

Retrofitting S-Bahn multiple units for the Stuttgart Digital Node project

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Motivation and background

Digitalisation of the railways is by no means an end in itself. It must be measured in terms of its tangible benefits for its customers. Experience hitherto gained with the European Train Control System (ETCS) in Switzerland in particular has admittedly been mixed; for instance, there have been some reports of declining capacity (e.g. [1, 2, 3]). Scepticism about the extent to which it makes sense to equip hubs and other high-traffic areas with ETCS has also been an underlying theme for the Stuttgart Digital Node (Digitaler Knoten Stuttgart, or DKS) from the outset.

The DKS is a pilot project as part of the Digital Rail for Germany (Digitale Schiene Deutschland, or DSD) starter package, which is intended to lay the essential groundwork for the network-wide rollout of digital interlocking technology (DSTW), ETCS and other technologies in Germany [4, 5]. This marks the first time in Germany that a major railway hub is being equipped accordingly. The project pursues a number of different goals. Among other things, the effects of closely synchronised on-board and infrastructure equipment are to be demonstrated, as are the possibilities and limits of increased "digital" capacities [6].

The initial spark behind the DKS was the ETCS equipment for the S-Bahn Core, which had been the subject of consideration since the mid-2010s. This line is divided into two sub-sections: On the northern branch, from the Central Station to the Schwabstrasse turning facility, which went into operation in 1978, the command, control and signalling technology (CCS) has been extensively optimised, including short main lineside signal intervals of 0.3 km in some cases and the omission of distant lineside signals in order to operate scheduled 2.5-minute headways (with trains that are up to approximately 205 m long, 30-second dwell time and buffer time). This track section is controlled from the Central Station's relay-based interlocking system (RSTW). An extension to the north around Mitnachtstrasse station was already under construction as part of the "Stuttgart 21" (S 21) project back then. The southern section of the Core, via the university as far as Stuttgart-Vaihingen, has been in operation since 1985 with a scheduled five-minute headway [7].

The interlocking system at Stuttgart Central Station was to be dismantled after the S 21 commissioning (originally planned for 2021) and replaced by several ESTWs (electronic

interlockings). Consequently, new signals (Ks signals) were to replace the previous signals (H/V signals). Such a 1:1 replacement of the Core of the S-Bahn system [8, 9, 10], which had already been plagued by worsening punctuality at the time, would have involved enormous expense, such as for numerous light signals, PZB (German inductive train protection) speed check sections and cables, but would not have brought about any notable improvements. Other interlockings were to undergo extensive modification as part of S 21, including the Stuttgart-Vaihingen RSTW, which controls the southern section of the Core, among other things to incorporate the planned Rohrer Kurve [11], a new piece of track created as part of the S 21 project to connect the Gäubahn coming from Horb / Zurich with Stuttgart Airport.

Following numerous sceptical comments, a feasibility study, which was jointly commissioned by the federal state of Baden-Württemberg, the Verband Region Stuttgart (VRS, the political entity of the Stuttgart region) and DB Netz AG (now DB InfraGO AG), showed in late 2018 that ETCS Level 2 and semi-automated train operation with a driver (Automatic Train Operation Grade of Automation 2, ATO GoA 2) are not only feasible from a technical perspective, but can also be expected to increase capacity significantly. Even on the basis of conservative assumptions, a reduction in the average minimum headways on the Core of approximately 20 % (in other words, half a minute) and significantly greater increases in capacity in the surrounding area were expected [7, 12, 13]. At the same time, the postponed S 21 commissioning in January 2018 from December 2021 to December 2025 offered the opportunity to fundamentally rethink the CCS concept for S 21, which until then had largely envisaged dual equipment (Ks/PZB and ETCS Level 2), with ETCS intended to be used almost exclusively by long-distance trains.

With this in mind, the partners involved (the German federal government, DB, the federal state of Baden-Württemberg and VRS) seized the opportunity in 2019 and 2020 and paved the way for the DKS. As an alternative to the interlockings that were originally planned as part of the S 21 project and were to be extensively converted, a DSTW is now being built. ETCS Level 2 and other technologies are based on this standardised framework. This means that the DKS will extend far beyond S 21 and, in its final state, will cover the entire network

districts of Stuttgart and Plochingen, which make up a total of some 500 kilometres of track and hence approximately 1.5 percent of the DB network. In technical terms, the DKS encompasses far more than DSTW and ETCS, because it, for example, also features ATO GoA 2, CTMS (Capacity and Traffic Management System) and FRMCS (Future Railway Mobile Communication System). The project is organised into three spatial and functional modules (see [11, 15]):

- module 1 is based on the feasibility study and comprises the infrastructure in the S-Bahn's Core area and the equipment of the entire S-Bahn vehicle fleet.
- module 2 comprises equipping S 21 as well as the consequently requisite equipping of regional multiple units [16].
- module 3 will include equipping the rest of the region, at least as far as the area bordering the Stuttgart and Plochingen network districts, including the entire present-day S-Bahn network. Furthermore, other technologies will be implemented throughout the DKS, including CTMS and FRMCS.

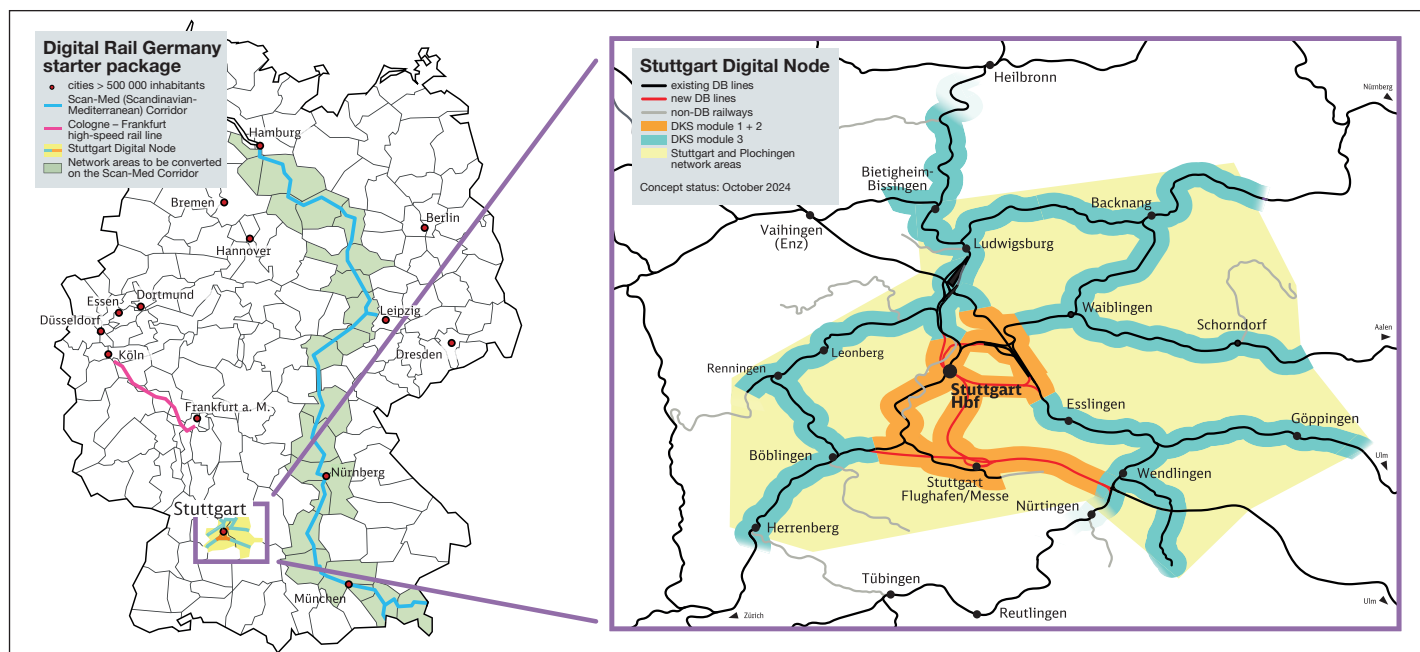
On the basis of a series of fundamental considerations [17] and practical experience both at home and abroad (for instance in Switzerland [18]), the fundamental decision was taken back in 2019 to equip ETCS Level 2 only, i.e. in particular without any main and distant lineside signals and without PZB train protection. This requires vehicles to be equipped accordingly in advance (vehicle-first approach based on the Swiss model, among others).

