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Avenio T1 – the new tram for Munich

Short delivery times and impressive characteristics in operation

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Introduction

In response to growing passenger numbers, the municipal utility company Stadtwerke München (SWM) and the city transport company, Münchner Verkehrsgesellschaft (MVG), placed an order in October 2012 for eight new low-floor trams in order to improve their timetabled service.

The new units were to provide space for 220 passengers each, thereby matching the capacity of the existing high-capacity trams of types R 3.3 (Bombardier / Siemens) and S (Variobahn; Stadler).

It goes without saying that a high level of ride comfort was expected, likewise low-wear and energy-saving operation on the demanding Munich route profile.

The ordering of eight Avenio T1 low-floor vehicles from Siemens was under severe time constraints from the very start, as the new trams had to be operational by the time of the timetable change on December 15, 2013.

As it turned out, it was possible to present the world's very first Avenio tram in Munich as early as the beginning of November 2013. The swift production of the new rolling stock was achieved thanks to the fact that the development of the Avenio platform with its modular design was already well advanced at Siemens.

After rectifying some minor technical deficiencies on the vehicles and after an extensive approval process to meet the standards of the responsible technical supervisory authority (TAB) in Munich at the Upper Bavarian regional government, the first vehicles entered passenger service in September 2014, initially with provisional approval. Since early 2015, all eight trains have been in daily scheduled service on the tracks in Munich, with final approval being completed on October 1, 2015. Reason enough to draw the first conclusions.

Fig. 1: The Avenio T1 in Munich (Source for all images: Siemens AG)

Vehicle design

The Avenio T1 for Munich (Fig. 1) is based on the single-articulated vehicles that have seen successful passenger service in Almada, Portugal, since 2005 and in Budapest, Hungary, since 2006. Each car body is supported on a centrally located bogie. Contrary to conventional bogies with stiff wheelsets, the Avenio motor bogie is equipped with two pairs of 600 mm diameter independently rotating wheels, which are coupled in longitudinal direction via one traction motor per side with bevel-gears at both ends ("longitudinal wheelset").

The bogies can turn by up to 4.5 degrees relative to the car body enabling the tram to negotiate tight curves and to achieve a comparatively smooth entry into curves. Although the left and right sides of the bogie are linked electrically, the two (longitudinal) wheelsets can negotiate the different length paths of the inner and outer rails on curves largely unhindered as there is no mechanical coupling of an axle shaft.

This concept lays the foundation for the most positive possible behavior of the vehicles in terms of ride comfort, tire wear and noise emission.

The bogie-car body interface has been revised compared to predecessor vehicles, so that now a comfortable arrangement of 16 seats above each bogie is possible. The secondary springs are functionally separated into vertical and horizontal suspension, eliminating the need for the hydraulic buckling protection system used on the predecessor vehicles. The vehicle, which has already been described in detail in [1] and [2], has a 100% low-floor design and with a payload density of 4 persons/m^2 has a total capacity of 216 persons, of whom 69 are seated.

The Avenio T1 has an attractively designed and spacious interior (Fig. 3), which allows a view through the entire vehicle and even through the driver's cab.

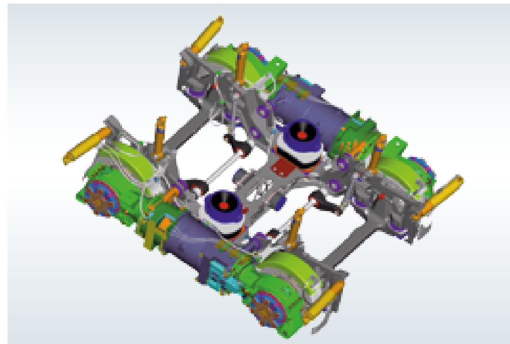


Fig. 2: Avenio, motor bogie

Eight double-doors on the entry side, each with a clear opening width of 1,300 mm, speed up the boarding and alighting process, thus contributing towards an extremely punctual service.

The electric lift at the first door allows unobstructed access to the vehicle for persons of reduced mobility. In the first and fourth segments of the tram there are spacious multifunctional areas for the stowage of baby buggies etc.

