existing and new LRT and streetcars), have responded differently than those on the American continent. They wanted to avoid lifts for wheelchairs, which are expensive to install and to maintain. Such lifts, when installed in conventional vehicles, provide accessibility for wheelchairs but do not help older or handicapped passengers, because they would still have to negotiate the usual steps at the doors to board and to leave the vehicles. The only other possibility to provide full accessibility was to lower the floor of the vehicles to a minimum value allowed by their structural design and thus avoid all steps at the vehicles' doors. First, buses were fitted with the kneeling system in which the front end was lowered at stops and a depressed floor was provided at the rear entrance with small retractable plates to bridge the gap between the bus floor and the platform.

Because of the longer working life of rail vehicles, existing rail systems have had a limited chance to build new vehicles accessible to handicapped and wheelchairs. Thus the first European low-floor rail vehicles were built for two smaller systems, one of which was built entirely new (Grenoble, France); the other, which already existed, replaced all of its car fleet at once (Geneva, Switzerland).

Although this paper deals with light rail vehicle (LRV) development, it is necessary to distinguish among

- Light rail systems built entirely new,
- Light rail systems or lines upgraded from existing surface streetcar systems, and
- Classic surface streetcar systems.

The systems built entirely new can be designed and built to be completely accessible to the handicapped and wheelchairs, either by providing high platforms throughout (e.g., Calgary, Edmonton) or by using low platforms or by loading from the street level and providing low-floor cars (e.g., Grenoble), or both.

The upgraded streetcar systems are usually not accessible to the handicapped and wheelchairs, or only partly so. They frequently have tunnel stations with high platforms of about 900 mm (35 in.) above the top of the rail (TOR) in the city center, but low platforms in the connecting surface stations. The high platforms in the tunnel stations can be made accessible by lifts (and any high platforms on the surface by ramps), but the cars, which must then have movable steps, remain inaccessible from low platforms.

The development of low-floor cars began on classic streetcar systems (*1–3*) in which cars are boarded or exited by means of three to four steps either from street level or from platforms about 150 mm (6 in.) above TOR. Installation of wheelchair lifts was excluded from the outset because of issues of reliability, high costs, and excessive time loss connected with their use.

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In the introduction of low-floor cars on those systems, operation on the same routes of the existing high-floor cars with fixed steps or even of new light rail cars with movable steps with the new low-floor cars can produce problems such as the following:

1. Low-floor cars with a greater width (after the track centerline distance had been widened during maintenance);
2. Differences in the kinematic envelopes for whatever reason, for example, the unpowered running gear is not under the articulation;
3. The understandable wish to further increase the height of the platforms from the 150 mm mentioned earlier to about 200 to 250 mm (8 to 10 in.) above TOR in order to lessen the difference between platform height and car floor height, making access still easier; and
4. Use of outside-swing or swing-slide doors instead of folding doors.

Thus, before new low-floor cars are introduced into an existing system, a careful assessment must be made to avoid later problems with the operation of both old and new cars on the same route or routes. Factors to be considered here are wear of the tires, compression of the springs (primary and secondary suspension) under the load, wear of the rails (both vertically and horizontally), and construction tolerances for platforms with regard to TOR and track centerline; also important are differences within the kinematic envelopes of the existing older cars, which may have tapered ends, and the new low-floor cars. The assessment may result in major rebuilding of some stops situated on or near curves and also used by buses (*1,4*).

Therefore, entirely new-built systems are better because only one car type is used and an optimal layout can be achieved between position and height of the platforms and the car floor height.

LOW-FLOOR CAR DESIGNS

The three basic types of low-floor cars (*5*) are vehicles with

1. Low-floor area of less than about 15 percent of the total floor surface,
2. Low-floor area of about 60 to 70 percent of the total floor surface, and
3. Low-floor area of 100 percent.

All these designs are built as articulated cars. For streetcar and LRT systems, a four-axle low-floor car design appears to be technically unsuitable and uneconomic because of problems with the installation of the electric or pneumatic equipment, or both, and because of the reduced car length. Thus, these cars have been built only rarely during the last two decades.