It was planned that only two areas (Stuttgart-Vaihingen to Böblingen and the Stuttgart-Bad Cannstatt-/Untertürkheim-/Münster area) would be temporarily provided with dual equipment. Not only is this intended to take account of regular freight traffic (not yet comprehensively equipped with ETCS in Germany), but it is also meant to create areas in which ETCS can be put through its paces, teething problems can be eliminated and train staff can gain experience on the Core and infrastructure of Stuttgart 21 as early as 18 months before the start of high-performance operation with ETCS Level 2 only.

Course of events

The initial situation

The L2oS infrastructure equipment for the Core itself requires all 215 of the Stuttgart



The Stuttgart Digital Node forms part of the DSD starter package, including part of the Scan-Med Corridor and the Cologne – Rhine/Main high-speed rail link (drawing: DB).

S-Bahn electric multiple units (EMU) to be equipped with ETCS as a preliminary measure:

- 60 Class 423 EMUs dating back to the early 2000s [19],
- 97 Class 430.0 EMUs from the 2010s, and
- 58 Class 430.2 EMUs delivered in 2021 and 2022.

The four-part trainsets, which are around 68 m in length and travel at a speed of 140 km/h, were built by Bombardier Transportation (operating under the name of Alstom since 2021). In 2023, 958 scheduled train services were provided per working day (predominantly in triple traction) on the 215-km-long rail network, with its 83 stations, thus covering a total of around 10 million train kilometres and carrying 101 million passengers in the process [20]. The multiple units were or are operated and maintained by DB Regio S-Bahn Stuttgart as part of a transport contract that was concluded in 2009 [21] and has been in force since mid-2013.

Back in January 2019, the Regional Assembly of the VRS, with a view to the DKS, decided to extend the transport contract by four years until late June 2032. In addition to the retrofitting of vehicles for the DKS, the overall package – worth almost EUR 1 billion – also included the procurement of 58 new Class 430.2 S-Bahn trainsets and renovation of the interior and exterior design of the entire fleet. In conjunction with some accompanying supplementary infrastructure measures, services were to be significantly increased and the declining operational quality improved [22, 23].

Procurement of the 58 Class 430.2 multiple units in 2019 constituted the final option, which was fully utilised, from the original supply contract agreed in April 2009. In line with the contract, Class 430.2 essentially

has the same design as the original Class 430.0, except for a few mandatory adaptations, such as modified acoustic door signals in conformity with the TSI (Technical Specification for Interoperability), which has since been updated. For this reason, the Class 430.2 was also included in the programme of vehicle retrofitting and redesign.

The concept and tender procedure

The on-board equipment was assessed in depth in the 2017/2018 feasibility study already. The vehicle retrofitting concept seamlessly followed on from this and other underlying principles in 2020. It involved three key parameters:

Firstly, the fleets had to be made fully equipped in good time prior to ETCS L2 only commissioning in the Core node. In advance of the S 21 commissioning planned for December 2025, the Core (continuing initially with 24 trains per hour and direction) was to commence operation with ETCS L2 only as early as September 2025. This was preceded in particular by commercial ETCS L2 only commissioning planned for January 2025 on the branch line that runs to the airport with four trains per hour and direction. For test purposes, ETCS with dual equipment was to be installed in an initial area around Bad Cannstatt and Untertürkheim as early as April 2024 [18, 24]. At least this meant that a significant number of trainsets had to be retrofitted by the end of 2024 and all of them by mid-2025 at the latest, also to allow sufficient time for extensive testing and to eliminate any teething problems.

Secondly, it became clear early on that retrofitting could only be carried out sensibly in conjunction with the redesign. For instance, both measures required that the vehicles be taken out of service and transferred, new cables laid and, among other things, new connections between the carbodies and diverse panelling removed. The price to be paid for such synergies was a higher level of complexity. For example, the redesign alone (in accordance with the European Commission's fourth railway package) would not have been subject to

official approval, since the basic character of the vehicle is unaltered. In conjunction with retrofitting, the changes resulting from the redesign must nevertheless now also be reviewed for approval (re-authorisation).

Thirdly, in order to fulfil DKS project goals and funding conditions, various enhancements and optimisations needed to be taken into account that were not covered by previous ETCS equipment projects in Germany and which would probably not be available for commercial operation at the start of 2025: for instance, ATO GoA 2 over ETCS, which was to be available in a stable and interoperable specification for the first time in the next TSI expected in 2022. Other elements included Train Integrity Monitoring (for moving block / "ETCS Level 3") and FRMCS [25].

DB Procurement and DB Regio developed a two-stage concept based on a number of findings, including a market and product survey conducted in 2016/2017 as well as consultations with DB and partners (2019/2020): Stage 1 was designed to ensure that all multiple units will be able to operate with ETCS in the hub and have completed the redesign in 2025. An upgrade to the next ETCS specification would then follow in stage 2. Given the far-reaching interventions that are already required for a mere ETCS retrofit, the overall package was to be planned "from the same mould" as far as possible and implemented gradually. Amongst other things, an innovation co-operation (IC) was planned for this purpose [26].

Original plans to carry out conversion work at the Plochingen S-Bahn depot near Stuttgart were shelved due to the excessive expense and the time available. Several considerations ultimately led to the development of a two-stage retrofitting concept: The contractor for the retrofit was therefore only to retrofit the first multiple units of a series (first-of-class, FoC) themselves; the serial retrofit, on the other hand, was to be carried out by DB Fahrzeuginstandhaltung (DB Fzl, Vehicle Maintenance), which was to be commissioned by DB Regio for this purpose. The equipment supplier was expected to

provide all materials, tools and operating procedures for this and support the conversion on site. The entire redesign process, including that for the FoC trains, was to be carried out by DB FzI.

On the basis of this, retrofitting for both S-Bahn series was put out to tender in July 2020 with one lot each [27]. The contracts to be awarded covered not only the design, manufacture, assembly and/or delivery and supervision of the assembly of the vehicle equipment, but also an innovation co-operation, homologation and recommissioning, coordination with the redesign project and with the DKS infrastructure, various documentation, spare parts supply and a hardware and software maintenance contract.

In view of the particularly complex nature of the project, a competitive tender phase was organised beforehand in which, among other things, substantial experience with ETCS, ATO and retrofitting projects had to be demonstrated. Four requests to participate were submitted. There were two suitable contenders remaining after a series of interviews and the subsequent submission of documents. Both received RFP (request for proposal) documents on 26 October 2020 and were called upon to make an initial offer, which was to be submitted by 1 February 2021 following an extension. The contract award criteria were price (75 %), contract (20 %), based on negotiable terms and conditions) and technology (5 %, on the basis of fewer target criteria). Moreover, both contenders were able to take a close look at vehicles in Plochingen and, for example, record measurements. Following negotiations in February 2021, the bidders were requested to submit a final offer on 1 March. In the meantime, in November 2020, the infrastructure for modules 1 and 2 was awarded to Thales (now Hitachi Rail) [28], and Bombardier Transportation was commissioned to redesign prototypes of Class 423, 430.0 and 430.2 vehicles.