Fig. 3: View through the passenger compartment of the Avenio T1 for Munich

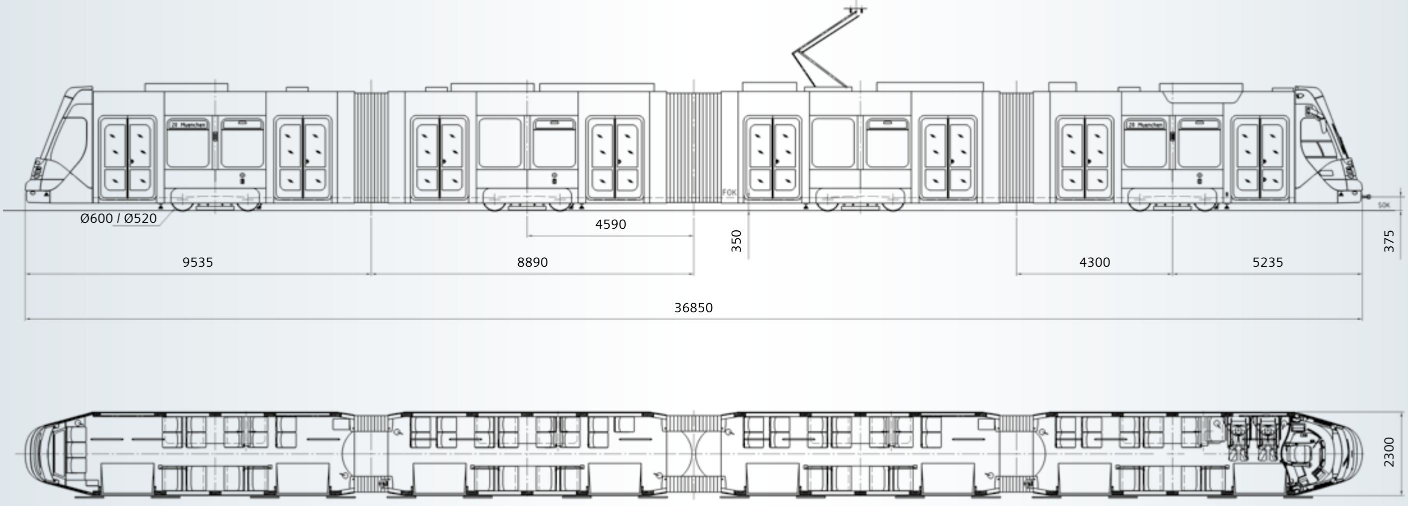


Fig. 4: Dimensions of the Avenio T1 for Munich

Between these there are three smaller multifunctional areas opposite the doors. Air conditioning systems ensure a pleasant atmosphere in the light-filled passenger compartment and in the driver's cab. The SWM / MVG commissioned the Munich design consultancy ergon 3 to contribute toward this pleasing design.

The essential dimensions and technical data can be found in Fig. 4 and Table 1.

The carbodies are based on a welded construction made of weathering structural steel (Corten steel), which is covered after the coating process with painted aluminum sheets. After sandblasting, the car bodies are given an epoxy resin-based corrosion-proof coating by means of cathodic dip-painting (CDP).

Vehicle	Four-section low-floor articulated tramcar for unidirectional operation
Axle arrangement	Bo'2'Bo'Bo'
Line voltage	750 V DC
Gauge	1,435 mm
Vehicle length	36,850 mm
Vehicle width	2,300 mm
Vehicle height	3,550 mm
Wheel diameter max. / min.	600 / 520 mm
Percentage of low floor	100%
Entry height	300 mm
Capacity (at 4 persons/m²)	216, of which 69 seated
Maximum speed	70 km/h
Max. gradient	max. 6%
Tare weight	approx. 47 metric tons

Table 1: Technical data of the Avenio T1 for Munich

Before the coating process, a DC voltage is applied to the carbody, which is then dipped into a paint bath containing paint particles with an opposite charge (Fig. 5). The particles of paint are attracted by the carbody and deposited on it to form an even film of paint over the entire surface. The electronic attraction causes the paint to adhere to the metal with extraordinary strength, enabling it to penetrate into all corners, nooks and crannies during the dipping process. The bodyshell components remain immersed until the coating has reached a specified thickness; this coating is then baked on in the oven.