Low-Floor Area Less Than 15 Percent

Designs with less than 15 percent low-floor area are usually an outgrowth of standard streetcars, which have a floor height of about 850 to 900 mm (33 to 35 in.) over TOR. All vehicles are three-section, eight-axle articulated cars in which a small part of the floor in the center section has been lowered to a height of about 300 to 350 mm over TOR. The low-floor area is thus only sufficient for two wheelchairs. Fixed seats are almost impossible; only tip-up seats can be used. Between the low- and high-floor sections, usually two to three steps (rarely four) have to be provided.

Because of all these limitations, such low-floor cars as those running in Freiburg (*6*), Würzburg (*4,7*), and Mannheim and Nürnberg in Germany; in Basel, Switzerland; in Nantes, France; and in Amsterdam, Netherlands (*8*), can only be considered a bad compromise. Because they could be built quickly, and especially because existing powered and unpowered trucks could be used without any problems, they were used mostly to offer handicapped passengers some relief. In some of these cases (Mannheim, Nürnberg, Basel, and Nantes) existing two-section, six-axle cars have been converted into three-section, eight-axle cars by adding a center section with a low-floor area.

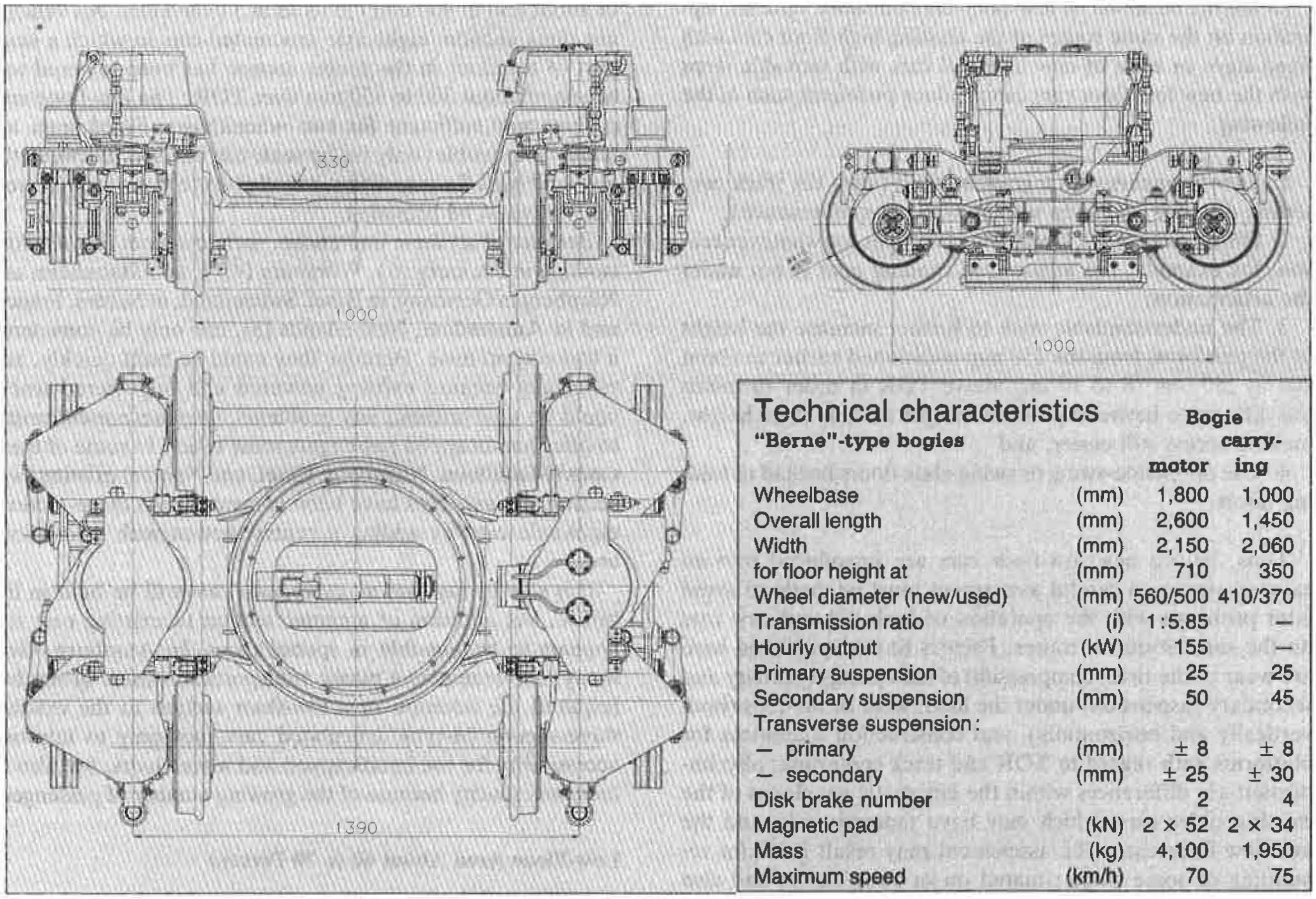
It is safe to say that no more such cars will be built in the future, but addition of a center section to existing cars still appears to be possible in special cases. In Augsburg, Germany, for example, a public transportation users group has required the addition of a low-floor section to the existing three-section M-type articulated cars, not only to improve accessibility for the handicapped and wheelchairs, but also to increase capacity because of the growing number of passengers.