Submission of proposal and award of contract

Alstom had prepared a joint proposal for both lots by January 2021. Besides the documents provided by DB, an integral element of this was also a laser measurement of relevant parts of the trains, from which 3D models were created. The bid encompassed more than 40 concepts (in eight chapters totalling more than 1000 A4 pages) and included in particular detailed information on

- technology such as system architecture and function, integration into the train control management system (TCMS) and innovation cooperation,
- organisation, for instance, with regard to coordination between the retrofit project and the redesign project,
- related topics, such as operating efficiency, availability, operation, training and carbon footprint.

The technical backbone of the bid was the new EVC-3 platform, now part of Alstom's Onvia Cab product family for train control systems on rolling stock, which has merged the previously separate Alstom ATLAS and Bombardier EBICAB platforms. The ETCS vehicle computer (European Vital Computer, EVC) constitutes the core of the on-board

equipment, which also comprises other elements such as antennas (for balises and radio) and sensors (in particular for odometry).

The EVC-3 is the third generation of Alstom's ETCS on-board equipment and follows on from the EVC-1 dating from the 2000s, with which the ICE T, for example, was equipped, and the EVC-2 from the 2010s, which can be found on the Class 401, 403 and 407 ICEs, among others. Development of the EVC-3 platform commenced in 2019 and is based, among other things, on what is now around 25 years of operational experience and the equipping of more than 19 000 ETCS on-board units in more than 200 vehicle types. Numerous suggestions from customers, such as DB, as well as foreseeable new requirements, such as those arising from the DKS, were also incorporated into developing the EVC-3.

A number of EVC-3 innovations also play a key role in the S-Bahn retrofit project in the context of the DKS, in particular:

- the space required by the EVC (650 x 530 x 330 mm) has been reduced by around 60 %, which means that the EVC can be integrated in the ceiling area (and thus without any loss of seating space),
- integrating the hitherto EVC-external radio modules (ETCS Data Only Radio, EDOR), the standstill monitoring of vehicles in shutdown mode (Cold Movement Detection, CMD), and interfaces to other peripherals,
- improved operability and maintainability as well as diagnostics and low life cycle costs,
- the multiplied computer performance and significantly reduced processing times,
- the ATO GoA 2 integrated in the EVC-3 as software without the need for any additional hardware,
- upgradeability to the future FRMCS radio standard,
- numerous additional optimisations, such as improved odometry and cybersecurity.

Timely and gradual provision of the new technology was but one of several major challenges facing the project. The technical equipment is more complex than that used in any of Alstom's previous retrofit projects in Germany. Another challenge was and still remains the sheer number of vehicles to be equipped and the very limited time available, around three and a half years – from the expected awarding of the contract to the planned first ETCS L2 only operations in January 2025.

With its many years' experience acquired from major national ETCS retrofit programmes in various European countries or from its ICE fleet, Alstom felt sufficiently confident to work in a highly parallelised manner. The two S-Bahn series (along with the two regional train series) were initially to be equipped in parallel on a pilot basis (first-of-class, FoC) and then approved within two and a half to three years, in order to equip the remaining more than 200 S-Bahn trains and a further 110 or so regional multiple units accordingly within a year or so.

Also with an eye to the expected rapid rollout of ETCS and other technologies on vehicles and infrastructure in Germany, a large number of investments and optimisations were initiated. By way of example,

- a "first-of-class factory" for the retrofit of electric multiple units (EMU) was to be established at the Hennigsdorf plant, equipped with the infrastructure, expertise and resources to be able to carry out up to 25 FoC projects in parallel.
- as part of EVC 3 product development, the DB specifications further developed for the DKS were to be implemented in order to gain a higher generic share and consequently ensure simplifications for subsequent projects.
- the vehicle interface was to be further simplified by a standardised data coupler (DACO) in order to implement safety-critical TCMS functions and data transfer to the ETCS.

Yet another challenge was the triangular relationship between Alstom, DB Regio and DB FzI. Co-operation with the client's work capacities is not uncommon in retrofitting projects. For example, Alstom has had very positive experience as a sub-contractor for ICE trainsets in Germany (with DB FzI) or ÖBB Talent multiple units in Austria (with ÖBB-Technische Services, or ÖBB TS for short). In the set-up for the S-Bahn DKS project, however, the newly adopted structure not only entailed increased retrofitting capacity, but also greater complexity. On the one hand, the supplier was to act primarily as a turnkey supplier, fully integrating the new technology into the existing rolling stock and ultimately providing "turnkey" retrofitted multiple units. On the other hand, DB FzI was to be contractually bound by DB Regio and made available to the supplier.

In June 2021 Alstom was awarded the contract for both lots. With Alstom's takeover of Bombardier Transportation, retrofitting and redesign were concentrated at Alstom. The prototypes were to be converted at Alstom's Hennigsdorf site, and the series conversion at DB FzI, under the supervision of Alstom. The order value for Alstom totalled approximately EUR 130 million. Alstom also won the contracts to retrofit 118 regional multiple units and to equip an initial 130 new Coradia Max double-decker multiple units (in 2022) with the same technology [16].

First-of-class (FoC)

The main product developments (EVC-3 in 2019 and EBICAB-PZB upgrade in early 2021) had already emerged before the contract was awarded. The generic ETCS software development was carried out in line with the ETCS specification, additional national requirements, customer requirements and feedback from operational experience.

At the same time, Alstom embarked on the signalling project (based on the CENELEC V-cycle methodology). This project was the first time that an Alstom EVC was integrated into Bombardier vehicles. Furthermore, the vehicle installation design was developed in detail and the initial eight multiple units, four Class 423 multiple units and two Class 430.0 and 430.2 multiple units each, were retrofitted on a pilot basis at Alstom's Hennigsdorf site from April 2022.

The number and choice of FoC multiple units for the Class 423 were the result of three different series, which were manufactured at different locations and at different times, differ at least in some details and also vary in weight. Class 430.0 and 430.2 also differ in

some respects and are stand-alone vehicle types because they were approved at different times in different legal frameworks. Other multiple units, including a fourth Class 423 multiple unit, were required for (re-)approval for journeys in all conceivable combinations of multiple traction [26]. This approach and the underlying comprehensive verification process was new and was also agreed with the German Federal Railway Authority (EBA) at an early stage.

The many facets involved in planning both series included installation space and cable routes as well as the effects on mass balance, power supply, cooling and ventilation (including on the EVC) and fire protection. For both classes of vehicle, it was possible to demonstrate that retrofitting and redesign are collectively load-neutral. In the case of Class 430 trains designed for ETCS, ETCS was taken into account from the outset in their mass and energy balance, and open spaces and fastening options in the underfloor area could also be utilised. In contrast, the energetic design of the older Class 423 vehicles, which had undergone a number of modifications over the years (such as LED lighting), required more in-depth examination. A major challenge lay in the vehicle documentation (with the exception of Class 430.2), because, for example, documents had to be researched in archives or were available in digital form, but in outdated file formats.

From an early stage, a great deal of attention was also paid to a full integration of the technologies into the vehicle control system (TCMS). The EVC-3 already gathers a wealth of information from this for the ETCS automatic train control system: with regard, for example, to traction and braking in order to calculate braking curves and also visualise the status on the displays (Driver Machine Interface, DMI). Additional information, such as current speed, service brake demands or the train number entered are transferred back to the TCMS. For ATO GoA 2, this integration process had to go one step further, for example to control traction and brakes accurately or even to access a large amount of vehicle status data and make it available for operational optimisations. Some adaptations to the TCMS hardware were necessary for the older Class 423, for example with repeaters. Alstom was able to consult TCMS specialists for both vehicle classes, which simplified the integration process.

After nine months of planning, the first multiple unit train, the 423 462, arrived in Hennigsdorf on 21 March 2022; another five had followed by 28 February 2023, or were taken from production on site (Class 430.2). The first trains initially were principally used to validate the planning, for example to check whether installation space was accessible as planned, and to gradually install the technology mechanically and put it into operation electrically. This was accompanied by a series of design sessions in which the planning was assessed in the 3D model and on the vehicle and continuously optimised.

