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Technical Comparison of Commercially Available Trams and Review of Standardization Frame and Design Principles

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Abstract Tram manufacturers have different ways of approaching the design of low-floor trams with compact and reliable running gears, and therefore several tram architectures can still be found. A complete standardization of trams is nearly impossible, and technical innovations can be more easily introduced if compared to conventional railway vehicles, but the trend towards large-scale standardization based on vehicle "platforms" can be seen in recent years. However, the current "standard" tram architecture, which includes only non-pivoting bogies, is not able to solve some typical problems of tram operations, such as high wheel and rail wear and high-pitched tonal noise (squeal) in sharp curves, which are described in the present paper. This research analyses the tram market with the aim of describing the state of the art of currently available products and comparing their main technical parameters. The analysis is based on information available from the literatures (journals, web) where data about the vehicles can be found, while a new designation code (tram architecture designation, TAD for short) is specifically introduced for easier identification of the different tram architectures. Even if the complete low floor is still one of the main requested features, several solutions combining pivoting and non-pivoting bogies are commercially available, showing a tendency to give more relevance to running quality performance with respect to the recent past.

Keywords Light rail vehicle · Tram · Urban vehicles · Low floor · Steering vehicles · Tram architecture designation

1 Introduction

In the nineteenth century, tramways quickly developed around the world and remained a backbone of city transport until the advent of the internal combustion engine and private mobility. Being essentially a local (non-interconnected) rail system, nearly each city developed its own solutions.

Old trams are relatively simple electromechanical machines, and this allowed for the flourishing of many local or regional manufacturers. This approach changed in recent decades, when the trend towards a slow decay of the tram system was reversed. A number of manufacturers in fact have started developing "platforms", i.e. trams usable in many cities and countries with a limited number of variations.

The outcome of this trend is analysed in this paper on the basis of the information available in sector journals and on the web. The authors analysed the market situation within the frame of a larger project aimed at finding the optimal architecture to develop a tram with both "environmentally friendly" characteristics, with the lowest noise and vibration impact in densely populated areas, and "track-friendly" characteristics, in order to reduce wheel and rail wear and therefore maintenance costs.

Today, environmental factors are the main parameters considered during the tram selection process, with particular attention to CO_2 emissions [1]. However, power consumption can be optimized by considering regenerative braking, energy management with hybrid energy storage

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systems and modern air-conditioning systems [2–4], while problems like smooth guidance during curve negotiation cannot be easily tackled with the conventional tram design. This is particularly true for noise and vibrations and their impact on citizens.

The purpose of this paper is therefore to give an overview of the current structural architecture of commercially available trams, comparing the main parameters for more than 30 trams selected during the review of the light rail vehicle (LRV) market segment. The comparison considers operational parameters, such as low floor percentage, accessibility and performances, and technical solutions, such as the carbody arrangement and bogie and wheelset design principles. An innovative code to easily identify the tram architecture is also proposed. The main issues related to the current technical solutions adopted by tram manufacturers are analysed, describing the possible alternatives and giving some general guidelines for future tram design and evaluation.

2 Background of the Research

2.1 Standardization in the Tram Sector

Compared to other means of urban rail transport, such as metros and monorails, tramway systems are still growing rapidly in Europe [5]. However, a comprehensive European technical regulation for LRVs is not yet defined, as the "Urban Rail" working group of the European Committee for Standardization/Technical Committee 256 (CEN/TC 256) "Railway Applications", established nearly a decade ago, is still under development [6]. Although many member states of the European Union still use national regulations for LRVs (e.g. the BOStrab regulation in Germany [7]), European standards developed by CEN for conventional railway vehicles are often also used for other vehicles such as LRVs.

As an example, the Italian National Unification (UNI) standardization body released two standards defining the essential requirements for trams [8] and metro vehicles [9]. The standards extensively refer to European "norm" (EN) standards, resulting in an increased tendency towards product standardization. Standardization helps both local authorities in issuing more accurate tenders and vehicle manufacturers in developing families of similar vehicles (often called "platforms"), reducing manufacturing costs.

The drawback of adhering to standards is the reduced opportunity to introduce innovative technical solutions for problems such as wheel and rail wear or flanging and squeal noise that are widespread in urban railway systems. While the architecture of metro vehicles is similar to conventional trains, trams show several "unconventional" architectures mainly because of the *low floor* requirement that has become the preferred solution for tramway systems all over the world. As it will be shown later, several manufacturers only offer fully low floor solutions in their portfolio.

While low floor solutions improve passenger access to the vehicle, especially for people with reduced mobility (PRM), they strongly impact the architecture of running gear, forcing manufacturers to design unusual and often complex solutions for wheel mounting, motor/transmission and braking component arrangement. Therefore, standards for trams cannot prescribe mandatory rules for running gears, and often only basic (or "system") requirements are defined. As an example, basic requirements defined by the Italian standard [8] are shown in Table 1, while referenced EN standards are shown in Table 2. To appreciate the difference with the railway case, consider that the wheel profile is not defined, and it should be designed to optimize the wheel–rail contact.

2.2 Evolution of Tram Design

The development of trams over the years has been largely driven by the development of smaller and compact bogies. Conventional tram bogies can be defined considering their connection to the carbody, and three main categories can be found:

- Pivoting bogie, with a physical or virtual slewing bearing, located either under a carbody (classical

Table 1 Basic requirements for a tram vehicle as defined by the Italian standard [8]

Length of uncoupled vehicle	< 45 m
Recommended carbody width	2.3–2.4 m
Running horizontal curve radius	≤ 25 m
Running vertical curve radius	≤ 350 m
Running track slope	$\geq 5\%$
Doorstep height	≤ 350 mm
Door width	≥ 1200 mm
Comfort ratio	$\geq 15\%$
Floor slope inside the vehicle	$\leq 5\%$
Longitudinal jerk	≤ 1.5 m/s^3
Noise emission (40 km/h)	≤ 75 dB(A)
Noise emission (0 km/h)	≤ 68 dB(A)
Axle load (seats + 420 kg/m^2)	≤ 10 t
Braking performance (service braking)	≥ 1.3 m/s^2
Average acceleration between 0 and 30 km/h	≥ 1 m/s^2
Acceleration on 5% track slope	≥ 0.1 m/s^2
Speed	≥ 60 km/h

Table 2 EN standards referenced by the Italian standard [8]

EN standard	Field of application
EN 12299	Riding comfort
EN 12663-1	Carbody structural requirements
EN 13103	Axle design
EN 13272	Lighting
EN 13452-1/EN 13452-2	Requirements for brake system
EN 13749	Bogie structural requirements
EN 14363	Safety on twisted track
EN 14750-1/EN 14750-2	Air conditioning
EN 14752	Doors
EN 14813-1/EN 14813-2	Driver cab air conditioning
EN 15227	Requirements for crash safety
EN 15461	Noise emission
EN 15663	Masses definition
EN 16019	Automatic couplings
EN 45545	Fire protection

railway solution) or at the end of two carbodies (see Fig. 1 for an example)

- Non-pivoting bogie (or fixed bogies), bolsterless bogies directly connected to the carbody by means of a more or less rigid secondary suspension
- Shared bogie with two carbodies separately resting on the bogie frame (so-called Jacobs bogies)

An overview of the history of tram design can be found in Viganò [10], in which the technical solutions adopted since the development of the first low-floor tram in 1984 and the main features of partial and fully low-floor trams are critically discussed. Detailed information about several trams developed between 1984 and 1992 can also be found in Hondius [11], in which the author describes the higher costs due to the transition from high or partial to fully low-floor trams.

In general, the classical design between 1950 and 1980 was derived from conventional train architecture with the introduction of the articulation between the carbodies, as shown in Fig. 1, while in the early 1980s, prototypes of modern trams appeared with the introduction of the low floor requirement. This design principle led to deep modifications of the classical architecture by lowering the central part of the vehicle to a maximum height of 350 mm by the introduction of a central trailing bogie with independently rotating wheels (IRWs). From this single articulated vehicle, still partly connected to the railway practice, several different and more complex solutions were developed over the years.

The central articulation was firstly replaced by a dedicated short module, in which the carbody was fixedly connected to the trailing bogie, articulated with both the longer front and rear carbodies. Then the fully low-floor concept was developed in the early 1990s, and pivoting bogies, especially if powered, began to face limitations, for two reasons:

- The aisle width inside the vehicle was limited by the large bogie rotation during running in small-radius curves.
- The floor level over the pivoting bogies was too high, introducing an obstacle inside the vehicle.

With further developments for the suspension and motor arrangement, non-pivoting bogies were adopted instead of pivoting bogies at the ends of the vehicle as well. This tram architecture rapidly evolved in the most modern design of *multi-articulated* trams with suspended carbodies, which is the most common tram architecture nowadays. A synthetic overview of this evolution is shown in Fig. 2.