Low-Floor Area About 60 to 70 Percent

The car type that is most common at present has about 60 to 70 percent low-floor area. Because the floor area above the powered trucks at both ends of the car is not lowered, standard powered trucks can be used. Between these and across the articulations, the entire width of the floor is lowered to about 350 mm (14 in.) above TOR. Provision of ramps at the doors permits the entrance height of the latter to be lowered still more to about 250 to 280 mm (10 to 11 in.).

However, the design of these cars requires special measures for the unpowered running gear to achieve a continuous lowering of the floor between the powered trucks. At this time the following possibilities are available:

1. Trucks with very small wheels [diameter of about 350 mm (14 in.)] designed by Ateliers de Constructions Mécaniques de Vevey (*1, 9*) and used on the cars running in Geneva (*10,11*) and Bern in Switzerland and in St. Etienne, France.
2. Trucks with normal-diameter wheels supported on short axle stubs, which eliminates a through-axle shaft, used on Italian cars in Rome and Torino (*12,13*) as well as on cars in Grenoble (*14*).
3. Single (steered) axles under the center section, used by Bombardier-Rotax on cars in Wien, Austria, that are to be used exclusively on the U 6 *Gürtel* (Belt) route, which runs on viaducts, in tunnel, and on reserved surface track. Platform heights locally are generally 350 mm, allowing reduction of the low-floor height to only 440 mm (17 in.) over TOR and permitting normal wheelsets and providing a slope between the low-floor area and that over the powered trucks, which is 525 mm (21 in.) over TOR.



Technical characteristics "Berne"-type bogies		Bogie motor	Bogie carry-ing
Wheelbase	(mm)	1,800	1,000
Overall length	(mm)	2,600	1,450
Width	(mm)	2,150	2,060
for floor height at	(mm)	710	350
Wheel diameter (new/used)	(mm)	560/500	410/370
Transmission ratio	(i)	1:5.85	—
Hourly output	(kW)	155	—
Primary suspension	(mm)	25	25
Secondary suspension	(mm)	50	45
Transverse suspension:			
— primary	(mm)	± 8	± 8
— secondary	(mm)	± 25	± 30
Disk brake number		2	4
Magnetic pad	(kN)	2 × 52	2 × 34
Mass	(kg)	4,100	1,950
Maximum speed	(km/h)	70	75

FIGURE 1 Unpowered truck on Bern low-floor car.

4. Single wheels, also supported on axle stubs. Apart from the three prototypes built by Verband Offentlicher Verkehrsbetriebe [VÖV, now Verband Deutscher Verkehrsbetriebe (VDV)], to be described later, this design has so far been used only for the cars in Kassel, Germany (*1*).