Extensive integration tests on the first equipped trains commenced at the end of 2022. For this purpose, mobile TCMS test

Balise antenna on pre-fitted installation frame (photo: DB Regio / Nieder-müller).



cabinets were also brought onto the train-sets in order to detect and eliminate software errors as early as possible during tests involving a large number of variants and configurations. The knowledge thus gained was in turn used to develop the (generic) EVC-3 software, which was ongoing at the Alstom site in Charleroi, Belgium.

In order to harmonise the project's goals, challenging as they are with regard to time and content, and to gradually return the trains into service, the newly developed EVC 3 software was (and is) to be made available in several versions (baselines):

- initial release (3.1) for PZB operation and test purposes, without active ETCS,
- 4.0 off, for PZB operation with passengers, with software-suppressed ETCS, including first-time coupling capability between Classes 430.0 and 430.2,
- 4.0 on, for ETCS operation with passengers,
- 5.0 also with ATO GoA 2 for test purposes,
- 5.2 also with ATO GoA 2 with approval for passenger service,
- further software versions will follow as part of level 2 with ETCS in accordance with TSI ZZS 2023 or higher (with ETCS system version 3.0) and FRMCS (currently expected with TSI 2027).

By the end of 2023, the integration process had progressed so far and been tested at the Alstom plant site that series retrofitting was able to commence at all three locations on this basis.

In turn, the FoC vehicles completed test runs on the factory premises in Hennigsdorf at the same time. The extensive test infrastructure at this site has been further upgraded for

ETCS and future ATO test runs. By spring 2024, the EVC-3 software, the updated PZB, the vehicle control technology and the parallel redesign project had also advanced sufficiently to carry out test runs (with PZB) on the DB network for the first time in April 2024 and to further improve the software in the following months. At long last, on 16 October 2024 an FoC multiple unit provided proof of vehicle-track system compatibility (ETCS System Compatibility, ESC) at a Siemens ETCS Radio Block Centre (RBC) during ETCS journeys on the Berlin – Dresden route, without there being any problems. On this basis, the EVC-3 platform will be approved for ETCS operation on the DB network for the first time [5]. Further successful ESC tests with an RBC from Hitachi then followed on 28 November 2024 on the Rheintalbahn near Freiburg im Breisgau.

On 19 December 2024, around two and a half years after it was delivered, the first equipped FoC multiple unit (430 070) was transferred from Hennigsdorf to Plochingen and initially used to train operating personnel. The remaining FoC Class 430 multiple units are expected by March 2025, and those of Class 423 towards the end of 2025.

Postponements

While still in the first-of-class phase and even before series retrofit began, it became apparent in the course of 2023 that the commissioning sequence for the new CCS infrastructure, which had been pursued since 2020 and also formed the basis of the invitation to tender, was at risk. Initial commissioning of DSTW and ETCS for test purposes, planned to start at the turn of the year 2023/2024, did not materialise [29, 30].



Two S-Bahn multiple units during first-of-class equipping in Hennigsdorf in December 2022 (photo: Alstom).

Conversion of the S-Bahn multiple units										
	2024 (current situation)			2025 (in planning)			2026 (in planning)			Total
	423	430.0	430.2	423	430.0	430.2	423	430.0	430.2	
Hennigsdorf	4	2	2	–	–	–	56	–	–	64
Villeneuve	–	–	10	–	–	46	–	8	–	64
DB FZI	–	9	–	–	57	–	–	21	–	87
	4	11	12	0	57	46	56	29	0	
Total		27			103			85		215

On 11 June 2024, DB then finally announced a new sequence: the first ETCS L2 only commissioning, on the airport S-Bahn, was now planned for May 2026 instead of January 2025; the ETCS L2 only commissioning of the Core was postponed by one year until September 2026 [5, 31].

Since both the infrastructure and the FoC phase required more time than initially planned, it was decided to slow down and reorganise some aspects of the series retrofit equipment, which was launched on schedule at the end of 2023:

- instead of retrofitting the Classes 423 and 430 to a large extent in parallel, this is now being done sequentially: first of all, much of Class 430.0/2 will be equipped before Class 423 follows. This also opens up the opportunity to learn from the first series for subsequent ones, and to equip Class 423 directly with baseline 4.0 on instead of carrying out the intermediate steps, namely baseline 3.1 and baseline 4.0 off.
- the allocation of multiple units to different plants was reassessed (see table above): in particular, Alstom’s Villeneuve plant in the Swiss canton of Vaud was consulted and the retrofitting of 64 multiple units was intended to be performed there [32]. At the Alstom plant in Hennigsdorf, not only the FoC equipment but also the series retrofitting of the 56 Class 423 multiple units is now being implemented. Alstom and DB Regio signed a supplementary contract in March 2024 detailing this amended service content, which also includes the redesign of the corresponding EMUs. The remaining 87 multiple units are to be further retrofitted by DB Fzl in Nuremberg and Hagen (in the region of Westphalia), with Nuremberg shouldering the

bulk of this work, and the exact allocation has not yet been finalised.

The Villeneuve plant was owned by Bombardier Transportation and then acquired by Alstom as part of the takeover that was legally concluded in 2021 [33]. After the final assembly and commissioning of the SBB long-distance double-decker multiple-units class RAB(D)e 502 (FV-Dosto), which had been in progress at the site since 2014, was completed in 2022, the plant was repositioned as a production and service site and extensively converted and expanded for this purpose. Following the completion of a retrofitting project for 23 Prima H4 locomotives for SBB Infrastructure back in 2022/2023, the site’s wealth of experience and capacities will also be increasingly utilised for further (ETCS) retrofitting projects.

Integration of the Swiss plant also resulted in significant changes to the logistics concept. This meant that Alstom had to regulate the cross-border import and export, which also includes customs clearance in Villeneuve (with temporary import and export to Switzerland and customs clearance in Villeneuve) and the sales tax treatment of trains which have increased in value, as well as the import and export of materials.

On 18 July 2025 a new commissioning sequence was presented, postponing the ETCS commissioning on the Core to July 2027, among others.

Series equipment

Owing to the tight schedule, preparations for the series equipment began already in spring 2023, in the middle of the ongoing FoC phase. Once the FoC equipment had reached a satisfactory technical level, the first Class 430.0 multiple units were transferred to Villeneuve, Nuremberg and Hagen in November 2023 in order to train employees, practise the prepared retrofitting processes and also specify work instructions and steps at the plants. The actual conversion work began at all three locations in January 2024.

The first trains were designated “first-of-series” (FoS) and enabled practical testing of the retrofitting processes developed. In the first few months of retrofitting and redesign, this resulted in a total of more than 100 necessary clarifications of details, in particular regarding:

- individual inconsistencies within the retrofitting documentation,
- disparities between the documentation and the vehicles found,
- different approaches and perspectives at Alstom and DB Fzl,

- standards to be applied, necessary certifications and qualifications for certain activities, for example for bonding.

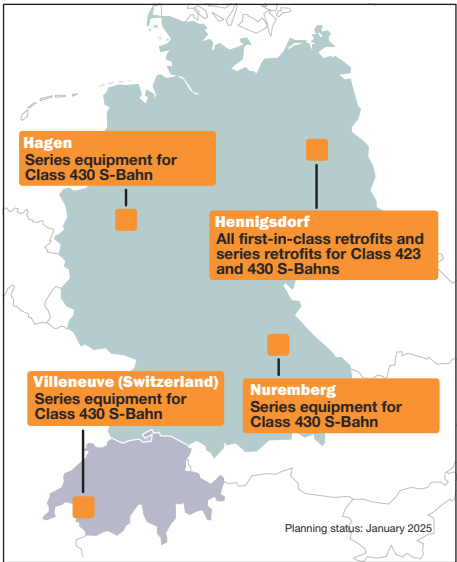
The start of the retrofit was hampered by several modifications from the previous FoC projects, which were channelled back into the ongoing series equipment. A number of improvement opportunities were also identified, such as in cable concepts or in the positioning and assembly sequence of individual components. The optimisations also extended to incidentals such as connectors that can be installed more quickly, and types of screws. In turn, many changes had to be taken into account in the FoC equipment, which was still running in parallel, in order to obtain approval again later for homogeneously retrofitted multiple units. These clarifications and optimisations occupied much of 2024.