2.3 Current Tram Issues

As described in the previous paragraph, bogie development has been crucial for the evolution of tram design. However, independently from the connection to the carbody, bogies are made of two wheelsets, conventional or IRWs, connected to the bogie frame with a relatively high primary yaw stiffness. Therefore, the wheelsets tend to remain

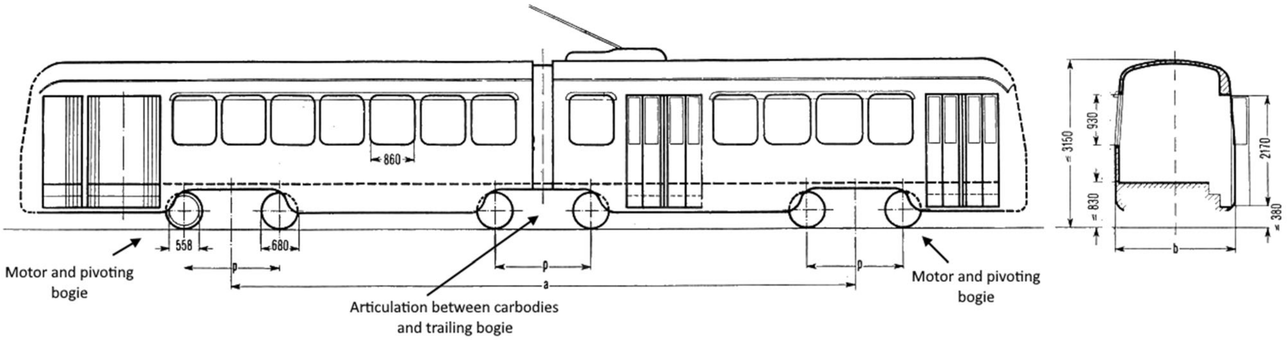


Fig. 1 Example of early standardization of a single articulated tram with a fully high floor in Italy (UNI 3192:1952)

a) 1984 - Firema
ATM 4500 series

b) 1987 – Alstom
TSE Grenoble

c) 1990 – MAN
GHH GT6N

d) 1994 – Bombardier
Eurotram

Fig. 2 Overview of the evolution of tram architecture. From the left: **a** tram with central low-floor section above an IRW bogie and pivoting bogies at the ends, **b** tram with central low-floor section above a non-pivoting bogie attached to a dedicated module and pivoting bogies at the ends, **c** tram with a fully low floor and three non-pivoting bogies, and **d** tram with a fully low floor, non-pivoting bogies and suspended carbodies. Images taken from Viganò [10]

parallel to each other in all running conditions, reducing the steering ability of the vehicle. The tendency to maximize the free space inside the vehicle and the consequent extensive adoption of non-pivoting bogies have further reduced the curving ability of trams, increasing the issues of wheel and rail wear, flanging noise and squeal noise. Examples of design of pivoting and non-pivoting bogies are shown in Fig. 3. Other solutions adopted for motor bogies with IRWs can be found in Kolar [12].

If trains run reasonably well in curves down to approximately 400 m, creepage at the wheel–rail contact becomes serious in metros (curve radius often around 200 m) and severe in trams (curve radius down to 18–20 m). In the latter case, wheel tread taper can be omitted (there is not enough compensation due to the steering effect), and wheels are often made independent, although IRWs only eliminate longitudinal creepage. As a result, rail and wheel wear remains a central issue in modern trams.

The comparison of running behaviour of trams characterized by different technical solutions can be found in Capek and Kolar [13] and Richter and Vemmer [14], showing how non-pivoting bogies exert higher lateral forces when entering small-radius curves, especially if long driver cabs are installed at the vehicle ends. Figure 4 (left) shows the lateral wheel force while running in a 20 m radius curve at 15 km/h for a pivoting bogie and a non-pivoting bogie. It is evident that the rigid connection between the bogie and carbody results in higher transient forces in the first part of the curve, exerting severe wheel–rail contact conditions. The energy dissipated at the contact can be estimated with Eq. (1), in which X is the longitudinal force, Y is the lateral force, γ_x the longitudinal creepage and γ_y the lateral creepage. The ratio between the total tangential force and the normal force (T/N) is also the friction value f at the wheel–rail contact. If f is higher than the maximum available friction f_a, slip occurs. All these parameters influence the growth of wear, tear and noise.

$$T\gamma = X\gamma_x + Y\gamma_y \tag{1}$$

Due to the very severe conditions, especially in curves, flanging and squeal noise are still serious problems for almost all urban railway systems, affecting citizens in densely populated areas. If flanging noise can be tackled with proper wheel flange lubrication, squeal noise remains an erratic and particularly disturbing pollution [15]. It is due to the stick-slip phenomenon triggered by the "falling

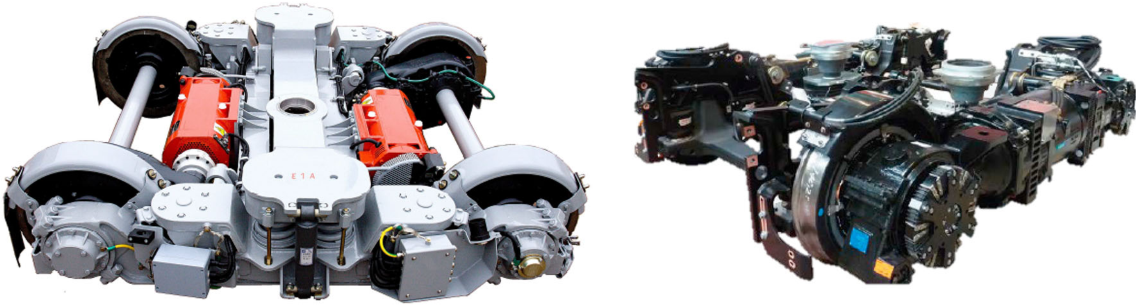


Fig. 3 Motor bogies for low-floor trams. On the left a pivoting bogie with conventional wheelsets and transversal motor arrangement (available at http://www.pragoimex.cz/en/download/default/90). On the right, a non-pivoting bogie with IRWs and a longitudinal motor arrangement (available at https://assets.new.siemens.com/siemens/assets/api/uuid:67afff1c-e169-4470-a6a1-bf105db846b1/mors-b10025-00-datasheet-bogies-sf35-deenus-144_original.pdf)

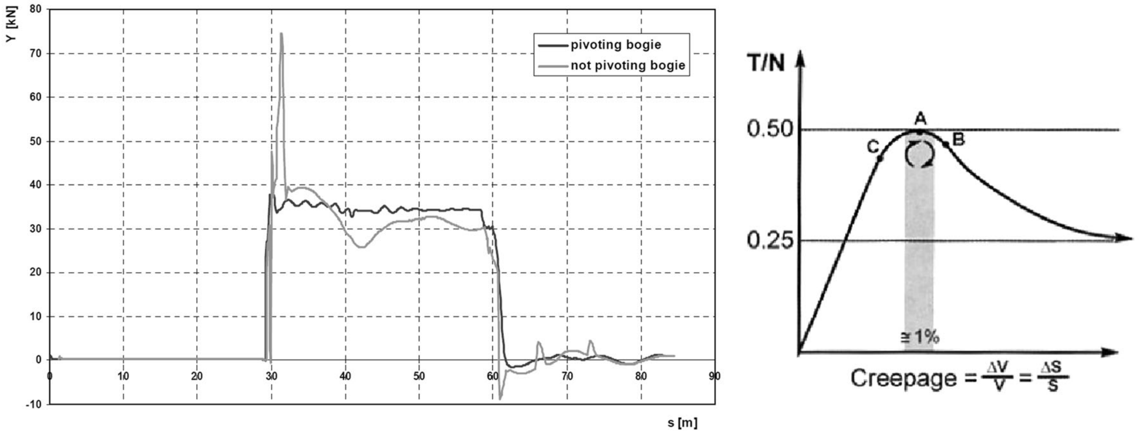


Fig. 4 Left: lateral wheel force for a pivoting bogie and non-pivoting bogie while running in a 20 m radius curve at 15 km/h [13]. Right: friction curve for dry rails and representation of the “stick-slip” behaviour due to the falling friction

friction” part of the adhesion curve at the wheel–rail contact, as show in Fig. 4 (right), in which the *T*/*N* ratio has reached an f_a value of 0.5, i.e. dry rails.

As IRWs only eliminate the longitudinal creepage γ_x by free relative rotation of the wheels, they are not able to solve the problem if they are installed in bogies, especially if non-pivoting bogies are used. In fact, even with short-wheelbase bogies, relevant values of angle of attack remain, and therefore lateral creepage is still present. Also, IRWs eliminate the natural centring effect of conventional wheelsets, and solutions with a transmission shaft reconnecting the independent wheels only in straight track via self-locking differential gearboxes have been developed [12]. However, the adoption of this solution has been limited by the complexity in terms of operation and maintenance.

The simplest way to mitigate squeal is to avoid the falling slope of the friction curve either by spraying water on the contact areas or by using solid or liquid friction modifiers. In any case, adhesion is necessary on city roads for other users (pedestrians, cars, bikes, etc.), and any kind of “lubricant” must be used with great care to avoid other problems.

Resilient wheels are also used to reduce the noise emitted by LRVs due to their greater damping compared to monoblock wheels. According to the report by the Federal Transit Administration [16], noise reduction up to 2 dB for rolling noise on tangent track and up to 20 dB for squeal noise on curved track can be reached with resilient wheels. However, the report states that their cost is about four times higher than conventional wheels and that their effect is strongly dependent on the rubber configuration and the compromise between axial and radial stiffness.