At the Fraunhofer Institute IFAM in Bremen, the CDP coating used on the Avenio was subjected to the salt spray test as specified in DIN EN ISO 9227 [3] for 1,440 hours and the condensation water test according to DIN EN ISO 6270-2 [4] for 720 hours.

The tests showed that the coating system with an overall thickness of about 25–30 µm meets the toughest requirements according to DIN EN ISO 12944-6 [5] with the corrosiveness category *C5 M long* (corresponds to use in offshore installations).

Externally, i.e. on the roof, front and underfloor areas, the CDP coating is additionally coated with proven topcoat systems to further improve the corrosion protection. This lays the foundation for an extremely durable carbody.

Fig. 5: Avenio carbody during cathodic dip painting

Initial operating experience

Acoustic characteristics
One of the development goals of the Avenio platform was to create a vehicle that was comfortable in every respect. With regard to the acoustic behavior, apart from the usual sound-deadening measures on the vehicle, further design measures were adopted which help to keep noise emissions to a minimum.

Fig. 6: Noise level outside at standstill, max. heating level

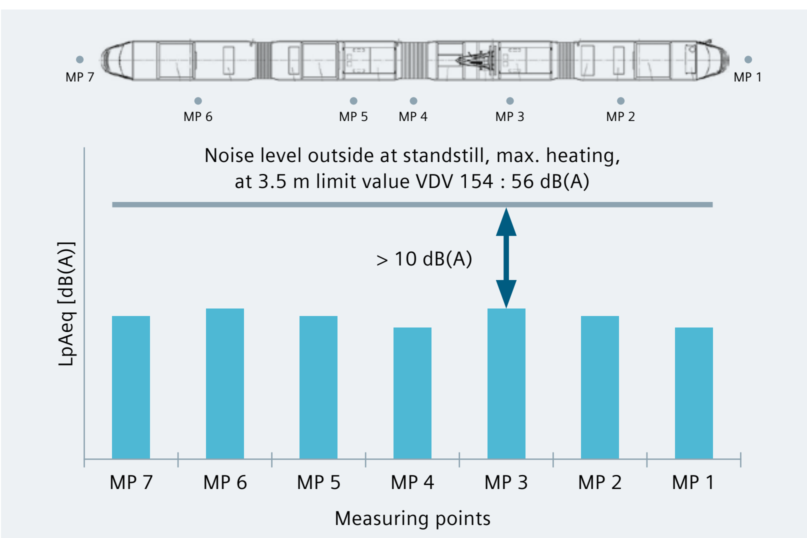
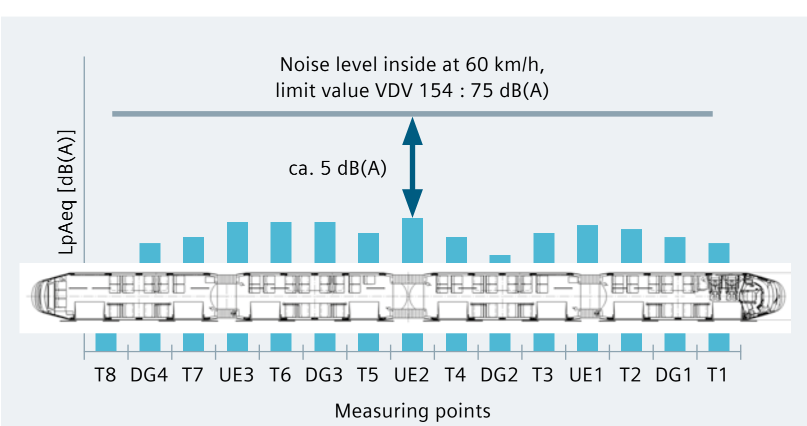


Fig. 7: Noise level inside at 60 km/h



A selection of the soundproofing measures:
- Use of modern suspension and linkage systems for reducing the transmission of structure-borne noise into the vehicle and infrastructure
- Use of special sound absorbers in the ventilation systems
- Use of wheel flange lubricators for reducing squeal in curves
- Electrical braking to standstill
- Throttling of auxiliary units when vehicle is stationary

The acoustic demands of the SWM are oriented toward the levels recommended in Recommendation 154 of the Association of German Transport Companies (VDV) [6]. These requirements were checked in the course of several acceptance measurements that were performed in accordance with DIN EN ISO 3095 [7] and DIN EN ISO 3381 [8] at the Siemens Wegberg-Wildenrath Test and Validation Center and on a track operated by the SWM / MVG.

