Caravaggio: the New Hitachi High Capacity EMU Platform

New double-deck trains are needed to meet the increasing demand for high-capacity mass transportation systems used to provide regional and commuter services linking major cities to their hinterlands. Thanks to framework agreements for the supply of up to 300 trains to Trenitalia and 120 trains to Ferrovie Nord Milano in coming years, this new rolling stock is set to become the backbone of the main Italian operators' fleets. Compared to current fleets operating in Italy, the performance of Caravaggio Electric Multiple Unit trains is state-of-the-art in terms of transportation capacity, acceleration and speed, reliability, and environmental impact. This performance will allow the demand for mobility to be met in efficient and sustainable ways. The new product platform is also a demonstration of Hitachi's capacity for developing innovative and competitive solutions for the railway market.

Marco Sacchi
Stefano Ambrogio
Beniamino Cascone
Luca Lenzi
Simone Sinatti

1. Introduction

The Caravaggio Electric Multiple Unit (EMU) is part of Hitachi's new family of double-deck high-capacity trains. The trains were developed using the best technologies available at Hitachi, both in Italy and Japan, and are to be assembled at Hitachi's Italian plants in Pistoia and Reggio Calabria using technological components manufactured at the Mito and Naples factories. This is the culmination of more than 20 years of experience, including the manufacture of the more than 200 EMU double-deck trains and 700 double-deck coaches that are currently in commercial operation on the railway networks of Italy and Morocco.

Hitachi currently has two framework contracts: one with Trenitalia for up to 300 trains and the other with Trenord for up to 120 trains. (The contract with Ferrovie Nord was signed on the 12th of September, 2018).

The train architecture features aluminum carbodies, distributed traction power, spacious passenger compartments, and cutting-edge performance in terms of weight per passenger, seating capacity per meter of length, and energy consumption per passenger-kilometer (30% lower than the current generation of regional trains operating in Italy). The environmental footprint of the Caravaggio EMU has recently been certified by the Climate Declaration as having carbon dioxide (CO_2) emissions of only 5.1 g/pass-km, a level of performance that is state of the art. This means that the Caravaggio EMU has a lower environmental impact than any other mass transportation vehicle currently operating in Italy.

The train represents a quantum leap relative to the current rolling stock operating in Italy. This has

Table 1 — Specifications of Different Train Configurations

The table lists the key features of Caravaggio.

Composition	4-cars	5-cars	6-cars
Length (m)	109.6	136.8	163.2
Gauge (mm)	1,435		
Height for top of rail (mm)	4,300		
Bogie wheelbase (mm)	2,650		
Speed (km/h)	160		
Mean acceleration (0-30 km/h)	1.1 m/s^2		
Total seats	>500	>650	>800
Places for bicycles	15	18	21
Places for wheelchairs	2		
Doors per side	8	10	12
Toilets	2 (1 UAT + 1 standard)		3 (1 UAT + 2 standard)
Motor bogies	4		6
Trailer bogies	4	6	6
Traction power (kW)	2,800	3,400	4,200
Max axle load (t)	18.5		
Supply voltage	3 kV-DC		

UAT: universal accessibility toilet   DC: direct current

Figure 1 — External Aesthetic with the Trenitalia Livery

The picture shows a Caravaggio double-deck electric multiple unit (EMU) in operation.

been achieved through technological innovations in its components, optimized accessibility for people with reduced mobility in accordance with the latest European Regulation (TSI PRM 2014), and spacious passenger compartments made possible by a new roof-mounted traction converter and by the flexibility of layout and configuration provided by the train architecture that allows for trainsets of four, five, or six cars (see **Table 1**).

Moreover, a focus on aesthetic design has given the trains an innovative and recognizable shape that stands out in the current market. The overall impression is of dynamic vehicles with a strong lineage that embody both novelty and strength of character (see **Figure 1**).

2. Traction Architecture

The innovative solutions adopted in the design of the roof-mounted traction converter and auxiliary power supply (APS) for the double-deck train mean that each traction converter can supply peak power of 1 mW and continuous power of 500 kW to the two motors, and each APS can supply continuous power of 100 kVA to the auxiliary loads. The result is a power system that is very small and light relative to the power it delivers.