Resilient wheels are also not very effective at mitigating another important issue related to urban rail mobility, i.e. ground-borne vibrations. Vibrations can appear on both straight track and curved track depending on rail and wheel conditions, and monitoring procedures are still needed to keep the problem under control [17]. Due to the low unsprung mass installed on trams and the requirements for life endurance of the rubber under sever conditions of traction and braking which lead to radial stiffness values between 20 and 200 kN/mm, the effectiveness of resilient wheels against ground-borne vibrations is usually very low, especially for vibrations below 80–100 Hz [16, 18]. Sometimes old vehicles offer better performance than new vehicles [19], and wheel properties can be one of the reasons.

Although all the vehicles considered in the following are equipped with conventional bogies, solutions for trams equipped with steering mechanisms have been developed in the past to help the vehicle running through a curve. A short description is reported in the following.

The only structural way to definitively solve the problems related to curving is the use of steered axles with IRWs to eliminate (or to drastically reduce) the angle of attack of the “wheelset” that is responsible for large lateral creepage. Possibly the two most famous examples of trams with single steered axles and IRWs are the COBRA tram in Zurich [20] and ULF (Ultra-Low Floor) tram in Wien [21].

While the COBRA architecture was already a multi-articulated tram with two suspended carbodies, the ULF tram has a completely different arrangement as it is made by five carbodies on six axles having a portal frame running gear with vertically arranged motors and bevel gears, for a total length of 35 m. Figure 5 shows the general view of the tram and a detailed description of the portal frame. Secondary suspension, made of helical springs and hydraulic actuators, is located in the upper part of the portal and can be raised by the driver to increase the ground clearance. Axles between intermediate carbodies are steered by adjacent carbodies with the TALGO connection,

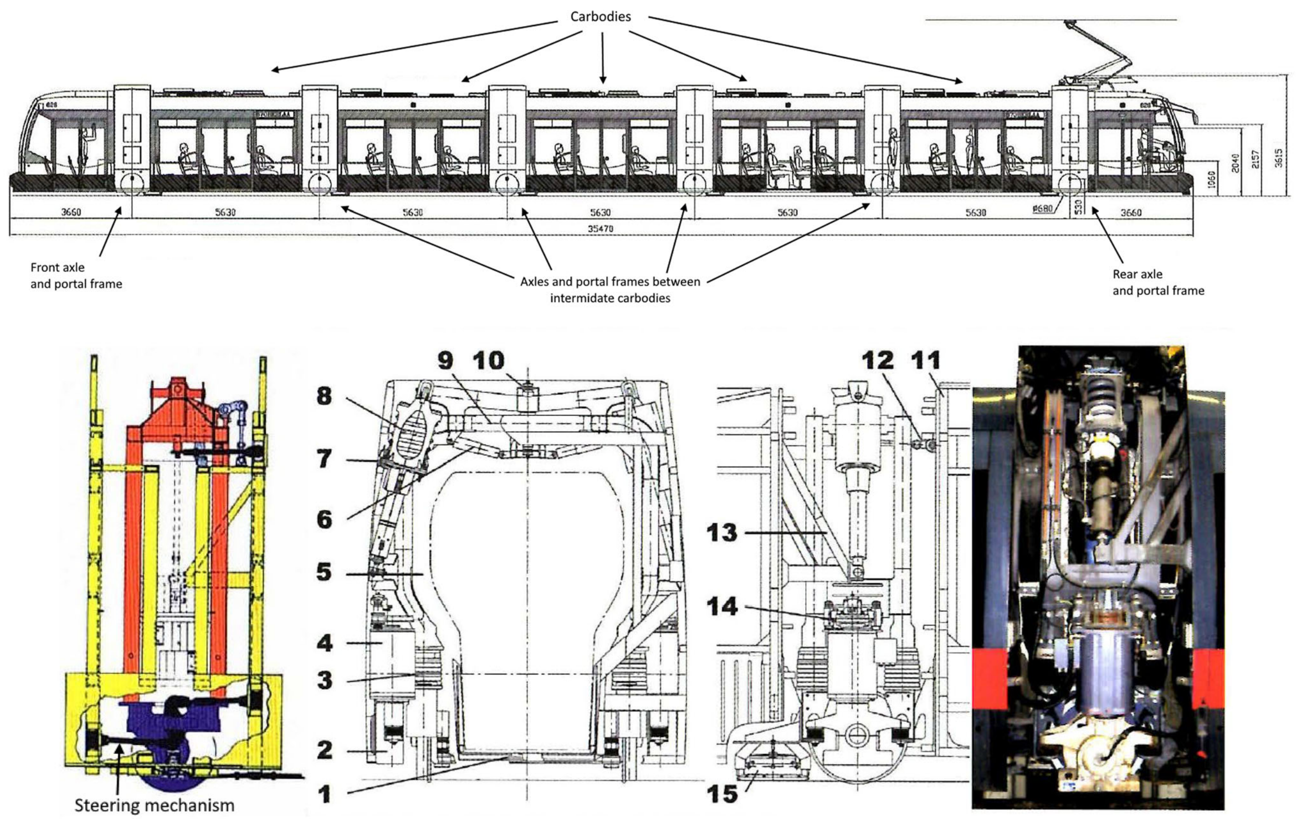


Fig. 5 Ultra-low floor (ULF) in Wien. Above: external view of the complete tram. Below: TALGO-like steering mechanism between intermediate carbodies and detailed description of the portal frame (1 = joint between carbodies; 2 = gearbox; 3 = primary suspension; 4 = vertically arranged three-phase asynchronous motor; 5 = interior panelling; 6 = lateral damper; 7 = hydraulic height levelling; 8 = secondary suspension; 9 = portal frame; 10 = vertical damper; 11 = carbody; 12 and 13 = carbody connections; 14 = brake disc connected to the motor; 15 = magnetic brake). Images modified from Mattersdorfer [22]

while the front and rear end axles are steered by linkages. This solution allows for a floor as low as 197 mm [21].

Developed in the 1990s and still in service, the production of these advanced trams was stopped, and they are offered nowadays neither by the respective manufacturers nor by any other manufacturer. The complexity of running gears and maintenance problems may have acted as a deterrents for further applications.

3 Research Methodology

In the present work, a new designation code for tram carbodies and bogies arrangements is proposed to easily compare the different vehicle architectures. The new code was used during the vehicle selection process for a comparative analysis over the worldwide market and main manufacturers.

The results of this analysis are evaluated to understand whether the standardization trend that started in the 1990s with multi-articulated vehicles is still dominant, or whether other solutions have been adopted to mitigate the previously shown issues. The impact of vehicle architecture on operational and performance parameters is also discussed.

3.1 Proposal for a New Designation Code for Tram Architectures

Currently available trams do not fit into the “standard designation of axle arrangement on locomotives and multiple-unit sets” historically defined by the International Union of Railways (UIC) [23], which only describes the number of motors and trailing axles, whether they are grouped in bogies and whether the bogie is pivoting.

This designation scheme is not suitable for many modern tram architectures, such that the so-called *multi-articulated* tram, which is one of most common solutions today, as the sequence of short carbodies attached to a single non-pivoting bogie and completely suspended carbodies cannot be described by UIC designation.

For this reason, a new unambiguous designation scheme for trams, called *tram architecture designation* (TAD), based on carbody typology and support

Table 3 Description of symbols for tram carbody TAD designation. Symbols for different carbodies are separated by a space

Symbol	Description	Equivalent UIC
Designation of a carbody fully resting on a non-pivoting bogie		
`M`	Carbody on *motor bogie*	B or B_0
`T`	Carbody on *trailing bogie*	2
Designation of carbody ends resting on pivoting bogies, single axles or other carbodies		
`m`	Carbody end above a *pivoting motor bogie*	B′ or B_0'
`t`	Carbody end above a *pivoting trailing bogie*	2′
`J`	Carbody end above a *Jacobs motor bogie*	B
`j`	Carbody end above a *Jacobs trailing bogie*	2
`S`	Carbody end above a *single motor axle*	A
`s`	Carbody end above a *single trailer axle*	1
`^`	Carbody end suspended on an adjacent carbody	N/A

arrangement is introduced and compared (Table 3) to UIC symbols. Some examples of how the TAD better defines tram architecture are shown in Table 4, where it can be seen that all four tram arrangements are described by the same UIC designation (`B 2 2 B`), and it is only possible to distinguish between pivoting and non-pivoting bogies, while the new designation gives a unique code for each vehicle, as it is based on carbody arrangement.

The new designation proposed in this paper also applies to ULF and similar trams. Referring again to Table 3, the tram shown in Fig. 5 would be classified as `sS SS SS SS Ss`.