The measurement results confirmed what was expected during development of the vehicle: The Avenio is a quiet vehicle. In all areas the customer specifications, as well as the limit values of VDV Recommendation 154, were complied with and in many cases by a considerable margin.

Regarding external noise at a standstill, the measured sound pressure level in maximum heating mode is more than 10 dB(A) below the specified values (Fig. 6). Even in the air conditioning and ventilation mode with a full payload, the levels are almost 10 dB(A) below the limits. As a reminder: A clear margin of 10 dB(A) below the limit represents a subjective halving of the perceived noise level – in other words, when standing at a tram stop the vehicle emits only half the specified noise level.

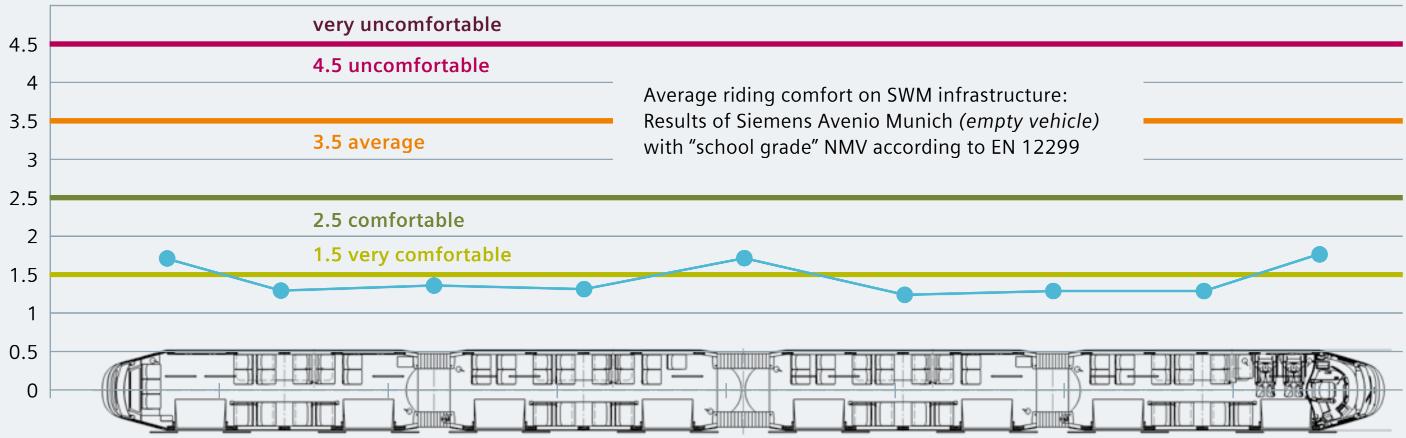


Fig. 8: Average measured comfort NMV in accordance with EN 12299

Internally, at a speed of 60 km/h and even at the noisiest location in the vehicle, the double articulation gangway, the interior noise is about 5 dB(A) below the limit of 75 dB(A), while in the other areas of the passenger compartment the measured sound levels are even lower, thus contributing to a comfortable ride experience (Fig. 7). The measured values are also reflected in the subjective impressions of the passengers.

In the "as-delivered" state of the trams, however, some noises in the driver's cab were regarded as annoying. These were generated by the compressor of the wheel flange lubrication system mounted below the cab. Additional decoupling and sound insulation has since achieved a noticeable improvement in this situation.

The vibrations emitted by the vehicle are very slight in comparison with other vehicle concepts. Two major factors contribute to this: On the one hand, resilient wheels of type SAB V60 were used and, on the other hand, both the motor and trailer bogies of the Avenio have low unsprung masses of just 1,500 kg or 1,840 kg, respectively.

Ride comfort

The normal gauge route network of SWM is very demanding for low-floor trams and includes curve radii of as little as 17 m, tight curve entries, numerous switches and a low flange clearance of just 5 mm.

This applies in particular with regard to ride comfort, in which the Avenio can show its full strengths due to the advanced vehicle concept and the well-balanced running gear.