In the course of retrofitting and the redesign process, two lorry loads of material are installed in each EMU, the majority of which is made up of redesign parts such as seats, panelling and monitors, while the remainder is for retrofitting, such as sensors, displays and covers. Additionally, there are more than ten kilometres of all kinds of cables as well as numerous small components required in large quantities, such as screws and other standard parts. Whereas the redesign work lessens the vehicle weight slightly, around 500 kg of new material are installed as part of retrofitting.

Alstom’s logistics centre in Braunschweig coordinates and inspects deliveries from its own and other suppliers, and stores the material. The large parts required for the redesign process are already made to measure and are essentially just channelled through. For retrofitting, on the other hand, individual items such as screws and clamps are first counted from the warehouse stock or cables are cut, labelled and packed. These packages are in turn used to assemble defined installation kits. Besides the parts required for a process such as the installation of a sensor, these also include checklists that need to be acknowledged after installation and testing. All the kits for a particular train are in turn put together into load carriers (such as mesh cages, pallets and boxes). The 30 or so load carriers required are delivered on two road trucks on call from the respective plant. Reusable containers and unused material are later returned to Braunschweig. Reserves of individual parts are also kept in stock as a back-up.

The main challenge before the start of series equipment proved to be the deliverability of individual components that were critical in terms of on-time availability, for example certain microchips. Some small components are also increasingly procured and supplied directly from the production plants.

Now that many initial difficulties have been overcome, the series equipment is picking up speed. On 8 November 2024, the first series-retrofitted but not yet approved multiple unit arrived in Plochingen from Nuremberg, hauled by train, followed by the first two from Villeneuve on 12 November 2024. On 17 January 2025, a trainset (the 430 220) was presented to the public in Plochingen. By the end of January 2025, a further four had been transferred to Plochingen, while other fully equipped trains were still at other locations. They headed



Conversion facilities for the S-Bahn EMUs destined for the Stuttgart Digital Node (drawing: DB).

A class 430 multiple unit during retrofit at the Villeneuve workshop (photo: Alstom).

to Plochingen under their own power and waited for authorisation.

The first class 423 multiple units (FoS) are to be retrofitted since June 2025. With growing experience and optimisations, the multiple units of both classes – in steady-state condition – are to be retrofitted within four weeks per multiple unit in multi-shift operation; retrofitting will take correspondingly longer in single-shift operation. In addition to the retrofit and redesign (each lasting around one week), these four weeks also include accompanying processes such as transfer journeys, decommissioning and commissioning, acceptance testing, documentation, recommissioning and approval/declaration of type conformity. More than 1500 direct labour hours in total are required per multiple unit for the retrofit and redesign work. DB Regio and the vehicle experts from DB AG closely monitored the retrofit and, in particular, the condition assessment of the first trains.

(Re)homologation and recommissioning

A significant aspect of the project, and one that should not be underestimated, lies in all manner of issues relating to homologation. All in all, the time and effort required for homologation in the project proved to be far greater than initially assumed.

To this end, so-called pre-engagement – early coordination with the EBA as the licensing authority – has taken place and continues to do so. Alstom provides the technical dossier for obtaining approval, DB Regio (as holder of the type-approval certificate) uploads this on the ERA’s One-Stop Shop portal and is the supervisory authority’s first point of contact. The focus here is on FoC multiple units, while only conformity to type (CTT) is to be declared for the multiple units retrofitted in series production. Finally, all modified vehicles must be re-entered in the European Centralised Virtual Vehicle Register (ECVVR) database.

Article 15 (1) a to d of EU Directive 2018/545 provides for four different categories of homologation procedure (see table on the right). Of particular importance here is whether

- the technical dossier, i.e. technical files accompanying the EC declarations for verification for the subsystems, are changed.
- basic characteristics of the vehicle (Basic Design Character, BDC) are changed.
- a threshold value is exceeded in relation to certain “acceptable parameters” in accordance with the TSIs.

For the first baseline (3.1), an homologation procedure in accordance with category “d” must be followed on account of the fundamental changes (BDC) compared to non-retrofitted vehicles. Due to the comparatively straightforward changes to baseline “4.0 off”, a category “b” procedure is required. For the changeover to “4.0 on”, a procedure according to category “d” is once again necessary due to significant changes (through the use of ETCS). An homologation procedure is also required upon commercial use of ATO GoA 2 (baseline 5.2). A procedure



in accordance with category “c” was proposed in the pre-engagement phase.

For all hardware and software changes, the same procedure must be followed for each of the three vehicle classes 423, 430.0 and 430.2. For categories c and d, a CTT procedure is, in turn, also required for each multiple unit. For every vehicle software baseline, six months need to be allotted for validation/verification by Alstom and evaluators alone; the EBA has a further six months for subsequent approval. Any change in baseline complicates operations, since only multiple units that share the same baseline can be coupled together within a class of trainset (423 or 430). Lastly, every new baseline also necessitates the corresponding training of employees. The common goal shared by Alstom and DB Regio is therefore to make as few baseline changes as possible.

Reliable and predictive infrastructure planning is also of vital importance. Due to the subsequent ETCS commissionings, for Class 423, baseline “4.0 off” can now be bypassed and “4.0 on” can be applied for and equipped directly for approval. For example, there is an ongoing consultation period between Alstom and DB as to when ATO will be used in accordance with the “Pre-TSI” and when in accordance with TSI CCS 2023.

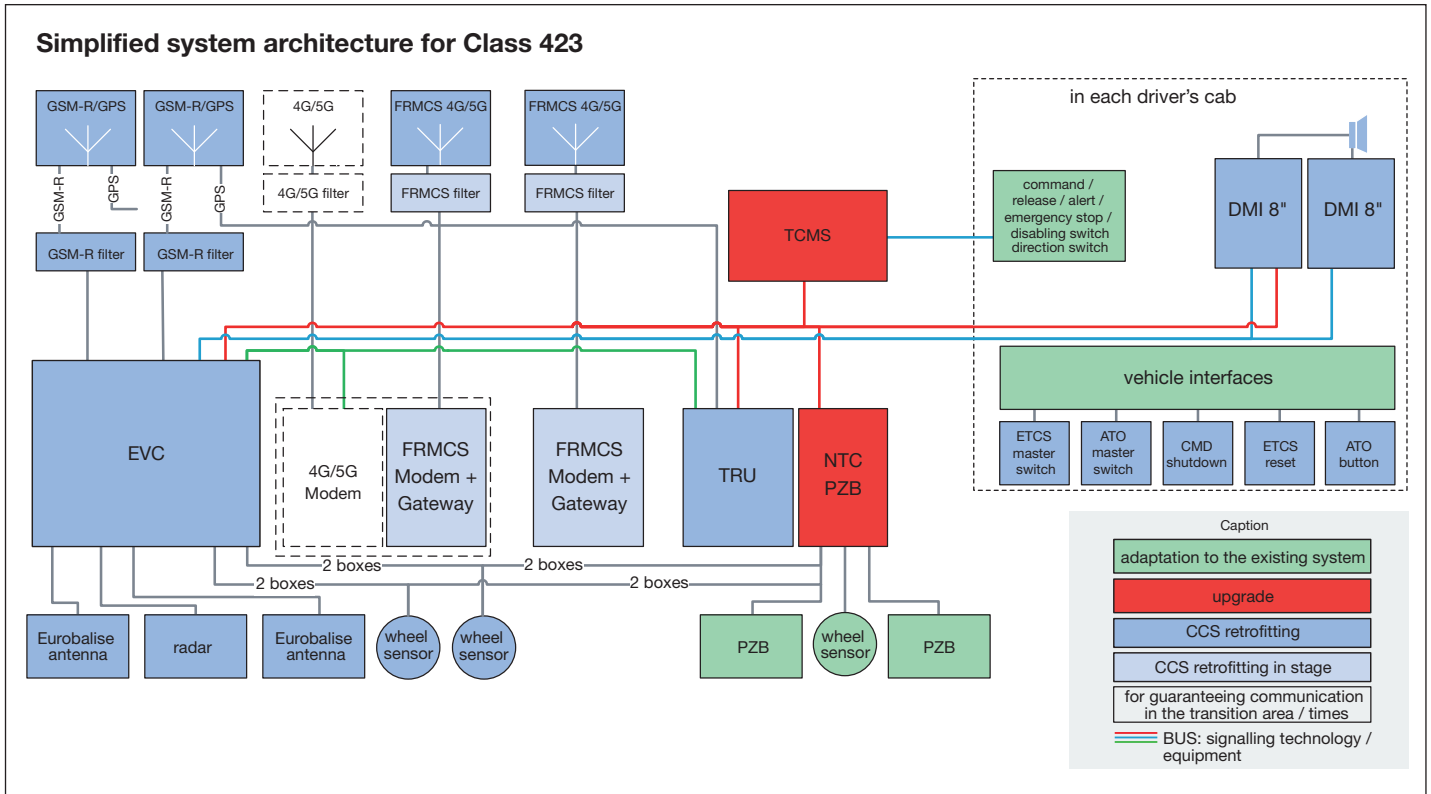
Baseline 3.1 was used for test purposes only and had no relevance for passenger