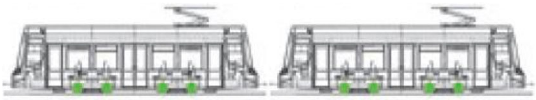
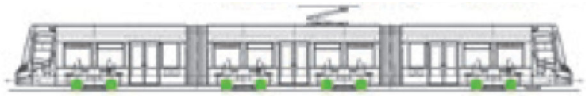
3.2 Vehicle Selection for Comparison

Data selection is crucial for obtaining comparable and reliable data, especially given the huge number of different trams operating across the cities in the last century. Instead of comparing existing vehicles, which in many cases are no longer produced and often survive thanks to their extreme simplicity (it is not unusual to see nearly 100-year-old, fully electromechanical vehicles still running in Europe, such as "Type 1928" in Milan [24]), the authors decided to conduct a market analysis to explore trams that are currently offered by manufacturers around the globe.

As an independent and well-known source of data on market trends, the issues of the international journal *Metro Report International* [25] published in 2017 and 2018 were analysed. The selection of the time interval was deemed to be sufficient to catch the most important innovations as well as "stabilised" portfolios. The analysis of the news on new tram commissioning was considered as a valid way to identify the most important (or at least the most "active") manufacturers, without any direct relationship to market volume or presence in the different scenarios.

At the end of the process, 25 vehicle manufacturers were identified, while browsing the Internet and collecting information from the authors' previous experiences helped

Table 4 Example of four different tram architectures described by the same UIC designation, but with unique codes using the TAD codification. Green dots identify wheels belonging to pivoting bogies, while red dots identify wheels belonging to non-pivoting bogies. Source https://www.skoda.cz/en/products/tramcars/

Tram architecture	UIC	TAD
	`B′ 2′ 2′ B′`	`mt tm`
	`B′ 2′ 2′ B′`	`m^ tt ^m`
	`B′ 2 2 B′`	`m^ T ^^ T ^m`
	`B 2 2 B`	`M ^^ T ^^ T ^^ M`

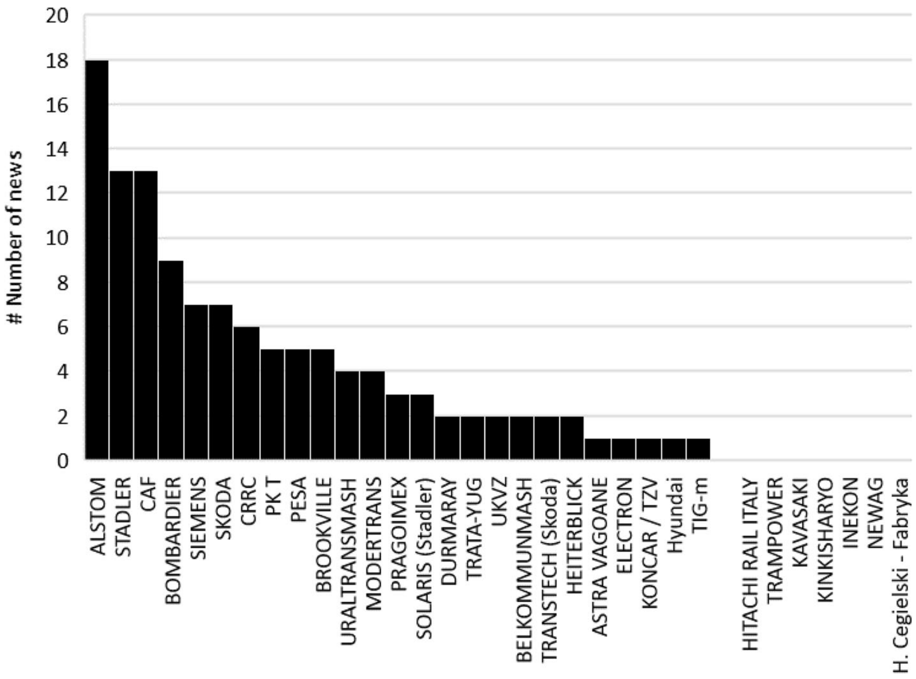


Fig. 6 News about new tram commissioning published in *Metro Report International* [25] in 2017 and 2018 grouped by vehicle manufacturers. Further manufacturers (on the right) were included after a World Wide Web search

to identify further manufacturers that were not found in the analysis described above. These manufacturers were included as well, and their products were analysed according to the information publicly available on the web.

A comparative analysis was therefore performed for 32 vehicles chosen from the portfolios of the whole set of manufactures, shown in Fig. 6, in which the largest share of news was about Alstom, mainly due to the news related to catenary-free systems, which is about 30% of the total number of news for this manufacturer.

Considering the difficulties in obtaining a complete set of data and the low availability of accessible sources, the set of vehicles selected for the comparison is considered a valid sample for analysing the state of the art of the tram architectures. The list of the vehicles chosen for the analysis is shown in the Appendix, in which the architecture is described according to the new designation code. The year of the order, the reference city and the track gauge are also shown, describing an important variety of systems chosen throughout the world.

3.3 Main Parameters for Comparison

Comparison of existing trams is crucial for selecting meaningful parameters, and a short description of selected parameters is presented in this section, while a comprehensive discussion of the outcomes of the comparison is presented later. To locate the selected parameters more easily, they will be listed hereinafter in *italics*.

The *percentage of low floor* is for obviously one of the main parameters on which this research is based. In fact, even if most of the vehicles today are based on the 100% low-floor philosophy, there are still solutions using a lower percentage. It should be noted that the selection of a fully low-floor or a partially low-floor architecture is often based on non-technical arguments.

Other parameters used in this comparison are related to the passenger transport capacity, such as the *number of seats per meter*, the *standing passengers per meter* and their ratio, i.e. the *comfort ratio*, and accessibility, which is a central issue in trams, as stops must be shortened as much as possible, offering wide and spacious entrance/exit areas to the vehicle (therefore limiting the number of seats). Doors also represent a central issue for reliability, and their design requires a careful evaluation. Therefore, the number of *single doors*, the number of *double doors* and the *mean distance between doors* are considered as important parameters in the work.

General architecture parameters as well as operating parameters were also considered in this research. The vehicles were then compared considering the *mean length of carbodies* and the *number of bogies*. The *axle load* in the condition of 4 pax/m^2 (280 kg/m^2) and *number of traction motors* leads to *power for unit of mass*, while performance is also evaluated considering the *maximum speed*, *starting acceleration* and *maximum running slope*.

As an overhead line is often criticized as having high visual impact, especially in historical cities, several *energy* *supply systems* are also available today as alternatives to the standard catenary–pantograph system. The offer of catenary-free vehicles has grown over the years, including the following:

- Ground-level power supply (GPLS) such as *APS* from Alstom and *Tramwave* from Ansaldo STS
- Onboard energy storage system (OESS) using *batteries* and *supercapacitors* charged at defined stations, such as the PRIMOVE system from Bombardier
- Onboard power generation system (OPGS) using *diesel engines* or, more recently, *fuel cells*

A description of the state of the art with a list of tramway lines using catenary-free systems can be found in Swanson and Smatlak [26], and advantages and drawbacks of the aforementioned technologies are explained. The systems are also described in Guerrieri [27], in which a comparison was performed between two different systems (APS and PRIMOVE) considering their possible application for new tramway lines in Italy. The research showed how the APS system is financially more feasible.

4 Results and Discussion

4.1 General Considerations

As shown in Fig. 7, in which an analysis of the sample of vehicles chosen for the comparison is presented, most of the trams are shorter than 35 m, with the larger proportion (43%) falling in the range of 30–34 m, even if in many cases the architecture is modular, and shorter (or longer) trams are theoretically possible. Nearly all the vehicles (72%) offered today have a 100% low floor, but it is worth highlighting that half of the considered vehicles in the cases are not related to multi-articulated trams, with the tram having at least one pivoting bogie and no suspended carbodies. For the multi-articulated architecture, about 30% of the vehicles have two suspended carbodies, but modularity of the platform is again a key factor for this parameter.

The *average length of the carbodies* appears to be a significant parameter useful for comparing all the properties of the selected vehicles. It can be seen that the multi-articulated architecture enables a reduction of this parameter, which becomes smaller as the number of suspended carbodies increases with the same overall length of the tram, as shown in Fig. 8.

Regardless of the architecture, all trams exploit the same kind of service, characterised by low average speed (normally below 20 km/h in most cases), short distance between stops, and high acceleration and braking. Maximum *starting acceleration* is declared to be about 1.2 m/s^2 for almost all vehicles, but the conditions for obtaining this value are rarely clearly stated. The maximum value can be maintained only until a certain speed, generally between 30 and 40 km/h, and the mean acceleration in the full range of speed and fully loaded is about 0.7 m/s^2.

Also, the performance is not strictly related to the architecture of the vehicle. All the trams have a *maximum speed* of 60–80 km/h, while the *maximum design slope* is in the range 6–9%. The *adhesion ratio*, i.e. the ratio between the number of motor bogies and the total number of bogies, varies from 0.5 and 1, and the most frequent values are 1 (38%) and 0.67 (35%). The *power per unit of mass* is quite variable, with a mean value of about 8.5 kW/t.