All the electrical and electronic components of the traction converters are housed in American Iron and

Steel Institute (AISI) 316L stainless steel frames. The light weight (less than 3700 kg) and small size (total volume of only about 6 m^3) of these units, which are installed on the roofs of double-deck regional trains, free up space inside the cars for passengers.

This compact design was made possible by using a single efficient cooling system for the traction and APS integrated-gate-bipolar-transistor (IGBT) converters and the magnetic components (line filter inductor, transformers, and three-phase transformers). The traction and auxiliary power units use liquid cooling (a mixture of water and glycol), while the magnetic components are designed for forced air cooling. External air drawn into the converter frame by a blower flows first through a heat exchanger (to cool the liquid coolant) and then through the magnetic components (first through the transformers, then the line filter inductor, and finally the three-phase inductors) (see **Figure 2**). Forced-air cooling of the magnetic components allows them to be smaller, while use of the same blower as the liquid cooling system reduces the component count and improves system availability.

The cooling system is very compact, being made up of a tank, a liquid pump, a 32-kW heat exchanger, and a blower with a flow rate of 2 m^3/s. It is installed inside the converter frame (see **Figure 3**).

The traction converter units are made up of the following components (see **Figure 4**).

- Two independent IGBT traction converters (three-phase inverters and braking chopper and control units)
- Two electrically independent IGBT auxiliary power supplies (three phase-inverters and control units)
- Two independent input inductor-capacitor (LC) filters
- Two independent three-phase output LC filters and three-phase transformers for the APS
- A liquid cooling system used by both the traction and auxiliary converters

Figure 2 — Air Cooling Flow through Caravaggio Traction Converter

The diagram shows the flow of air through the cooling system for the Caravaggio traction converter.

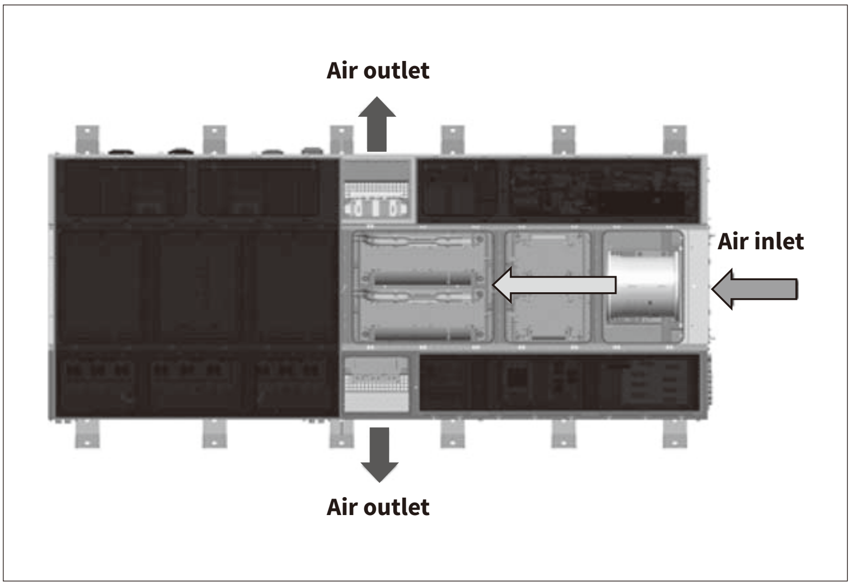


Figure 3 — Liquid Cooling System of Caravaggio Traction Converter

The diagram shows the air cooling system for the Caravaggio traction converter.