Because these designs lower the entire floor between the areas above the powered trucks, most of the seats are located directly on the low floor. Only the designs using normal wheels with diameters between 550 and 670 mm (22 to 26 in.) require so-called podia along the inside walls of the cars because the wheels protrude into the vehicle. Seats have to be mounted on these podia, which can cause a problem if such cars have to be built for meter gauge, because the space between the podia (i.e., the aisle) will then be very narrow. As with the car designs mentioned in the previous section, two to three steps are necessary to connect the low-floor area with the high floor over the powered trucks.

Another problem with this car design concerns the purchase of tickets. On many European public transport systems, single-ride tickets are still sold by drivers. A passenger requiring a ticket has to board the car at the front door, using the two or three steps necessary because of the high floor. The passenger can then stay in the high-floor section or walk down two to three more steps inside the car to reach the low-floor area and later leave the car there. (Leaving the car from the front door is not desirable because it hampers the boarding passengers.) Newly built systems usually provide ticket-vending machines (TVMs) at every stop and thus avoid this problem. With existing systems, especially larger ones, use of TVMs would be very expensive because of the larger number of stops to be so equipped. Sometimes TVMs are installed on the cars themselves. This solution, however, creates other problems, which cannot be discussed in detail here.

Low-Floor Area of 100 Percent

As discussed in the previous section, a car cannot be built with a low floor over its total length because of the use of more or less conventional powered trucks. Changes in the design of the powered trucks are inevitable if a vehicle with truly 100 percent low-floor area is to be achieved. However, there are physical restrictions that cannot be overcome.

The overall dimensions of traction motors, gears, and wheels cannot be reduced to values that allow the low floor to be extended over the powered running gear within the total car width, even if every effort is made to reduce as much as possible the total car weight and thus the power requirements. It must therefore be admitted that cars that are termed 100 percent low floor are really not. The low-floor area is limited here to all door areas and the aisles. Passengers having to buy a ticket from the driver no longer face a problem, since the front entrance area of these cars is at the same level as the other areas. All (or most) seats are mounted on podia, which are necessary to cover those parts of the running gear that cannot be kept under the car floor, the bottom surface of which is only about 200 to 250 mm over TOR. Even when seats could be mounted directly on the low floor, this is not normally done in order to have all seats at approximately the same level. The arrangement is very similar to that in buses; passengers have to board the podia, which are usually about 150 to 180 mm high, before reaching the seats. The podia above the running gear are elevated with boxes on which the seats are mounted directly without any seat brackets.

As with the designs mentioned in the previous section, cars for meter gauge encounter the problem of a rather narrow aisle between the wheels of the powered running gear.

The following car designs (all prototypes) to which these criteria apply have been built:

- The Maschinenfabrik Augsburb-Nürnberg (MAN) three-section type for Bremen (*1,15*) and München (*16*), Germany. About 200 cars of this design have been ordered for Bremen, München, Braunschweig, and Zwickau.
- The VÖV types for Düsseldorf, Bonn, and Mannheim/Ludwigshafen, Germany (*17–19*).
- The Brugeoise et Nivelles (BN) LRV 2000 type running in Bruxelles, Belgium.
- The Società Costruzioni Industriali Milano (SOCIMI) S-350 LRV running in Milan, Italy.

MAN Low-Floor Car

The general design for this type (Figure 2) is based on the cars that have been running for about 30 years in Bremen and for 20 years in München, developed by the now-defunct Hansa-Waggon. The construction rights were taken over by MAN.

The design is characterized by trucks at the center of each section rather than at the ends and under the articulations of the car. Thus there are only as many trucks as there are sections, and no additional trucks as with standard articulated cars. In the new low-floor cars, in addition to a completely new car body, the standard powered trucks have been replaced by specially designed new ones. (The old cars all have two-sections with powered trucks only, but there are some trailers of the same design in Bremen.)