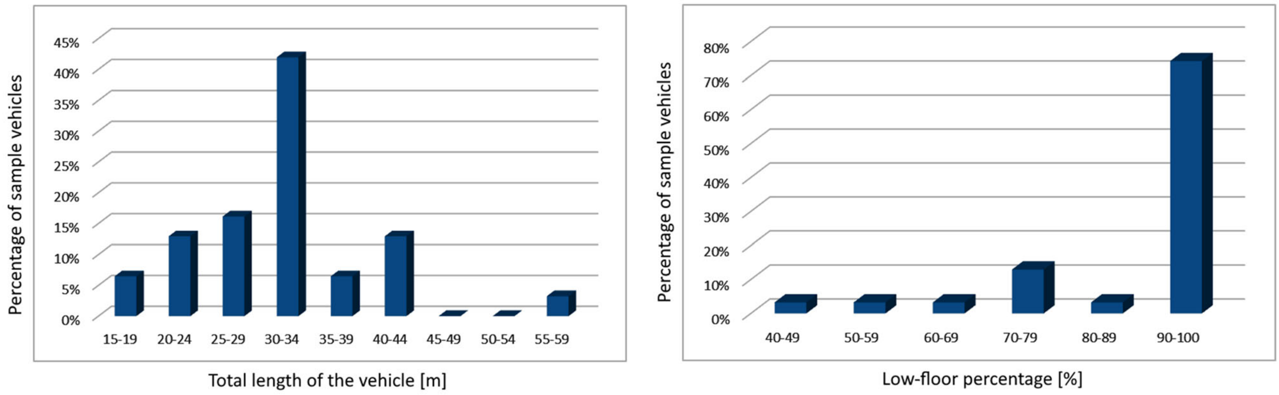
4.2 Kinds of Bogies

The renaissance of pivoting bogies emerges from this research, as different solutions adopted for the running gear technologies were found. The range of solutions extends from the more standard multi-articulated vehicle with only non-pivoting bogies to combinations of pivoting, non-pivoting and Jacobs bogies. An example is the *Škoda ForCity Plus* for Bratislava with a TAD of `m^ M ^^ T ^m`, shown in Fig. 9. The vehicle is designed for a 1000 mm track gauge, and it has 90% low floor with three different types of bogies: two motor pivoting bogies at the end of the vehicles (two steps are used over these bogies) with 1.8 m wheelbase, one non-pivoting trailer bogie with 1.8 m wheelbase and one non-pivoting motor bogie with 1.9 m wheelbase. Only conventional wheelsets with longitudinally arranged motors and gearboxes are used, and non-pivoting bogies can elastically rotate about ± 2°.

The use of pivoting bogies at the end of the vehicle is a clear trend, showing a return to older design philosophies. Pivoting bogies are installed near the driver cab, where a reduction of about 10–20% of the fully low floor and the aisle width inside the vehicle are not an issue. In many cases, the low floor extended for a limited length (from 70 to 95% of low floor) of the vehicle is often considered a sufficient solution for passenger comfort inside the vehicle. In some cases, users have shown a preference for "high-level" seats, especially for longer travels, as they are perceived as quieter. As a result, these seats are often readily occupied at the terminus.

Obviously, the use of several different kinds of running gears could be a problem for the maintenance costs, also considering a higher number of spare parts.

All the considered vehicles are equipped with bogies with primary and secondary suspensions. The bogie wheelbase is always between 1.7 and 1.9 m, with shorter values (1.6 m) only for some trailer bogies, and IRWs are mainly used with resilient wheels and longitudinally



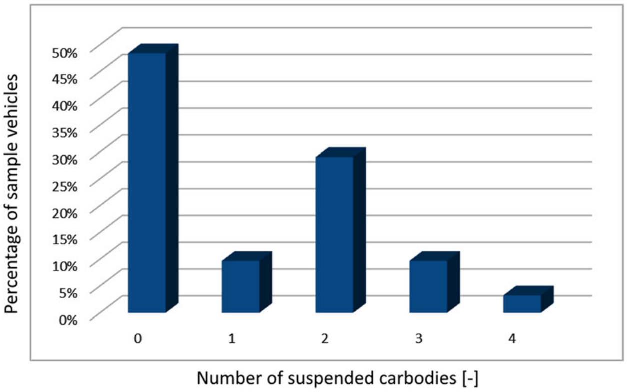


Fig. 7 Analysis of the sample chosen for the comparison, considering the total length of the vehicle, the low-floor percentage and the number of suspended carbodies

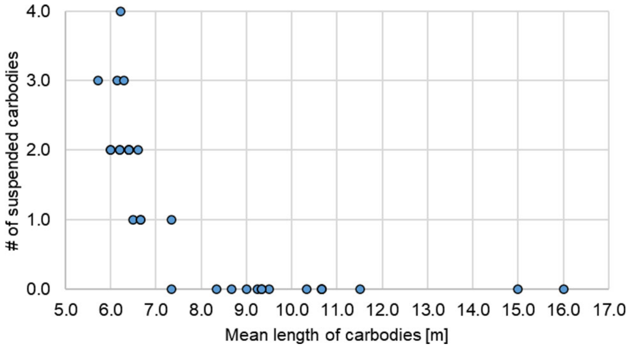


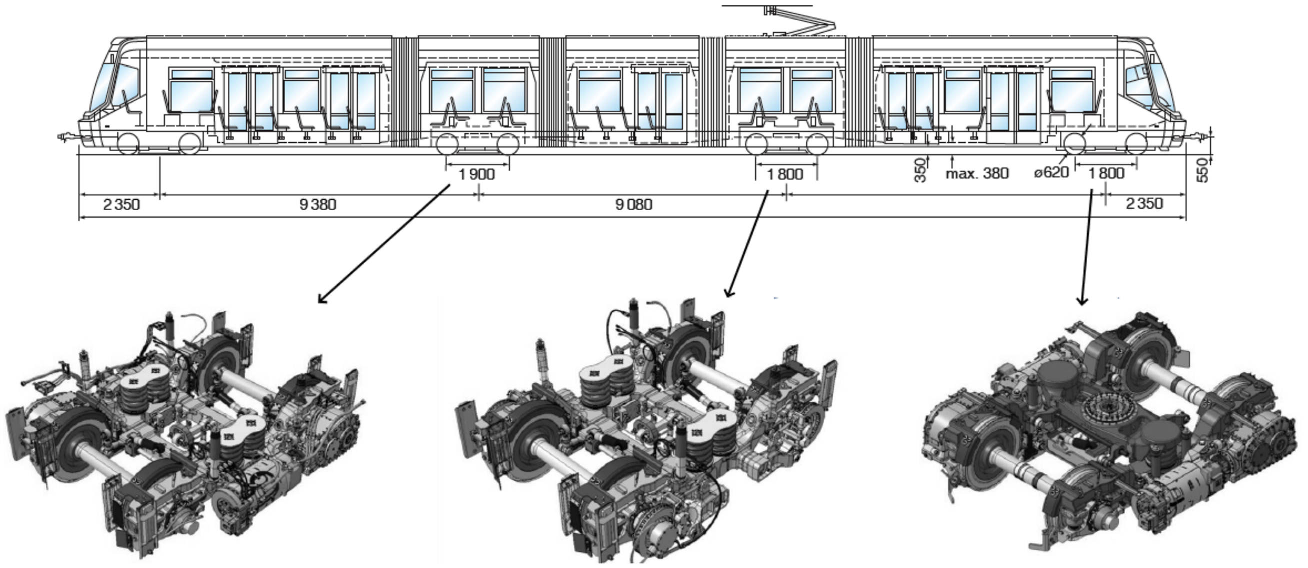
Fig. 8 Correlation of number of suspended carbodies (0 = no suspended carbodies) with mean length of the carbodies

arranged traction motors. However, the use of small-diameter wheels between 600 and 680 mm (and consequently low axle height above top-of-rail level) has made it possible to reduce the floor height above motor bogies from 900 mm to about 500–600 mm. This reduced height can be handled in the vehicle by smooth slopes instead of steps, avoiding obstacles incompatible with wheelchairs for example. This solution allows the use of more standard solutions for running gears, including conventional wheelsets and gearboxes grouped in pivoting bogies, reducing wheel and rail wear in sharp curves, and lowering manufacturing and maintenance costs. An example of a pivoting motor bogie with a 610 mm wheel diameter and 1.78 m wheelbase is shown in Fig. 3 (left), which is relative to the single-carbody mm vehicle *EVO1* from Pragoimex shown in Fig. 10. The height over the two motor bogies is only 500 mm.

Direct drive traction can also help to reduce the available space by removing gearboxes, which are often noisy and difficult to maintain. Research has shown only one vehicle with direct drive, which is applied to the fully low-floor tram *ForCity Alfa 15T* from Škoda [12]. The bogie is shown in Fig. 16, and it is worth highlighting that in order to further increase the space, hydraulic braking is applied directly to the tyres of the resilient wheels. Jacobs motor bogies with a double articulation are used for the connection of the intermediate carbodies (Fig. 11).