operations. The corresponding application for Classes 430.0 and 430.2 EMUs was submitted in February 2024, and approval was granted on 9 August 2024. The entry in the European Register of Authorised Types of Vehicles (ERATV) was then made by December 2024. On this basis, CTT applications for the “4.0 off” baseline were submitted for the first Class 430.0 multiple units on 12 December 2024 and on 2 January 2025 for Class 430.2. The application for approval for “4.0 on” (for Class 430) was submitted in February 2025 and is expected in late september 2025. Thereafter, Class 430 will switch from “4.0 off” to “4.0 on”, also so that it can complete test runs under ETCS. In February 2026, Class 423 trains are expected to be authorised for “4.0 on”, which means that retrofitted multiple units can be deployed in passenger service again (initially with PZB). This safeguards operation of all vehicles for the commissioning of the S-Bahn Core with ETCS L2 only. In parallel with these activities, the next authorisation steps for the imminent baseline “5.2” (primarily ATO GoA 2) and stage 2 (including an upgrade to the TSI ZSS 2023) are being prepared and driven forward.

Technology

The trainsets’ technical equipment far exceeds a plain ETCS equipment and has already been the subject of several reports

Classification of the vehicle modification category according to Article 15 (1) of EU Directive 2018/545			
category “a”	category “b”	category “c”	category “d”
no deviation from the technical dossier	deviation from the technical dossier, but no impact on BDC and overall safety level not adversely affected	deviation from the technical dossier, an impact on BDC, but below the threshold for initiating an obligation to obtain authorisation, and overall safety level not adversely affected (see [34])	deviation from the technical dossier, an impact on BDC, but above the threshold for initiating an obligation to obtain authorisation, and overall safety level adversely affected (see [34])
		Consequence: vehicle type version	Consequence: new vehicle type version or type variant



[including 27, 36, 37]. As part of the DKS pilot project, not only new technologies (such as ATO GoA 2, FRMCS and ETCS Level 2 with train integrity monitoring) are being trialled in a large node, but also closely harmonised on-board and infrastructure equipment, which not only promises a considerably more efficient infrastructure, but also a much simpler one [5, 30]. As far as possible, the on-board equipment is “cast from the same mould” and includes elements that will not be introduced in the infrastructure for some years and will therefore only be for on-board deployment.

Architecture

In the course of the retrofit, several dozen new components will be integrated into the multiple units (see picture). The key

component in every train is an EVC, to which – among other things – two displays per driver’s cab, five radio antennas, two balise antennas, four odometry sensors and various buttons and switches are linked. In order to connect the existing PZB with the EVC by means of a standardised interface (Specific Transmission Module, STM), this is upgraded from EBICAB 500 to 600 on existing vehicles; Class 430.2 is fitted with this ex works and Class 423 has its I60R upgraded. The current data recorder cassette is replaced by a standardised data recorder (Juridical Recording Unit, JRU) that can be read out via radio.

ETCS

The ETCS equipment is suitable for ETCS Levels 0 to 3 and STM PZB, and is

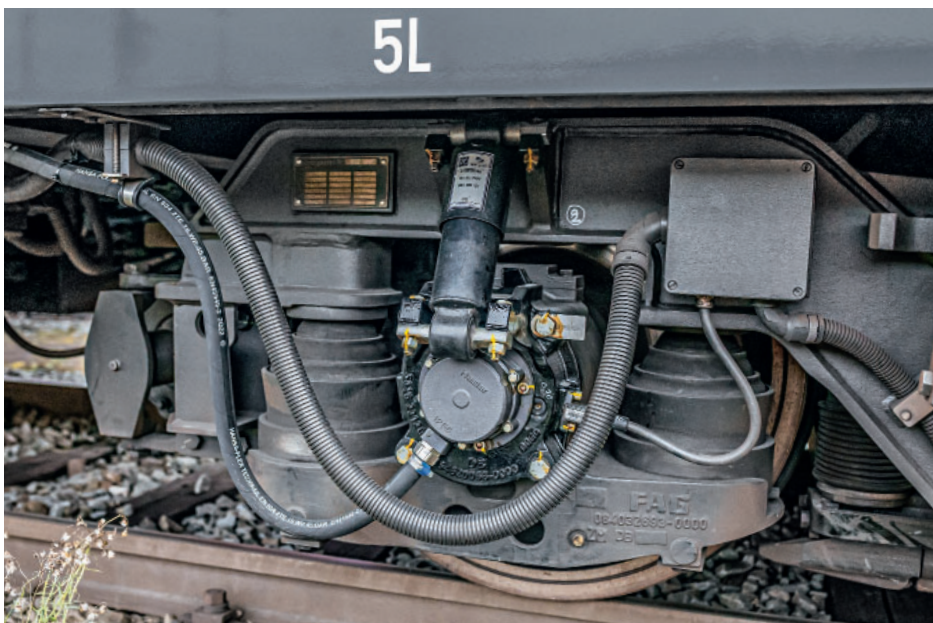
Simplified representation of the architecture of Class 423’s on-board equipment (drawing: DB).

implemented in two stages as part of the two-stage concept:

- in Stage 1, initially in accordance with baseline 3 release 2 (SRS 3.6.0), including recommended corrections to the ERA of 2019, for the initial start of operations in the DKS.
- Stage 2 involves upgrading to ETCS pursuant to TSI ZZS 2023 (baseline 4, SRS 4.0.0) and fully functional FRMCS.

The equipment far exceeds the minimum requirements stipulated in the TSI and by the DB network, and includes, for instance, CMD and other functions, which are described below.

Travel distance and speed measurement (odometry) is based on four sensors per multiple unit. The basis is provided by two distance encoders, which are arranged on both sides of a set of running wheels arranged approximately in the middle of the trains. In contrast to the Class 430, this wheelset is not braked on the Class 423 either. Consequently, the two sensors are intended to be largely insensitive to sliding and skidding. In addition, a Doppler radar aligned with the track is installed and an acceleration sensor (in the EVC) is used. In combination with each other, the sensors are intended to ensure precise positioning in standard operation that is accurate to $\pm 1\%$ of the distance travelled since the last group of balises used as a reference. This is much more accurate than the minimum requirement of $\pm 5\%$ laid down in the ETCS specification [35].