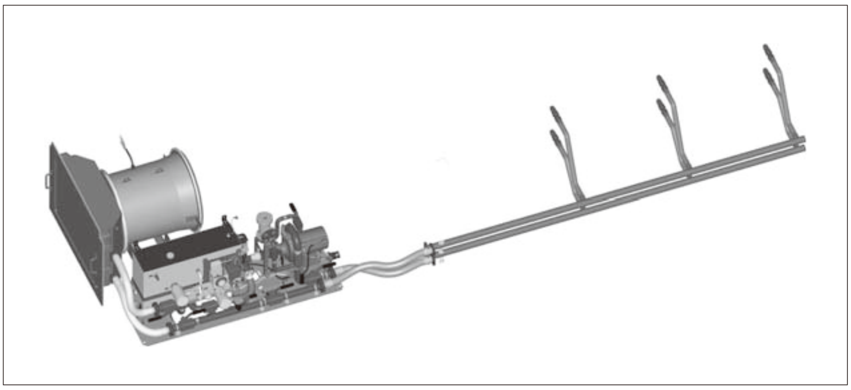
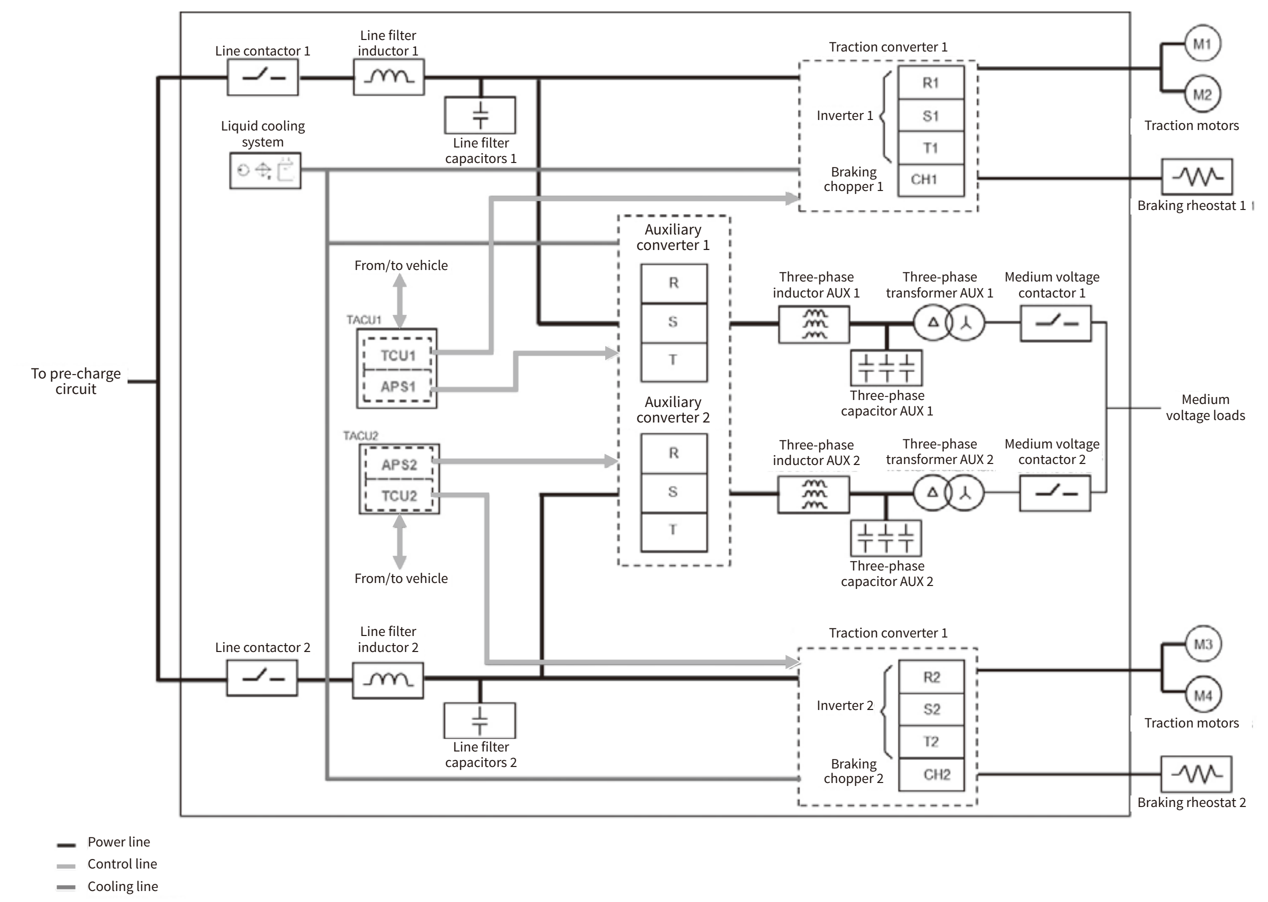


Figure 4 — Block Diagram of Caravaggio Traction Converter
The block diagram shows the structure of the Caravaggio traction converter unit.