The new trucks (*20*) have four independent wheels running on axle stubs mounted on an inside truck frame, which by its design allows a floor height of 350 mm (14 in.) between the wheels. Two of the wheels are unpowered. The other two wheels are driven by an AC motor via a longitudinal cardan shaft and two outside spur gear boxes connected by a transverse shaft under the floor and one gear box with additional bevel gears in order to transfer the rotation between these two shafts. The motor is located in the car floor on the side of the car without doors (the cars are single ended with doors only on one side).

The older cars had normal pivots and bolsters between the trucks and the car bodies and thus needed a rather complicated mechanical (later hydraulic) steering system to keep the articulation within the kinematic envelope of the car. The low-floor car dispenses with bolsters and pivots. Thus the trucks are connected to the car bodies only by simple rubber springs (or air springs, as in München) that provide the steering force and movement for the articulations and the secondary suspension.

Inside the car, podia 180 mm (7 in.) high cover the wheels, gear boxes, and motors. The modular design applied here allows cars with two sections and more to be built [the Bremen series order is for four-section cars, which will be 35 m (115 in.) long]. There is, however, a disadvantage with this design: the car cannot easily be built with 100 percent adhesion or as a double-ended car, or both. In both cases, the placing of the (additional, if applicable) traction motors is likely to present problems, because these would have to be located partly below the entrance areas, in which podia would be impossible.

VÖV Low-Floor Car

The most radical change from any conventional streetcar or LRV design has been achieved with the VÖV low-floor car in Germany, which was a joint development by four German car builders [Düsseldorf-Uerdinger Waggonfabrik AG (Due-

FIGURE 2 München-Bremen low-floor car.

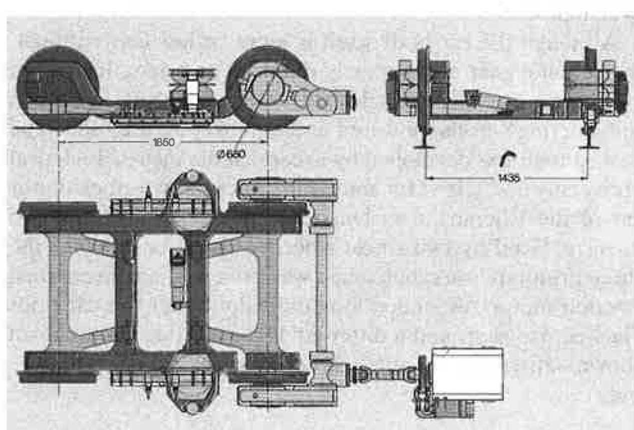


FIGURE 3 Powered truck arrangement of München-Bremen low-floor car.