4.3 Masses and Axle Loads

Compared to other architectures, multi-articulated trams of the same length have the advantage of using a lower number of bogies. As a result, the mean distance between the bogies is greater, resulting in a higher axle load



Non-pivoting motor bogie

Non-pivoting trailer bogie

Pivoting motor bogie

Fig. 9 Škoda ForCity Plus for Bratislava with three different kinds of bogies. Modified from Hondius [28]

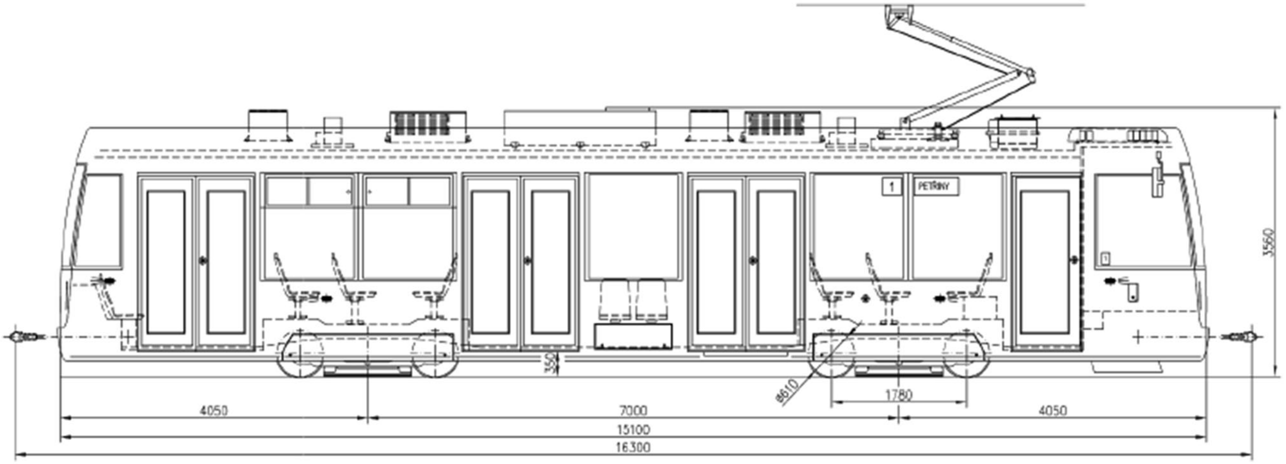


Fig. 10 Single-car tram EVO1 from Pragoimex. The vehicle can be considered 100% low floor, as the height of the floor over the bogie is only 500 mm, and the difference with the doorsteps at 350 mm is accommodated by a smooth transition. Source http://www.pragoimex.cz/en/page/barrier-free-tramcar-evo1-276

(Fig. 12). The axle load is always lower than 10 t/axle, but all the multi-articulated trams have an axle load in the range of 8–10 t. This means that values greater than 10 t are achieved in the exceptional loading conditions of 6 pax/m^2, i.e. 420 kg/m^2.

The lightest tram (6.2 t/axle) is the *Leoliner*, developed by HeiterBlick for Leipzig (Fig. 13). The vehicle, with three pivoting bogies with conventional wheelsets, two carbodies and a 70% low floor (the height over the motor bogie is 900 mm), has been in service since 2006, and the manufacturer has launched two subsequent models, the Vamos 70 (70% low floor) and the Vamos 95 (95% low floor), which have the same concept but with four bogies and three carbodies.

A similar solution but with two Jacobs bogies was adopted by Škoda for the tram *ForCity Alfa*, which has an axle load of 6.8 t (Fig. 14). This solution also allowed the installation of six double doors with only 5.2 m of distance between doors. Also, the single carbody tram EVO1 has a very low axle load, i.e. 6.6 t.

It is worth highlighting that the mass per unit of length of the empty vehicles is always in the range 1.2–1.4 t/m, independently from the carbody material, i.e. steel or aluminium. Considering that, as shown in Fig. 15, 6 pax/m can be considered for all vehicles, the payload can be

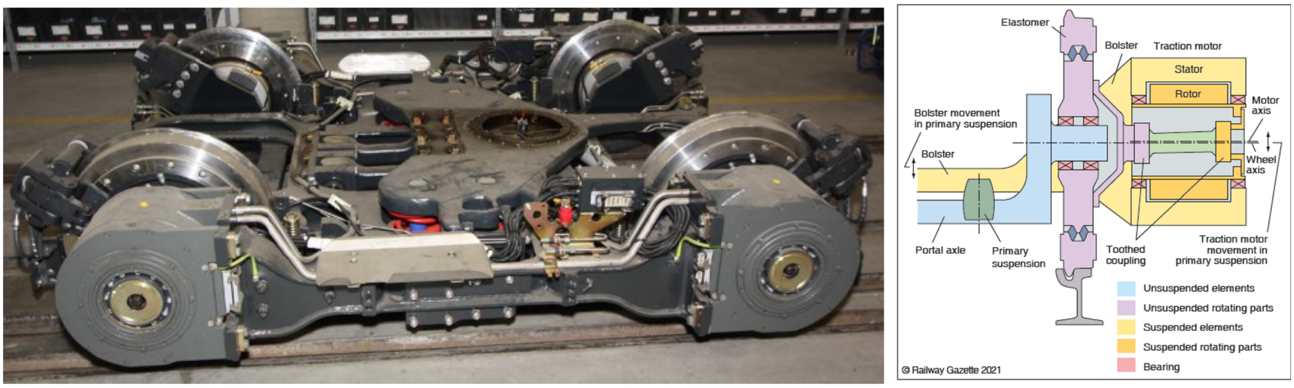


Fig. 11 Pivoting bogie of the Škoda ForCity Alfa for Prague (left) and detail of the direct drive arrangement (right) [28]

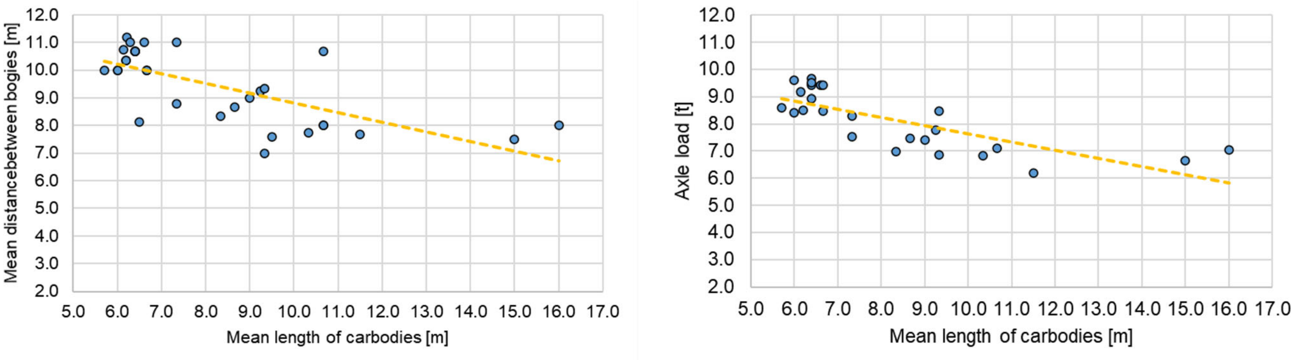


Fig. 12 Mean distance between bogies (left) and axle load (right) versus average length of carbodies

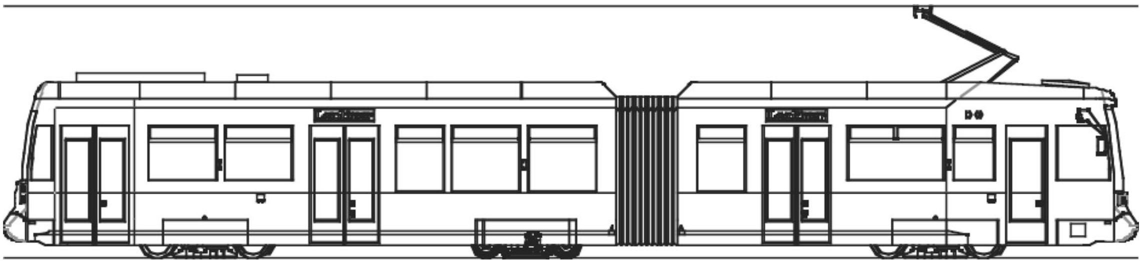


Fig. 13 Leoliner tram from HeiterBlick. Source https://www.heiterblick.de/fileadmin/template/downloads/Produktblaetter/LeoLiner.pdf

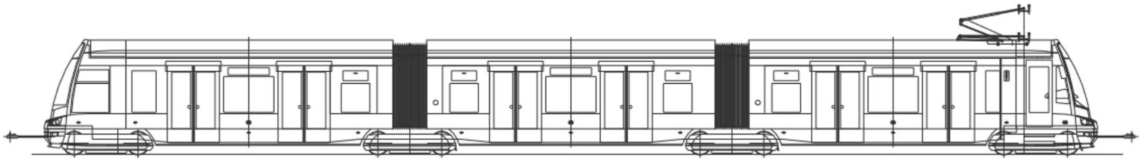


Fig. 14 ForCity Alfa from Škoda. Source https://www.skoda.cz/data/catalog/6/99/888.pdf