The progressively designed rubber-metal molded springs permit an almost constant vertical natural frequency of the vehicle in all load situations. This results in a constantly high level of ride comfort. The Avenio is not affected by the intervention of additional vertical buffers which otherwise occurs in the case of above-average payloads. The progressive characteristic also permits comparatively low static spring travel and can thus guarantee minimum platform gaps for boarding from the platform level.

The result of combining ample lateral spring travel and a stiffly tuned lateral suspension characteristic is that the transverse bump stops do not come into contact, even on a very challenging track. Even the fully laden vehicle does not touch the bump stops when traveling at speed on curved tracks. The Avenio also exhibits excellent ride characteristics in the case of lateral accelerations. With a combination of progressive rubber springs, long lateral spring travel and stiffly tuned anti-roll links, it exhibits excellent anti-roll characteristics. In combination with the side wall inclined at 1.4°, the optimized dynamic clearance requirement enables a maximum area of passenger compartment to be achieved on the existing route.

The excellent ride characteristics or the expected high level of ride comfort were confirmed during the exhaustive type testing measurements. On sections of the Munich network specified jointly with the approval authority, a total of 13 runs were made with an empty vehicle and 12 runs with a fully laden vehicle. During this test, nine positions in the vehicle were equipped with accelerometers, enabling 225 measurements to be recorded.

The measurements were analyzed according to DIN EN 12299 [9] and in each case the continuous ride comfort level C_{Cy} and mean comfort level N_{MV} were determined. C_{Cy} represents the vibration comfort exclusively in the lateral direction and N_{MV} combines the comfort values of all three spatial directions.

In the entire load range from empty to fully-laden a level of ride comfort was achieved which is classified according to DIN EN 12299 as *very comfortable or comfortable* (Fig. 8), the assessment being recorded on a scale from 1 (very comfortable) to 5 (very uncomfortable).

The following average values were achieved for the mean comfort N_{MV}:

- Seats and standing areas in the car body: ≤ 1.3
- Articulation areas: ≤ 1.7
- Driver's cab: ≤ 1.8
- Rear area: ≤ 1.7

Tire wear

The experience gained with the Siemens single-articulated vehicles in Hungary and Portugal suggests a high mileage for the tires in Munich too, even if for the Avenio T1 Munich – unlike the vehicle in Budapest – no "wear profile" is used for the wheel profile and, due to the small track gauge clearance of about 5 mm, more frequent contact between rail and wheel flange is probable in curves.

The theoretical background factors and interrelationships that are largely responsible for the low tire wear of the Avenio have already been published several times – see [10] and [11].

They are therefore only listed here in brief outline:

- The longitudinal wheelset of the drive provides additional help to the centering lateral profile force to prevent wheel flange contact on straight track.
- In curved track sections, the decoupling of the independently rotating wheels ensures rolling without enforced longitudinal creepage forces. In contrast to conventional wheelsets, the longitudinal wheelsets can roll at different rotational speeds according to the different lengths of track on the inside and outside of curves.
- Due to the rotary elastic connection between bogie and carbody, the guiding forces when entering a curve and in the case of track disturbance are considerably less than on a vehicle with substantially fixed running gear connection. This results in a positive support of the lateral profile forces in straights as well. The secondary spring system always strives to adopt the lowest state of potential energy (i.e. bogie aligned to the car body).
- The absence of interfering forces due to longitudinal offset between bogie center and car body center of gravity or due to supporting forces of an adjacent sedan module in conjunction with the frictionless bogie connection enables the bogie to be centered on the track and allows a symmetrical development of wear.

It is to be assumed that the Avenio will also achieve long service life for its tires in Munich. The first vehicles have currently reached a mileage of about 65,000 km; no reprofiling of the tires has yet been necessary. To date, it can be ascertained that, as expected, the wheel flange angles have largely adapted to the rail gauge faces, thus improving safety in derailment protection. The wear over the tread profile is even and even the differences between the leading and trailing wheels are comparatively small. From the data available so far, it is difficult to extrapolate a reliably achievable tire life – although considerable mileages can be expected, especially considering the re-profiling strategy used in Munich, as well as regularly turning the bogies by 180°.

Maintenance and availability

The basic concept of the Avenio is geared toward excellent access to all components that require maintenance. This is confirmed by experiences gained so far from servicing and maintaining eight Avenios in passenger service. The trains can be processed in reasonable times; where some components are more difficult to access than is desirable, this can generally be attributed to the compromises necessary in order to achieve the low-floor design or meet fire protection requirements.