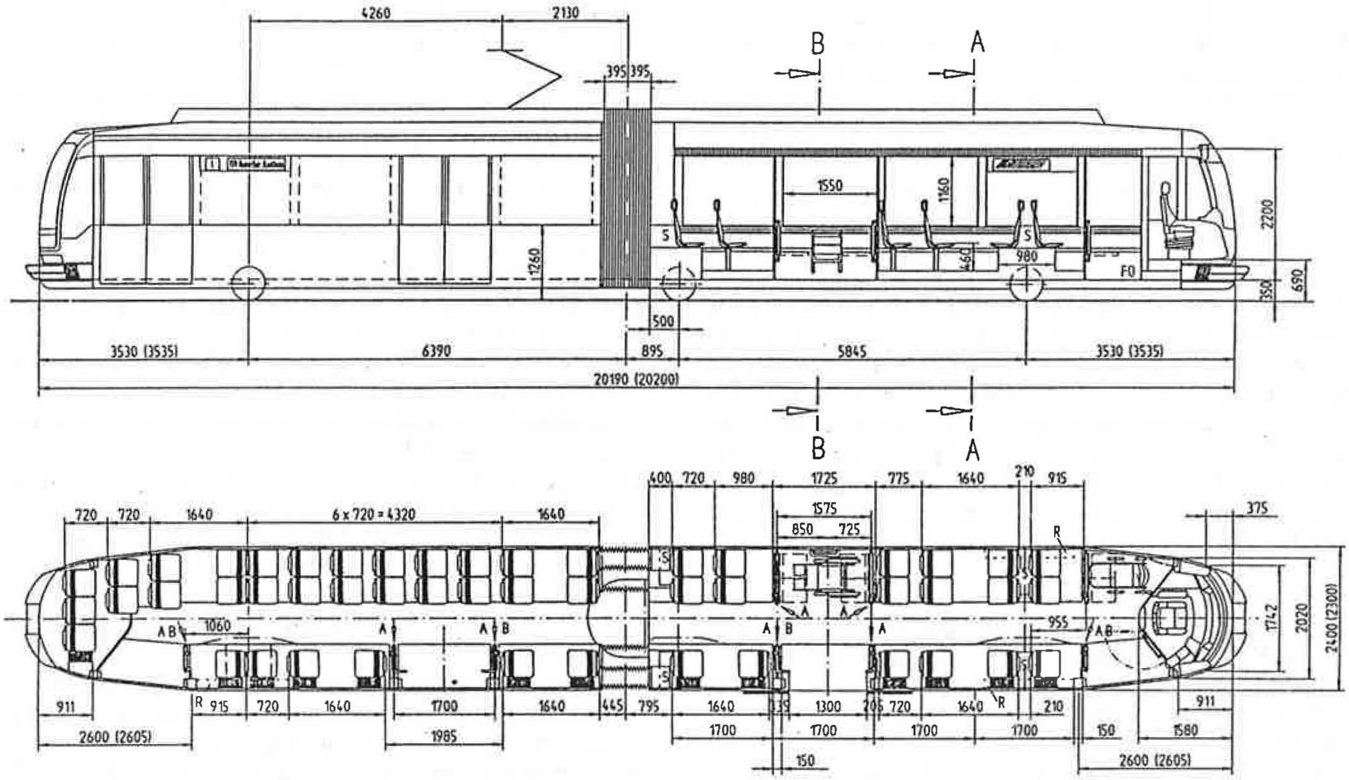


FIGURE 4 Principal dimensions of VÖV two-section low-floor car.

wag), Linke-Hofmann-Busch GmbH, MAN, and Waggon-Union], four German electric equipment builders (ASEA Brown Boveri AG, Allgemeine Elektrizitäts-Gesellschaft, Siemens AG, and Kiepe Elektrik GmbH), and four German public transportation authorities [Rheinische Bahngesellschaft AG, Düsseldorf (project leader); Stadtwerke Bonn, Verkehrsbetriebe; Mannheimer Verkehrs-AG; and Verkehrsbetriebe Ludwigshafen GmbH].

The development was promoted financially by the German Federal Ministry of Research and Development and the states of Nordrhein-Westfalen, Rheinland-Pfalz, and Baden-Württemberg.

Although the car body itself is more or less conventional, the running gear is completely different and new. Instead of conventional trucks or single axles with two wheels, individual self-steering wheels, powered and unpowered, are used. The basic design was developed by Frederich of Aachen Technical University and tested for some time under a two-truck motor car of the Rheinbahn in Düsseldorf whose front truck had been replaced by two single wheels as used later under the three prototype cars, but which was driven by a conventional traction motor suspended longitudinally under the car floor via a cardan shaft and a differential gear. After the tests had shown satisfactory results, three different prototypes were built:

1. A single-ended, two-section, six-wheel car 2.4 m (8 ft) wide with a steel body and four powered wheels under the front (A) section, of standard gauge, for Düsseldorf;
2. A double-ended, two-section, six-wheel car 2.4 m wide with a screwed aluminum body (ALUSUISSE patents) and four powered wheels under the A-section, of standard gauge, for Bonn; and
3. A single-ended, three section, eight-wheel car 2.3 m (7 ft 7 in.) wide with a steel body and six powered wheels under the front (A) and center (C) sections, of meter gauge, for Mannheim/Ludwigshafen.