New wheel pulse generator for odometry on a Class 430 multiple unit (photo: DB Regio / Niedermüller).

Driver's cab with centrally mounted Driver Machine Interface (DMI) (photo: DB Regio / Niedermüller).

ATO GoA 2

In view of the profound impact that the integration of ETCS already entails, the multiple units will also be equipped with ATO GoA 2 “from the same mould”. In keeping with the ETCS specification, it is designed as a non-safety-relevant system that can only operate within the safe framework of ETCS, and is implemented on an already existent EVC-3 plug-in card. The additional outlay comes to just a few per cent of the total cost of the on-board equipment [25, 35].

This means that the infrastructure tells the train when it should be at which location and also provides a host of (infrastructure) data that extends beyond ETCS. The train in turn provides autonomous feedback on whether it can fulfil these requirements and, if so, with what degree of deviation. The driver, still aboard, monitors the journey and can intervene at any time while the ATO is operating the train. The driver can activate ATO in suitable areas via an ATO button located on the driver's desk, deactivate it at any time and also set reduced friction coefficients. He or she also remains responsible for opening the doors and for dispatching. The multiple units are to stop at Core platforms to within an accuracy of +/- 50 cm [7, 35, 36].

Implementation occurs at the pre-normative level, as ATO GoA 2 is not specified until TSI 2023. With this in mind, a DKS-specific specification was agreed with DB Netz AG (today DB InfraGO) and Thales, supplier of trackside equipment, in April 2023. The generic version and the project-specific implementation were developed by Alstom on the basis of this specification. As the necessary packet-switched data transmission cannot happen via GSM-R, which is used for ETCS, the ATO data is initially transmitted via public mobile radio (encrypted and secured several times) and later via FRMCS.

Since January 2025, ATO GoA 2 has been used with baseline 5.0 for test purposes at the Hennigsdorf site and will subsequently be used on the network, most probably the Wendlingen – Ulm high-speed line. Baseline 5.2 will be used for tuning and characterisation on all classes of train and



for commercial operation. ATO is scheduled to go into passenger service around one year after the Core goes into ETCS operation.

Innovation co-operation (TIMS, OCORA, TCR, FRMCS)

Due to the novelty of the functions, the contractor's scope of work could not yet be fully detailed for the purpose of awarding the contract, so specifications and requirements were jointly drawn up for four innovation topics as part of an IC and implemented accordingly [26, 37]. Immediately after the contract was awarded, the innovation topics were finalised in close collaboration with DSD in the first six months, the results of which were taken into account in the ETCS generics, in the retrofit planning stage and in the integration into the vehicle.

One of the issues was the provision of information on train integrity and train length (Train Integrity Monitoring System, TIMS) as a prerequisite for ETCS Level 3 (now Level 2). For this purpose, a system was designed that determines the train length with the highest degree of reliability (Safety Integrity Level 4, SIL 4) and the integrity with a very high degree of reliability (SIL 2)

without the involvement of the train driver. Unintentional train decoupling, which would normally cause emergency braking anyway, is also to be detected within 3.5 seconds [37]. The solution developed is a software application in the EVC-3 and merely requires an additional switch on the coupling head of the automatic centre buffer coupler on the Class 423. The TIMS function will be activated with Baseline 5.2 in order to gain experience of availability at an early stage, although it is due to be used only in one subsection of the DKS on the infrastructural side not earlier than 2031 [5].

Within the framework of the IC, the previously non-standardised interfaces between the ETCS or ATO on-board equipment and the vehicle (“SUBSET 119/139”) from the OCORA (Open CCS On-board Reference Architecture) initiative were also examined, selectively detailed and implemented in a coordinated manner. This would make it easier to replace the ETCS/ATO on-board equipment at a later date [37, 38].

As part of the IC, a system to transmit numerous train data (Train Capability Report, TCR) was also defined [37]. Over and above the position and speed data already constantly transmitted by ETCS (position

Doppler radar for odometry on one of the first-of-class multiple units (photo: Alstom).



ATO button next to the driving/braking lever (photo: DB Regio / Niedermüller).





Three elevated antennas on the roof of the Class 430 multiple unit (to the left at the front and rear for FRMCS, to the right for public mobile radio) (photo: Alstom).

report), around 35 types of information are tapped and transmitted from the vehicle's TCMS via the ATO vehicle-infrastructure interface: for example, the status of traction, brakes, doors and pantographs. This is intended to significantly improve ongoing operational optimisation in the future by means of the CTMS traffic management system planned.

An additional element of the IC was the detailing process for the two-stage FRMCS on-board equipment.

Radio

The multiple units had already been equipped with six radio antennas prior to retrofitting: two each for energy data and the external connection to the passenger WLAN, as well as one each for GSM-R voice radio and for diagnostic and positioning data. The upgrade will initially see the addition of five more antennas: two each (redundant) for GSM-R and FRMCS as well as a further one for public mobile radio (for ATO GoA 2). This planning and implementation is also organised "from the same mould", with regard, for example, to the overall system's architecture and the positioning of antennas, filters and cables. Given the relatively large number of superstructures, such as air-conditioning cases, which jut out almost to the limit of the standard clearance gauge, variable height levels and the need for radiation far beyond the air-conditioning units, massive stands were constructed for the antennas.

A special feature is the two-stage equipment and not just the pre-fitting of the multiple units with FRMCS [39]. Although a stable and ready-for-use version of the FRMCS specification is not anticipated before the end of 2026, key features of the future radio system on the DB network (e.g. 5G standard as a basis, frequency bands) were already known in sufficient detail at the time of awarding the contract so that the actual equipment could also be put out to tender and awarded. Now that the specifications have been defined in detail in the IC and a requirements specification has been drawn up, much of the technology (antennas, cables, netboxes) is now being fitted in the vehicles together with ETCS. Only the modems with software, which has yet to be developed, and filters will follow as part of the upgrade to Level 2. Including tests and CTT, this should only require one week per

multiple unit. The advantages afforded by early equipment and the synergy effects of the "one-stop shop" approach are countered by an element of risk arising from any remaining uncertainties. The latter could cause oversizing (in the number of antennas, for instance) or subsequent alterations to the hardware [40].

Related aspects

Employees' competence

Retrofitting the entire fleet of multiple units will also mean some changes for a majority of the approximately 850 S-Bahn Stuttgart employees. Although the more than 450 train drivers (including trainees) and around 180 employees in the maintenance department are the target groups for the necessary qualification, on closer inspection the project also means changes and work for many other employees, such as those in the fields of despatch management and planning and also vehicle management.

With a view to successfully shaping this far-reaching transformation and competence, which far exceeds the mere technology of the vehicle equipment, S-Bahn Stuttgart set up the "S-Bahn 2025" team back in 2020. It is made up of about ten employees, engineers and experienced operators with more than 150 years of combined railway operating expertise. With their specialist knowledge and experience, they not only cover the entire spectrum of S-Bahn operations, but some of them also continue to drive the multiple units themselves on a regular basis. Together with DB Procurement and with the support of external engineering companies, the team also supports upgrading and retrofitting projects in the federal state of Baden-Württemberg in an advisory capacity after DB Regio won a corresponding tender [16].

The greatest challenge in terms of competence was and still is faced by train drivers. Not only are they by far the largest group, but they are also particularly in short supply. For this very reason, the six-day initial training programme was started back in summer 2022, with the aim of withdrawing no more than five train drivers from service at any one time and still having all drivers trained by the first commercial commissioning initially planned for January 2025. During these six days, the participants learn about ETCS in theory and practice (on

the simulator) and take a written, oral and practical (simulator) test. More than 80 % of train drivers have now completed this training.