Since they entered service, the availability of the vehicles has been at a comparatively high level for new rolling stock, already approaching the reliability of service proven vehicles in the existing fleet. To date, the vehicles in service have been largely free from faults and extremely reliable. Unplanned workshop time is essentially a result of minor technical deficiencies such as frequently occur with new rolling stock; some technical components, such as the door pushbuttons on the stanchions for example, have had to be replaced. Moreover, software has also been optimized, e.g. for the fine adjustment of the closing procedure for the passenger doors.

Passenger friendliness

Feedback on the Avenio from passengers in Munich has likewise been very positive. MVG asked the opinion of almost 200 passengers on the first new train on Line 19. In an initial survey, 97 percent assessed the vehicle overall as “very good” (47 percent) or “good” (50 percent). Just 3 percent were “undecided” and only one of those questioned found the new tram “not so good”.

The features identified by the respondents as particularly positive were:

- Very comfortable seating
- Pleasant ride experience
- Provision of eight double doors instead of usual six for even faster and more convenient boarding and alighting
- The large amount of space offered, for example by the multifunctional areas
- High-quality technical equipment (including air conditioning of the passenger compartment)

The vehicle was also received extremely positively by the operating personnel.

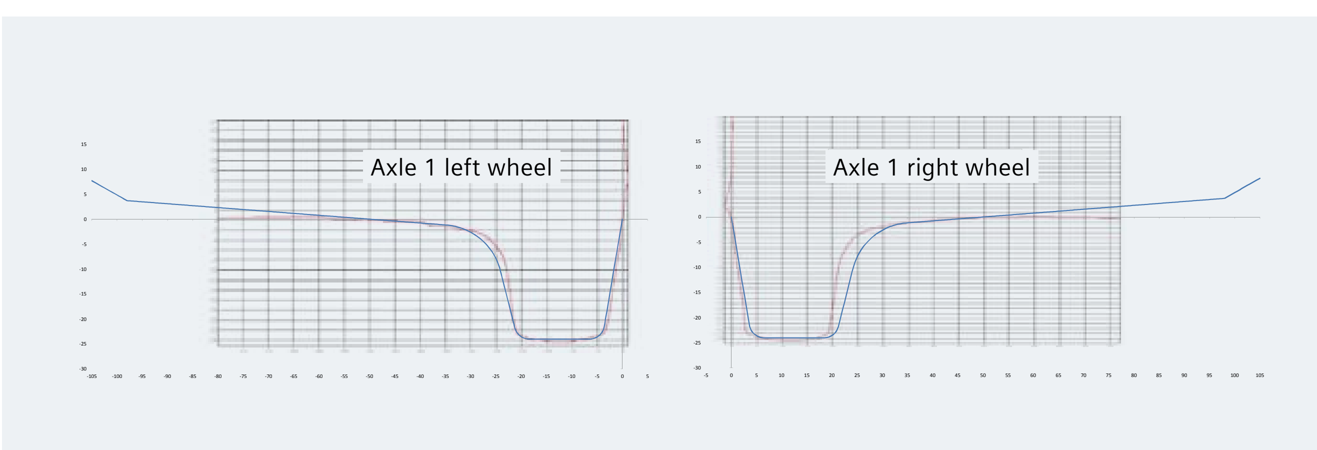
Possibilities for improvements

In the context of the passenger service so far, some potential improvements have emerged, in particular from the viewpoint of SWM / MVG, which should be taken into consideration in subsequent vehicle developments.

Specifically, these are:

- Relocation of the installation position of the wheel flange lubricator onto the roof with the aim of further improving the noise situation in the driver’s cab
- Optimization of the acoustic behavior of the power electronics, in particular at slow, constant speeds
- Making the glass fiber reinforced driver’s cab easier to repair
- Optimizing gap sizes at interior panels

Fig. 9: Wear-profiles of the leading wheels of the leading motor bogie, vehicle No. 2807, after app. 65000 km operation without reprofiling (red), compared to the wheel profile geometry in new condition (blue).
The profiles are matched at the measuring circles; wheel tread wear with respect to the radius amounts to app. 4 mm.