The running gear (*21*), which is the speciality of these cars and was designed by Duewag and Bergische Stahl-Industrie (BSI), cannot be described here in detail. It consists of a frame the transverse members of which are depressed to permit a low floor. The wheels are supported on axle stubs, but these can rotate in a horizontal plane around a vertical shaft slightly outside the wheels for about 15 degrees to both sides of the transverse centerline through the two wheels. Both wheels are connected by a gauge rod (as with the front wheels of an automobile). Each of the powered wheels is driven by a 60-kW AC motor via two intermediate spur wheels and a system of planetary gearing and three bevel gear wheels that allow the rotation of the stub axles around the vertical shafts. The unpowered wheels are provided with the same gear boxes (which are part of the running gear frame) but do not have motors or gear wheels. In order to provide smooth running and to avoid shocks when the wheel flanges touch the railhead, the wheel profile has been modified as compared with the standard ones used for streetcars and LRVs running on grooved rail track.

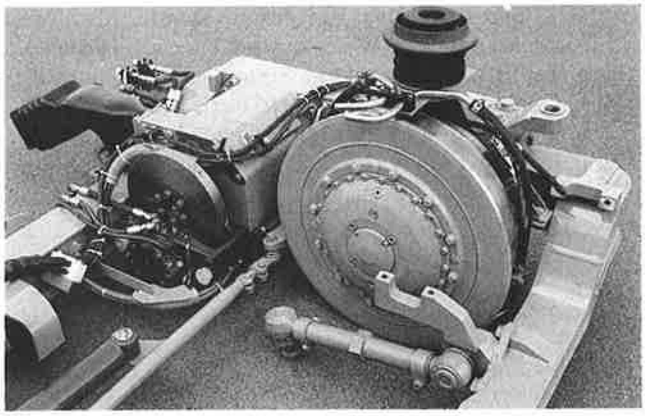


FIGURE 5 Powered single-wheel running gear of VÖV low-floor car.

All three prototypes are still being tested, and it is not possible to predict when they will go into revenue service nor when they will be ordered in series. However, the unpowered single-wheel running gear has already been used in a slightly different design under the central section of the Kassel cars mentioned earlier, and they will also be used in the Bochum-Gelsenkirchen, Rostock, Halle, and Bonn cars now under construction.

BN LRV 2000

The BN LRV 2000 runs on trucks with four single wheels, two of which have a small diameter [375 mm (15 in.)] and two of which have a large diameter [640 mm (25 in.)]. Each of the large-diameter wheels is powered by a 40-kW AC hub motor via planetary gearing. The truck looks very much like the maximum traction type used frequently for streetcars before the advent of the President's Conference Committee (PCC) car. The individual parts of the truck frame are connected by various link rods, so that it fits easily into even narrow curves.

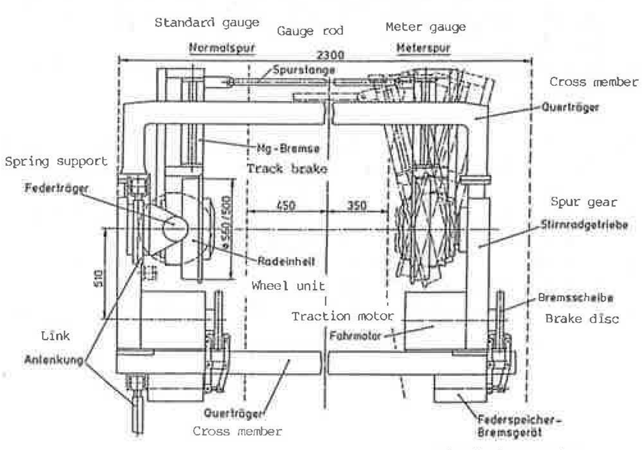


FIGURE 6 Diagram of single-wheel running gear of VÖV low-floor car.

The body of the prototype car was developed from that of a guided bus and has a floor height of 350 mm above TOR. Seats above the trucks are mounted on podia as with the other cars of this group. Cars of this design have been ordered for Bruxelles with a short center section as in the Grenoble cars and a four-motor, equal-wheel truck beneath.