CH: chopper AUX: auxiliary TACU: traction and auxiliary control unit APS: auxiliary power converter TCU: telematics control unit M: motor R, S, T: R, S, and T phases

3. Active Safety Systems

Active safety on Caravaggio trains is mainly based on the onboard technological system (STB), that includes the automatic train protection and automatic train control (ATP/ATC) system, the Global System for Mobile Communications – Railway (GSM-R) radio communications system, and the juridical recorder. The ATP/ATC system in turn is based on a "bi-standard" platform that integrates the functionality of the Italian legacy system [the Sistema Controllo Marcia Treno (SCMT)] with the European Train Control System (ETCS) developed in accordance with the latest version of the Technical Specification for Interoperability (TSI). Integration of the two systems has recently been upgraded to the highest level such that the SCMT and ETCS use the same odometry system, balise transmission module (BTM), and touch-screen driver machine interface (DMI). System reliability has also been maximized by using hot redundancy for the most critical systems, with the main control unit having a fully redundant two-out-of-two (2oo2) channel architecture. This redundancy extends to two antenna systems and two DMIs on the driver desk (see **Figure 5**).

The ATP/ATC system also includes a "vigilance system" and "passenger alarm system" that comply with the latest European standard, which stipulates new functions and more stringent safety requirements. This involves use of a simple algorithm based on speed and door status to detect when the train departs the platform and only permits the driver to use the DMI

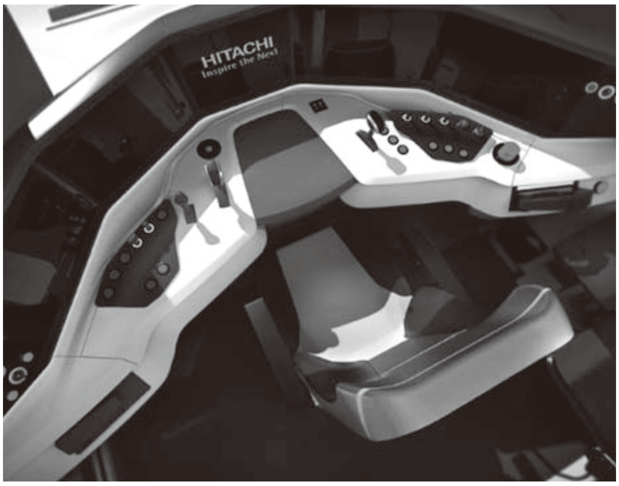


Figure 5 — Caravaggio Driver Desk

The central and left touch screen displays provide the driver machine interface (DMI) for the Sistema Controllo Marcia Treno (SCMT) and European Train Control System (ETCS). Redundancy is managed directly by the systems.

to override passenger-initiated emergency braking if the train is outside the station area.

The ATP/ATC, BTM, and DMI modules are key technological systems developed by Hitachi's subsidiary, Ansaldo STS.

The cab radio uses GSM-R and was developed to comply with the latest version of the European Integrated Railway Radio Enhanced Network (EIRENE) Functional Requirements Specification (FRS) 8.0 and System Requirements Specification (SRS) 16.0 standards.

A single juridical recorder unit records operational data for the entire train and is interfaced with a remote terminal in each driver cabin. The juridical recorder interfaces directly with the ATP/ATC system, cab radio, and train control and monitoring system (TCMS) through a digital Multifunction Vehicle Bus (MVB) to collect and record data from the main systems of the train. The system also has its own odometry system to provide an independent record of vehicle speed.

The recording system's speed signal can be used as a backup for displaying the speed to the driver in the event that the ATP/ATC system becomes unavailable.

The juridical recorder system also has an long term evolution (LTE)/Wi-Fi* module that is used to remotely upload the recorded data to dedicated servers at the railway operator.

* Wi-Fi is a registered trademark of Wi-Fi Alliance.

4. Carbody

The objective of carbody structure design is to achieve the best combination of safety, strength, lightness, and mechanical integration. The complexity of the systems and passenger layout in double-deck trains means that this latter challenge, mechanical integration, is crucial. An additional challenge in the case of the Caravaggio project was that the maximum permitted height of rolling stock in Italy is lower than the standard elsewhere in Europe.