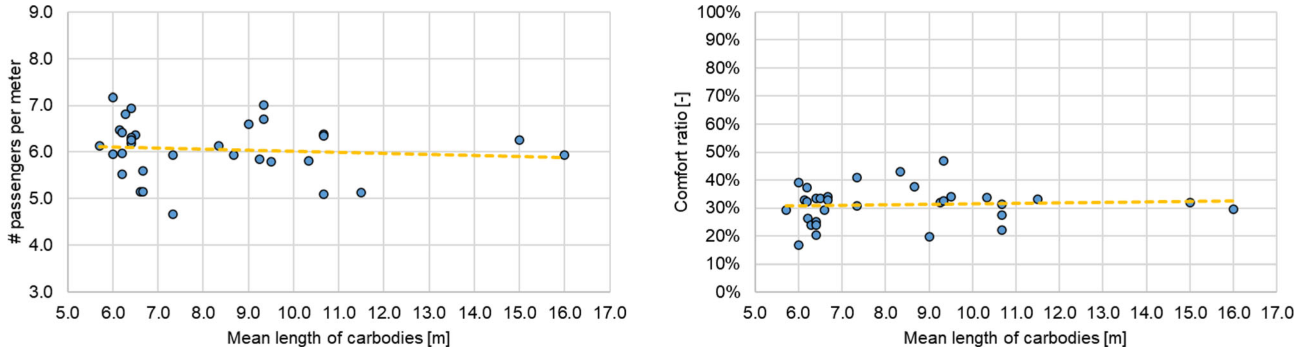


Fig. 15 Number of passengers per meter (left) and comfort ratio (right) versus average length of carbodies

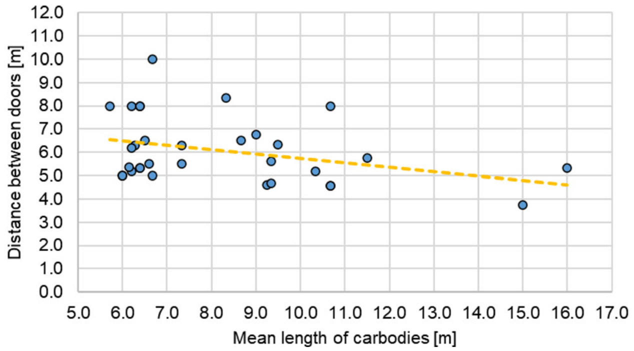


Fig. 16 Average distance between doors versus average carbody length

evaluated at about 0.42 t/m, resulting in an average *mass per unit of length* of 1.72 t/m.

4.4 Passenger Capacity and Accessibility

All the vehicles are 2.3–2.6 m wide and 3.4–3.9 m high over the top of the rail (without pantograph). It is not surprising, therefore, that passenger capacity is clearly not influenced by tram architecture. The number of *passengers per meter* in fact remains nearly constant, i.e. 6 pax/m, regardless of the mean length of the carbodies, and therefore the *comfort ratio* is always about 30% (Fig. 15).

However, as the length of the carbodies decreases, the number of doors per meter also decreases, and therefore the mean distance between the door increases in the range of 4–8 m, as shown in Fig. 16. The tram with the shortest door distance (3.8 m) is the single-carbody vehicle *EVO1* (Fig. 10), with a length of 15 m, one single door and three double doors.

Similar values with shorter carbodies can be achieved with vehicles with twice-supported end carbodies arranged as `m^`, as up to three doors can be installed. Examples are the *Moderus Gamma* from Modertrans in Poznan [29] and the *Nevelo* from Newag in Krakov [30], both reaching a mean distance between doors of 4.6 m. The *Avenio* developed by Siemens for Munich, shown in Fig. 17, is a single-articulated vehicle, and each carbody is supported by a central non-pivoting bogie. The length of the carbodies is 9.3 m, allowing for the installation of two double doors, and the mean distance between doors is only 4.6 m. However, the secondary suspensions of the bogies are designed to guarantee a relevant angle during curve negotiation. The bogies are able to rotate up to 4.5° with respect to the carbody [31]. The evolution of the *Avenio*, i.e. the *Avenio M* shown in Fig. 18, is in fact developed using the multi-articulated concept with suspended carbodies. For these trams, values no lower than 5 m can be reached if the suspended carbodies are long enough for the installation of two double doors. However, in multi-articulated trams, the fully low-floor design often requires the addition of doors near the driver cab at both ends of the vehicle, increasing the overhang with respect to the position of the non-pivoting bogies. The overhang can be reduced using single doors, which are normally sufficient due to the limited number of passengers passing through these end doors.

5 Conclusions

The technical comparison of currently available trams described in the paper shows that, while different solutions exist, most of the tram designs still belong to the category of fully low-floor vehicles with multi-articulated architecture, in which small-length carbodies and a limited number of bogies are used. With this solution, manufacturers tend to develop “platforms” to achieve standard and modular solutions that can be used in many situations, thereby drastically reducing selling prices and delivery times.

In the LRV sector, as a consequence of the current standardization frame in which only general rules and essential requirements are given, there is considerable freedom to introduce both unconventional and innovative solutions in the tram design. As an example, smaller

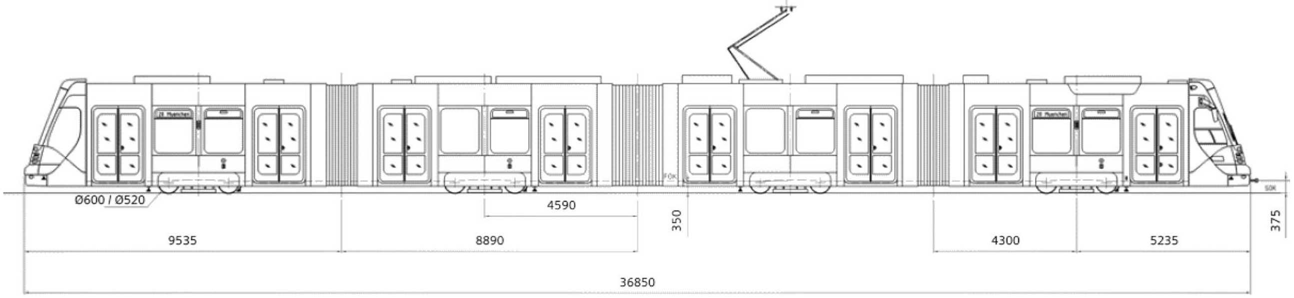


Fig. 17 Avenio tram from Siemens with two double doors for each carbody. Adapted from Schnaas and Karl [31]

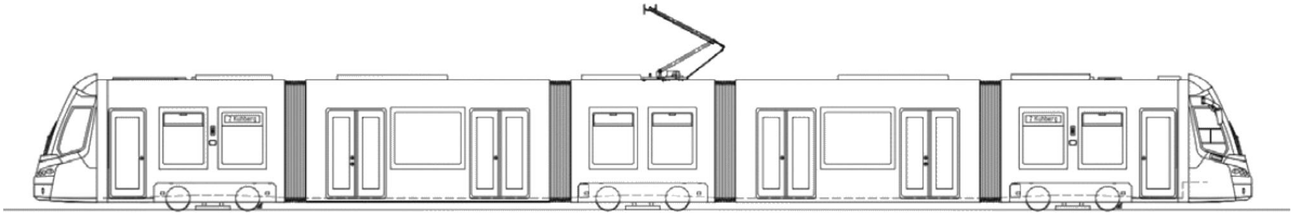


Fig. 18 Avenio M from Siemens with multi-articulated vehicle concept. Adapted from Späth and Walcher [32]

running gears are available today, allowing designers to take advantage of pivoting bogies on low-floor vehicles, once again making old-fashioned architectures competitive against multi-articulated trams in order to reduce the issues of urban rail operations. especially in very low-radius curves.

However, vehicles with steering axles and independently rotating wheels, which could be the only structural way to eliminate wear and noise problems related to sharp curves, are no longer available on the market, probably because of their lower modularity and high manufacturing and maintenance costs. Examples are the COBRA and the ULF trams, which are briefly described in the paper.

The research, based on publicly available information sources considered 32 vehicles selected from a set of 32 manufacturers identified by a worldwide market analysis. The vehicles were compared using a selection of the main parameters in terms of performance, capacity and accessibility, while a new designation code, called *tram architecture designation* (TAD), was proposed for easier identification of the tram architecture. Unlike the UIC designation historically used for railway vehicles and based on bogies, the TAD is based on carbodies and their supports, providing a unique code for all tram arrangements.

Combinations of pivoting bogies, non-pivoting bogies and Jacobs bogies are proposed as the multi-articulated architecture, which is identified in the simple case by a tram coded `M ^^ M` using TAD, is often not the best solution because of the greater distance between doors, higher axle load and lower ability for curve negotiation due to non-pivoting bogies. Trams with pivoting bogies placed at the ends of the vehicle, coded `m^` by TAD, are again very commonly used to improve the steering ability in sharp curves and accessibility without reducing the low-floor extension inside the vehicle.

Conversely, passenger transport capacity in terms of passengers per meter and comfort ratio are not clearly affected by the particular architecture, while from the performance point of view, all the trams show similar values in terms of maximum speed and power per unit of mass.