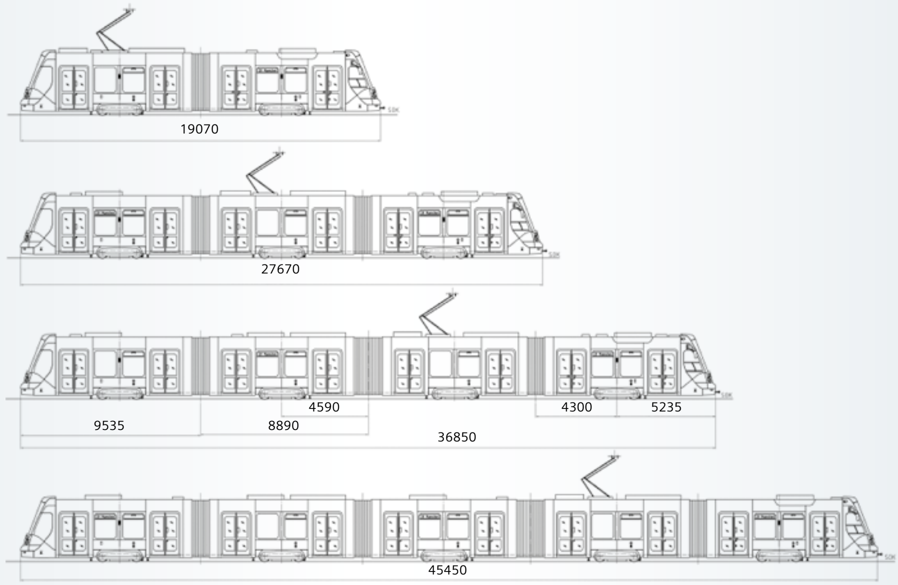


Fig. 10: The Avenio family T2 for Munich

Outlook

Following a pan-European invitation to bid, SWM / MVG ordered further Avenio vehicles in September 2015. The offer from Siemens won the contract because it scored the highest points in the assessment process in terms of price, technical criteria and contractual conditions. In a first batch, 22 trams are being purchased, specifically 9 x two-section, 9 x three-section and 4 x four-section trams, delivery of which is to start in mid-2017 (Fig. 10). The two- and three-section vehicles are to be coupled into double-traction units, and with a length of about 48 meters they will then be the longest trams ever used in Munich, offering space for about 260 passengers each.
In addition, there are options for as many as 124 additional units of between two and five sections, for delivery between 2018 and 2028. The overall value of the order, including all options, comes to around 370 million euros.

The vehicles on order represent a further development of the eight Avenio T1 type vehicles already in successful passenger service in Munich.

The essential differences include operation as double-traction units with semi-automatic coupling, a significant reduction of the maximum axle load in comparison with the max. 9,500 kg of the Avenio T1, the central electrical and hydraulic emergency release of the spring-loaded brakes, the possibility of integrating energy storage solutions, the provision of prepared diagnostics data and its transmission to the operations control center, and a driver assistance system for energy-optimized operation.

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Conclusion

Taking all experiences so far into account, the Avenio T1 is a very reliable and maintenance-friendly vehicle with an exemplary door arrangement for fast boarding and exiting. Passengers and drivers benefit in particular from a high level of ride comfort. The noise emissions are rated as comparatively low.

With the development of the Avenio, Siemens has succeeded in putting a tram on the rails that carries over the excellent vehicle characteristics of the single-articulated vehicles used in Almada and Budapest and, thanks to the successfully balanced bogies, exhibits a significantly above-average riding comfort.

Since November 2013, **Dipl.-Ing. Jürgen Schnaas** (51) has been head of Light Rail Engineering at Siemens AG, Erlangen, Germany. From 2008 to 2013 he was head of the engineering department at Bombardier Transportation GmbH, Locomotives Division, where he was responsible among other things for the product development of the TRAXX locomotives. Between 1994 and 2008 he was employed by DUEWAG AG, later part of Siemens AG, in various positions in the Engineering division, as well as in product and project management for low-floor trams.

After studying mechanical engineering at RWTH Aachen, focusing on rail vehicles, he began his professional career in 1990 as a development engineer and project manager for Rail Vehicles at VAW aluminium AG, Bonn.

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