These requirements, both general and specific, came together in the vestibule and doorway areas in particular where the carbody structure must accommodate the door pockets, movable step, air ducts, cables, and pipes in a confined space while also satisfying the minimum height requirements for the upper and lower decks and floors.

To satisfy these mechanical interfacing requirements within the limited space available in the carbody structure (including the underframe, upper deck, and roof), the designers chose to use different materials for each part of the carbody, as follows.

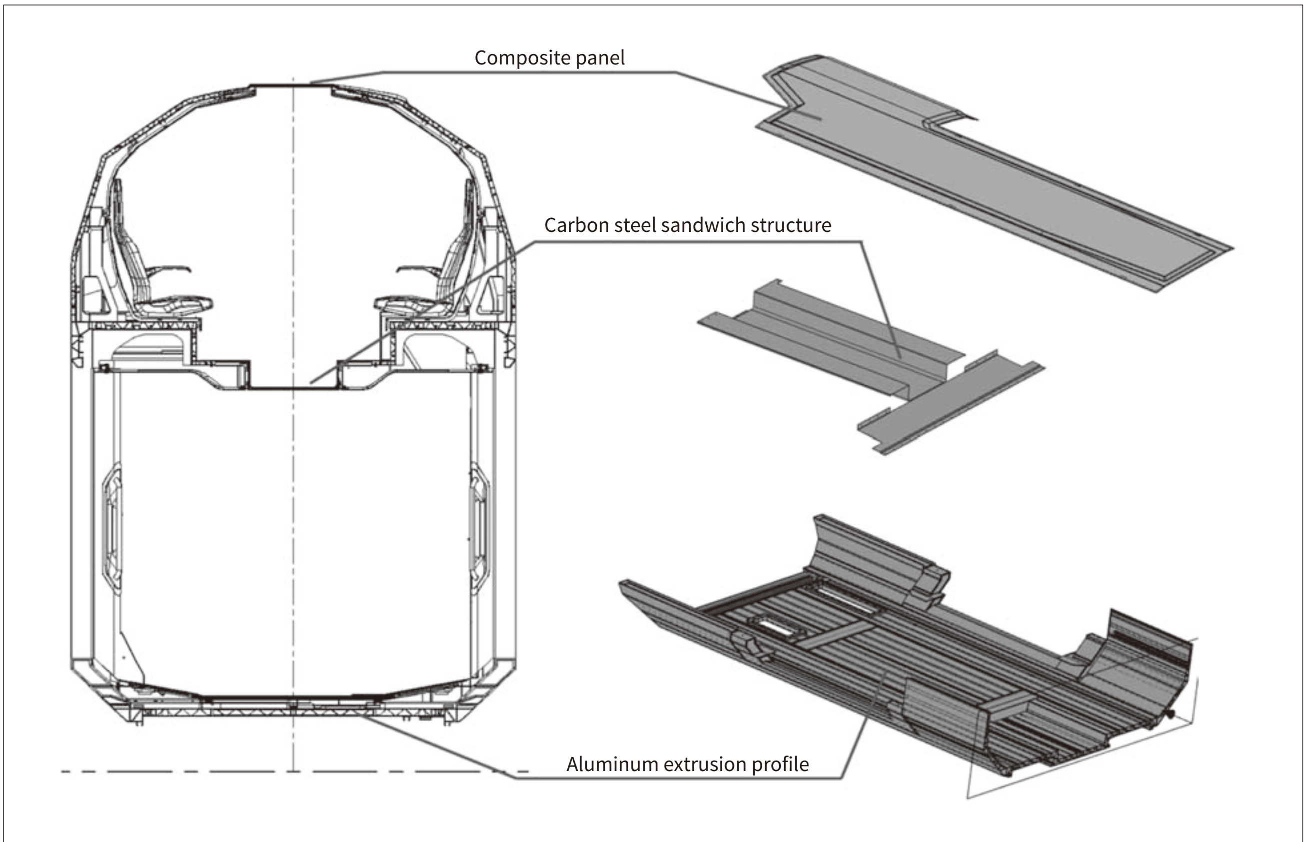
(1) Aluminum alloy extrusion profiles were used for the main underframe structure, simplifying the carshell subassembly manufacturing.

(2) To achieve the best mix of stiffness and thinness, carbon steel sheets joined using metal active gas (MAG) and spot welding were used to manufacture a complex sandwich material for the vestibule area of the upper deck.