Appendix: List of Vehicles and Features Compared in the Analysis

Manufacturer	Product	Reference city	Order Year	Track gauge	% Low floor	Length [m]	Width [m]	Height [m]	# pass (seats +4pax/m^2)	# Seats	# Seats per meter	Comfort ratio	pax per meter	# 1 sliding doors	# 2 sliding doors	Average distance between doors [m]	Empty mass [t]	Mass per meter [t/m]	Axleload [t] (70 kg/pax)	Speed [km/h]	# bogies	Average distance between bogies [m]	# modules	# of suspended modules	Average module lenght [m]	# motors	Power [kW]	Power/mass [kW/t]	Modules arrangements (TAD)									Adhesion ratio	Minimum curve radius [m]	Kind of traction
Siemens	Avenio	Munich	2013	1435	100	37	2.30	3.6	216	69	1.9	32%	5.8	0	8	4.6	47.0	1.3	7.8	70	4	9.3	4	0	9.3	6	720	11.6	M	T	M	M						75%	25	Pant
Siemens	Avenio M	Ulm	2015	1000	100	31	2.40		185	69	2.2	37%	6.0	2	4	5.2	38.0	1.2	8.5	70	3	10.3	5	2	6.2	4	480	9.4	M	^^	T	^^	M					67%		Pant
Bombardier	Flexity	Berlin	2006	1435	100	40	2.40	3.5	245	72	1.8	29%	6.1	0	5	8.0	51.5	1.3	8.6	70	4	10.0	7	3	5.7	12	600	8.7	M	^^	T	^^	M	^^	M			75%	17	Pant
Bombardier	Flexity 2	Blackpool	2009	1435	100	32	2.65	3.4	222	74	2.3	33%	6.9	2	2	8.0	40.9	1.3	9.4	70	3	10.7	5	2	6.4	4	480	8.5	M	^^	T	^^	M					67%	25	Pant
Bombardier	Flexity 2	Zurich	2017	1000	100	43	2.40	3.6	278	91	2.1	33%	6.5	2	6	5.4	54.0	1.3	9.2	60	4	10.8	7	3	6.1	6	660	9.0	M	^^	T	^^	M	^^	M			75%	15	Pant
CAF	URBOS 3	Budapest	2016	1435	100	56	2.40		309	81	1.4	26%	5.5	0	7	8.0				50	5	11.2	9	4	6.2	12	840		M	^^	T	^^	M	^^	T	^^	M	60%	18	Pant
Alstom	Citadis 405	Nice	2017	1435	100	44	2.65		300	72	1.6	24%	6.8	0	7	6.3				70	4	11.0	7	3	6.3	6			M	^^	T	^^	M	^^	M			75%	20	SRS
Newag	Nevelo	Krakov	2016	1435	100	32	2.40	3.7	204	64	2.0	31%	6.4	2	5	4.6	42.5	1.3	7.1		4	8.0	3	0	10.7	4	420	7.4	m^	tt	^m							50%		Pant
Skoda	Forcity Classic	Chemitz	2016	1435	100	31	2.65	3.7	199	64	2.1	32%	6.4	1	4	6.2				60	3	10.3	5	2	6.2	12	560		M	^^	M	^^	M					100%		Pant
Skoda	Forcity Alfa	Prague	2009	1435	100	31	2.46	3.6	180	61	2.0	34%	5.8	0	6	5.2	42.0	1.4	6.8	60	4	7.8	3	0	10.3	16	746	13.7	mJ	JJ	Jm							100%	18	Pant
Skoda	Forcity Plus	Bratislava	2014	1000	90	33	2.48	3.6	207	69	2.1	33%	6.4	0	5	6.5				65	4	8.1	5	1	6.5	6	600		m^	M	^^	T	^m					75%		Pant
PESA	Jazz 128NG	Gdansk	2014	1435	100	30	2.40	3.4	215	36	1.2	17%	7.2	2	4	5.0	42.5	1.4	9.6	70	3	10.0	5	2	6.0	8	480	8.3	M	^^	T	^^	M					67%		Pant
BKM	AKSM843	Kazan	2013	1524	80	25	2.50	3.9	153	66	2.6	43%	6.1	0	3	8.3	31.2	1.2	7.0	80	3	8.3	3	0	8.3	4	420	10.0	m^	T	^m							67%		Pant
UTM	71 - 409	Novgorod		1524	100	22	2.50		103	42	1.9	41%	4.7	2	2	5.5	26.0	1.2	8.3	75	2	11.0	3	1	7.3	8	240	7.2	M	^^	M							100%		Pant
UTM	71 - 407	Kolomna	2017	1524	40	16	2.50	3.1	95	28	1.8	29%	5.9	0	3	5.3	21.5	1.3	7.0	75	2	8.0	1	0	16.0	4	216	7.7	mm									100%		Pant
Hitachi	Sirio	Florence	2009	1435	100	32	2.40	3.4	198	50	1.6	25%	6.2	2	4	5.3	39.8	1.2	8.9	70	3	10.7	5	2	6.4	4	640	11.9	M	^^	T	^^	M					67%		Pant
Solaris	Tramino	Lipsia	2015	1458	65	38	2.30	3.5	220	75	2.0	34%	5.8	2	4	6.3				70	5	7.6	4	0	9.5	8	680		mm	^j	j^	mm						80%	17	Pant
Stadler	Tango	Geneve	2010	1000	75	44	2.30	3.6	261	80	1.8	31%	5.9	0	7	6.3	57.0	1.3	7.5	70	5	8.8	6	0	7.3	6	750	10.0	m^	T	^J	J^	T	^m				60%	20	Pant
Tatra-Yug	K-1M6	Kiev	2018	1524	70	27	2.50	3.5	178	35	1.3	20%	6.6	0	4	6.8	32.0	1.2	7.4	75	3	9.0	3	0	9.0				m^	T	^m							67%		Pant
Astra	Imperio	Oradea	2018	1435	100	32			163	36	1.1	22%	5.1	0	4	8.0					3	10.7	3	0	10.7				M	T	M							67%		Pant
Inekon	Trio	Seattle	2011	1435	50	20	2.46	3.5	112	38	1.9	34%	5.6	2	2	5.0	26.0	1.3	8.5	70	2	10.0	3	1	6.7	4	360	10.6	M	^^	M							100%	18	Pant / Batt
Konkar/TZV	TMK2200	Liepāja	2018	1000	100	32	2.30	3.4	202	41	1.3	20%	6.3	0	6	5.3	43.9	1.4	9.7	70	3	10.7	5	2	6.4	6	420		M	^^	M	^^	M					100%		Pant
Pragoimex	EVO1	Most	2016	1435	100	15	2.50	3.3	94	30	2.0	32%	6.3	1	3	3.8	20.0	1.3	6.6	70	2	7.5	1	0	15.0	4	260	9.8	mm									100%	18	Pant
Electron	T5B64	Kiev	2017	1524	100	30	2.50	3.4	179	70	2.3	39%	6.0	2	4	5.0	37.9	1.3	8.4	70	3	10.0	5	2	6.0	8	400	7.9	M	^^	T	^^	M					67%	16	Pant
Moderntrans	Moderus gamma	Poznan	2017	1435	100	32	2.40	3.7	203	56	1.8	28%	6.3	2	5	4.6				75	4	8.0	3	0	10.7	8	400		m^	mm	^m							100%		Pant
Durmaray	Panorama	Olsztyn	2018	1435	100	33	2.50	3.5	170	50	1.5	29%	5.2	2	4	5.5	44.6	1.4	9.4	70	3	11.0	5	2	6.6	4	272	4.8	M	^^	T	^^	M					67%		Pant
PKT	Vityaz-M	Moskov	2016	1524	100	28	2.50	3.5	197	64	2.3	33%	7.0	2	4	4.7	37.0	1.3	8.5	75	3	9.3	3	0	9.3	6	432	8.5	m^	M	^m							100%		Pant
UKVZ	71 - 633	Samara	2016	1524	100	26	2.50	3.7	154	58	2.2	38%	5.9	2	2	6.5	34.0	1.3	7.5	75	3	8.7	3	0	8.7	4	420	9.4	m^	T	^m							67%		Pant
Transtech	Artic	Helsenki	2012	1000	100	28	2.40	3.8	188	88	3.1	47%	6.7	2	3	5.6	41.6	1.5	6.8	80	4	7.0	3	0	9.3	8	520	9.5	m^	mm	^m							100%	15	Pant
Hyunday	-	Izmir	2014	1435	100	32	2.45	3.4	200	48	1.5	24%	6.3	0	4	8.0	43.1	1.3	9.5	70	3	10.7	5	2	6.4	6	360	6.3	M	^^	M	^^	M					100%	20	Pant / Batt
Brookville	Liberty	Oklahoma City	2016	1435	70	20	2.46	3.4	103	34	1.7	33%	5.2	0	2	10.0	30.5	1.5	9.4	75	2	10.0	3	1	6.7	4	396	10.5	M	^^	M							100%	18	Pant / Batt
Heiterblick	Leoliner	Lipsia	2004	1458	70	23	2.30	3.7	118	39	1.7	33%	5.1	1	3	5.8	28.9	1.3	6.2	70	3	7.7	2	0	11.5	4	260	7.0	m^	tm								67%	17	Pant

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