SOCIMI S-350 LRV

The SOCIMI S-350 LRV is, so far, the only double-truck car (without articulation) built as a low-floor car. The four wheels (550 mm in diameter) of each truck are again supported on stub axles. Each wheel is driven by a 20-kW AC motor mounted directly on the outside of the truck frame via a double-reduction spur gear. The low transverse members of the truck frame permit the car floor to be lowered to 350 mm. All seats above the trucks are on podia, and the electric equipment is located in boxes under the other seats.

The first series of cars built with this design will be for Strasbourg, France. It will be a rather unique car with seven sections, the four small ones (two at the ends with the driver's cabs and two in the middle) having trucks under them (three powered, one unpowered).

FURTHER LOW-FLOOR CAR DEVELOPMENTS

Although the cars described in the preceding sections (except those for Bruxelles and Strasbourg) have reached the prototype stage or have already gone into series production, there are further developments in low-floor cars that have not yet left the drawing board.

Among the car designs with 60 to 70 percent low-floor area, two three-section types should be mentioned that are equipped with four conventional trucks (in both cases with powered ones only) and where the low-floor area is about 40 to 50 percent. These are new cars for Freiburg and Sheffield, England, to be built by Duewag that have to negotiate heavy gradients up to 9 percent. For this reason, all axles must be powered.

A car for Frankfurt/Main (*22*), also to be built by Duewag, is still in the design stage. It will be similar to those for Bremen and München mentioned earlier in that the trucks are below the center of each section, but it will be a double-ended car. Each of the four wheels of the truck will be driven by a water-cooled, 50-kW hub motor via planetary gear. The Frankfurt car will have three sections and powered trucks under the end sections only. The unpowered truck under the center section will have wheels with a slightly smaller diameter, thus allowing the podia here to be somewhat lower.

A further interesting development is being pursued by Simmering-Graz-Pauker (*23*) and tested in Wien with a prototype center section between two trailers modified accordingly. The single wheels are arranged in the transverse centerline of the articulation. When powered, they are driven by vertical AC motors in the articulation portal. This design allows the floor height to be further reduced to 200 mm (8 in.) in the center of the car and to 150 mm (6 in.) at the doors. Clearance below the floor would be only about 130 mm (5 in.), which could present a problem at the peaks of vertical curves.

Schindler Waggon and Schweizerische Industrie-Gesellschaft are working on still another concept known as Cobra 370. This car will use a truck design with steerable wheel sets having independent wheels, the two on either side driven by a longitudinally mounted motor via cardan shafts and bevel gears. The wheels sets are steered by the articulations via a system of rods.

CONCLUSION

This review has shown that the development of low-floor cars has not yet finished. The prospective customers can select from more than a dozen designs, all of which have their advantages and disadvantages. The choice among them is made easier if prototypes have been built and tested. For an existing LRT or streetcar system, careful assessments will have to be made before low-floor cars are introduced, and these evaluations may result in excluding one or another design. The maintenance costs should be kept in mind. Another problem is the suitability of any existing shop for the maintenance work. In most low-floor car designs, it is necessary to move much of the equipment to the car roof. This requires elevated service platforms in addition to those existing for pantograph, lightning arrestor, main circuit breaker, and resistance maintenance. The maintenance shops, in which roof equipment components weighing up to 500 kg (1,100 lb) have to be removed and reinstalled, must have sufficient roof height to accommodate the necessary cranes.

In spite of all these problems, it is quite safe to state that almost all new LRV or streetcar procurements will have to be some type of low-floor car. However, low-floor cars cannot be used on those systems, especially in the western part of Germany (e.g., Hannover, the Ruhr area cities, Düsseldorf, Köln, and Frankfurt), where streetcar routes have been upgraded to light rail operation and have high platforms in the tunnel sections and at some surface stations and low platforms elsewhere. This may lead to a situation in which, after all the old streetcar-type vehicles for the remaining surface routes of these systems have been replaced by new low-floor cars, total accessibility is available, whereas on the light rail routes it is not. How this situation could be improved or changed is a consideration for the future.

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