(3) Composite materials were used for the roof to help satisfy the conflicting requirements of a complex geometry, thinness, lightness, strength, thermal and noise insulation, electromagnetic interference (EMI) performance, fire and smoke resistance, and exterior and interior finishing, all within the available 12 mm of thickness.

The carbon steel upper deck is attached to the aluminum structure by means of rivets. The composite roof material, in contrast, is bonded to the aluminum structure frame using only an elastomeric adhesive, without any mechanical fasteners.

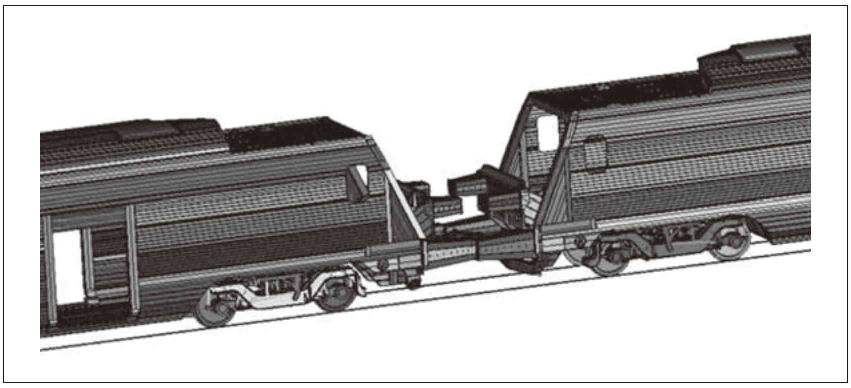
Figure 6 — Vestibule/Doorway Area
Use of a variety of different materials for the main carbody structures played a crucial role in successfully satisfying the conflicting requirements.



This use of a variety of different materials enabled the different needs of different areas to be satisfied efficiently while still remaining within the targets for the implicit requirements of weight, cost, and ease-of-manufacturing (see **Figure 6**).

The risks and development costs associated with a new design make it essential to take advantage of existing technologies where possible. In the case of the Caravaggio project, the crashworthiness design was based on use of components (front crash boxes and couplers) that had already been validated in the ETR1000 Very-high-speed project. This avoided the need for expensive and time-consuming full-scale crash testing. In fact, the level of accuracy demonstrated by the finite element method (FEM) models during experimental validation undertaken as part of the ETR1000 project was sufficiently high that the Agenzia Nazionale per la Sicurezza delle Ferrovie (ANSF), the Italian railway safety regulator, accepted virtual homologation for the train based on simulations that complied with the stipulations of the EN15227 standard (see **Figure 7**).

Figure 7 — Crashworthiness Design
Caravaggio was able to use a virtual homologation (approvals) process by using components and finite element method (FEM) models that had previously been verified by full-scale crash testing.



5. Bogie

The J200B bogies for the Caravaggio EMUs were newly designed by Hitachi Rail Italy, being based on the concept of the EMU V250 but with minor modifications to make them simpler and easier to manufacture and more cost-effective as well as having a shorter wheelbase (see **Figure 8**).

The bogies have a robust structure (20 t maximum axle load), making extensive use of forged parts rather than welded assemblies (the caliper supports, for example) to minimize the amount of welding required. Testing of the side frame design has also been conducted to verify that they can be welded by a new automatic robot at the Naples plant.

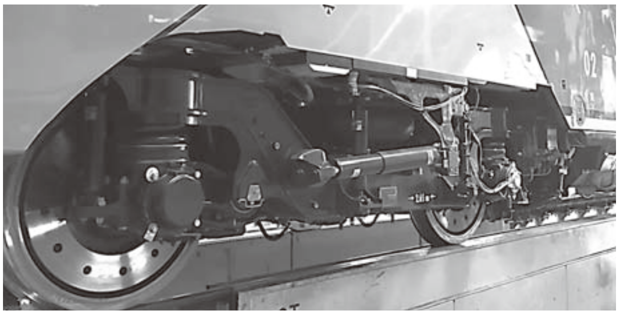
Although the maximum speed for the current project is 160 km/h, the bearings and axleboxes have been designed to reach 200 km/h.

The motor bogie has a compact gear-motor group arrangement, with the motor being suspended on entirely metallic elastic bushes (without rubber) so as to withstand the high temperatures reached by the motor. The gear unit is press-fitted onto the axle.

A bolster beam is used to allow the assembly of the "megarack" on the vehicle underframe. It is a welded structure with cast parts at the extremities. The bolster is a sealed box that also functions as an air reservoir, saving space that would otherwise be needed for tanks. A notable feature adopted from former projects is the installation of limiting rolls on the bolster beam with guides attached to the bogie frame instead of the carbody. This creates more space inside the car because it allows the carbody to be located closer to the ends of the bogie. The bolster is suspended on air springs that allow the vehicle to travel around curves with a radius of 90 m, as are present at rolling stock depots.

The stiffnesses adopted for the primary helical springs and secondary air springs are determined to cope with the challenging demands of double-deck trains where there is a large difference between the tare load and fully laden load. In particular, the motor primary spring has a special rubber element with a bilinear elastic characteristic that helps it achieve the low stiffness requirements while also satisfying the safety limit for minimum wheel load on canted track. The air springs include bumpers able to support the load of a moving vehicle, ensuring that safety and comfort are maintained even if the balloons become deflated.

Figure 8 — J200B Motor Bogie
The picture shows a J200B motor bogie.



The brake disks are installed on the wheel web, and the wheels are of the monobloc type.

The trailer bogies have the same design as the motor bogies except that the gear-motor group and its supports are removed. That is, trailer bogies have the same frame, bolster, and axleboxes, and use the same components as motor bogies wherever possible. This minimizes the number of different components, the total component count, the variety of production equipment, and the number of suppliers. For example, the brake discs for trailer bogies are mounted on the wheels despite the space available on the axle where the motor would otherwise be. By doing so, all bogies are able to use the same brake discs, calipers, and supports.

The low-voltage electrical systems are designed for bench assembly and are mounted on the bogie already fully boxed with the cables plugged into their connectors and the wires trimmed. This allows different tasks to proceed in parallel at the factory.

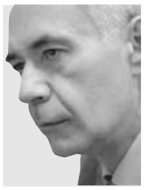
The mechanical connection of the carbody to the bogie is particularly simple, requiring only four M24 bolts on each side. The bogie has an antiroll bar mounted on the bolster (two times the suspended mass), with all connections located inside the carbody to eliminate the need to connect hangers when installing it on the bogie.

The intention is to use the J200B bogie as a platform for regional trains, with its suspension characteristics being adjustable if needed for use on single deck vehicles.

6. Conclusions

Caravaggio EMU is a newly developed rolling stock platform intended to satisfy the increasing demand for mobility. Its key achievements are very high capacity, low environmental impact, high reliability, and excellent acceleration performance. These features have seen the Caravaggio EMU selected by the two main Italian railway operators who are upgrading their high-capacity fleets, resulting in two framework contracts for up to 420 trains having been awarded to Hitachi.

Authors



Marco Sacchi
Design Engineering Department, Pistoia Branch Office, Hitachi Rail Italy S.p.A. *Current work and research*: Head of main line engineering and bidding.

Stefano Ambrogio
Design Engineering Department, Pistoia Branch Office, Hitachi Rail Italy S.p.A. *Current work and research*: Project engineer for the Caravaggio platform.

Beniamino Cascone
Design Engineering Department, Napoli Branch Office, Hitachi Rail Italy S.p.A. *Current work and research*: Head of traction engineering.

Luca Lenzi
Design Engineering Department, Pistoia Branch Office, Hitachi Rail Italy S.p.A. *Current work and research*: Head of carbody engineering.

Simone Sinatti
Design Engineering Department, Pistoia Branch Office, Hitachi Rail Italy S.p.A. *Current work and research*: Development of Caravaggio bogies.

Hitachi Review

Hitachi Review is a technical medium that reports on Hitachi's use of innovation to address the challenges facing society.

The *Hitachi Review* website contains technical papers written by Hitachi engineers and researchers, special articles such as discussions or interviews, and back numbers.

Hitachi Hyoron (Japanese) website	*Hitachi Review* (English) website
https://www.hitachihyoron.com/jp/	https://www.hitachihyoron.com/rev/

Hitachi Review Newsletter

Hitachi Review newsletter delivers the latest information about Hitachi Review when new articles are released.