The fact that the first commercial ETCS commissioning was postponed for more than two years means that the time between training and actual operational practice spans more than four – instead of two and a half – years. In order to make sure that competence levels are maintained, S-Bahn Stuttgart is adopting a variety of measures:

- once a year, every train driver attends a refresher course in the form of a 1-day training module dedicated specifically to ETCS, which includes a theory session (with a particular focus on regulatory changes) and simulator runs (featuring fault scenarios in which personal wishes are taken into account).
- twice a year, every train driver must undergo web-based training (including knowledge tests) on their work tablet. When it comes to topics where the train drivers feel confident, they can proceed directly to the questions; the other learning modules are first presented in video and audio format, and only after that are the questions presented for answering. This web-based training (abbreviated as WBT) was developed centrally by DB Regio on the basis of input provided by S-Bahn Stuttgart.
- in addition, videos on various operational situations are now available, which have been recreated on the simulator and contain in-depth information (for example, references to regulations).
- when the first multiple units are delivered, all train drivers receive one day of technical training directly onboard the vehicle, where they can literally "grasp" and "experience" this information and ask any questions. All participants receive an accompanying written handout, too.

The delayed infrastructural commissioning is the cause of significant complications in ongoing operations. After initial commissioning of the interlocking system, which was originally planned for the turn of the year 2023/2024 (in the Bad Cannstatt / Untertürkheim area), did not take place, the signal locations defined in the 2024 annual timetable were no longer valid. This resulted in a timetable arrangement in excess of 100 pages, which has to be adhered to alongside the operational timetables. Other such documents followed. The numerous line closures, often at short notice and sometimes over long distances, in order to bring the new technology into the field, are also a huge hindrance for train drivers and other S-Bahn Stuttgart employees, and severely test the political and public acceptance of rail digitalisation as a whole. One challenge here lies in maintaining motivation among drivers and dispatchers: not only in relation to ETCS and other technology, but also simply for daily operations, which are already subject to many difficulties and disruptions. As an example, the number of restrictions in the 2024 S-Bahn timetable was five times greater than in 2022.

Only a short time after the first retrofitted multiple units had arrived in Plochingen, the maintenance technicians began their training in December 2024. Their training focuses on scheduled maintenance, while

corrective and preventive maintenance is still carried out by Alstom during the warranty period. In late January, the maintenance manuals prepared previously were "read out" and checked in detail for their practicability.

Stable ramp-up operation and resilience

The operational maturity and everyday stability offered by ETCS is often underestimated. For example, in the first year of operation of the Wendlingen – Ulm high-speed line (SFS), fewer than 0.2 % of almost 30 000 train journeys were found to be problematic with regard to ETCS. Besides an inherent weakness in the interaction between vehicle and lineside equipment (which has since been rectified), a few isolated faults on vehicles were detected [41]. This is consistent with other findings in Germany (VDE 8, for example) and Switzerland. The vehicle equipment and related operational aspects therefore play a key role in ensuring a robust overall system. The decades of experience shared by Alstom, DB Regio and DB Procurement will also benefit the vehicle project in many details here, for example in choosing suitable installation locations in order to eliminate potential sources of interference as far as possible during the design phase.

The integrated EVC-3 platform is not only based on high-availability elements, but also has an almost end-to-end redundant design. As such, the EVC is designed as a 2-out-of-3 computer system; the driver's cab displays and antennas are each duplicated, and the odometry remains functional with two (different) of the four sensors. A few non-redundant components are particularly high in availability, including the balise antenna. The Mean Time Between Failures (MTBF) of the ETCS on-board equipment promised by Alstom is 45 000 hours, well above the minimum requirement (of the TSI) of 23 000 hours. [35]

In view of the sheer number of multiple units to be retrofitted and the large number of journeys planned with ETCS L2 only (almost 1000 per day on the Core alone), another major focus has always been on stable commercial ETCS L2 only commissioning of the S-Bahn. A key experience gleaned from other projects, such as the commissioning of the Ebensfeld – Erfurt high-speed line (part of the Munich – Berlin axis) in December 2017 [42], is to extensively test and "run in" all trainsets retrofitted with ETCS in good time prior to the commercial ETCS commissioning of the infrastructure. This is intended to eliminate initial irregularities (such as inadequately fixed cabling) as well as to gain experience and promote handling competence among the many hundreds of operational employees involved.

Errors that may occur in the interaction of the subsequent vehicle and infrastructural equipment are largely ruled out by extensive laboratory tests. Since as early as June 2024, numerous joint laboratory tests have also been conducted with the EVC-3 and the RBCs provided by infrastructure supplier Hitachi Rail and the project planning later used in the DKS (for instance, dense block division). The majority of possible isolated failures, including with the wiring, are already being ruled out during the recommissioning phase by means of tests lasting several days and short test runs at the production plant.

EVC lowered for maintenance (photo: DB Regio).



Based on this, each of the eight prototype multiple units must complete at least 4000 km in ETCS operation and at least 1000 km in PZB operation without any serious faults in order to validate the stability of the vehicle equipment itself in actual operation. Several PZB and ETCS runs are scheduled without passengers for each of the 207 series retrofitted EMUs, in particular to rule out errors as far as possible that arise during or after the transfer. In addition, the first commercial ETCS journeys of every single multiple unit and every single train driver will be accompanied by at least one experienced employee. The aim of this is not only to familiarise employees with the practical side of things, but also to increase the certainty of action in the event of expected infrequent faults that only become apparent in the ETCS area at the core of the node. Up to 14 employees per day are deployed for this purpose alone.

Availability of the infrastructure has proven to be particularly challenging: instead of the 17 months originally planned (April 2024 to September 2025), the actual (S-Bahn) ETCS infrastructure in the DKS will be available for only around nine months (April 2027) before the Core's ETCS L2 only operations commence (July 2027). This will be made difficult by a complete closure of the Core planned from early April 2027, with the Gäubahn already interrupted at the very same time. In this phase, the multiple units commuting between Stuttgart-Vaihingen and Stuttgart/Filderstadt Airport will not be able to use the Core, but will have to make a detour of around 30 kilometres via Böblingen – Renningen – Stuttgart-Zuffenhausen with several changes in the direction of travel in order to reach the Plochingen depot. For many multiple units the first ETCS journeys will be mostly away from the future area of operation, and most likely on the Wendlingen – Merklingsen and later Stuttgart-Feuerbach – Merklingsen sections of the new line between Stuttgart and Ulm.

The earliest possible and most comprehensive use of the on-board equipment is also important: even in PZB-only operation (baseline 4.0 off), a large proportion of the hardware required later for ETCS will be used: EVC, displays, odometry and JRU are already fully operational during this phase. Previous experience has shown that many faults that do not become apparent in the first days or weeks of ETCS operation

such as various faulty wiring or unintentional water ingress, can then be detected and rectified using diagnostics. Processes such as train data input and test runs will then also be used and drilled. However, balise antennas and radio in particular, as well as the ETCS-specific part of the EVC software, are not being used yet.

Great emphasis has always been placed on diagnostics. The vehicle diagnostics of both classes of train, which are already very in-depth and have been extensively optimised over the years, have been enhanced to include the components of the new on-board equipment. In addition, Alstom provides a comprehensive diagnostic and evaluation system in the form of Health-Hub [35]. The basis for both is the EVC-3's highly improved diagnostics, which not only meet DB's new and more in-depth specification requirements, but were also designed in detail in close collaboration between Alstom and DB Regio. Fundamentally, error messages are recorded as precisely as possible: at the level of individual parts (such as processors), with a location and time reference. Errors are also no longer lost when the ETCS on-board equipment is switched off. Additional emphasis was, of course, placed on automatically and immediately reporting all faults to the depot, but displaying only serious faults directly to the driver and suppressing subsequent errors that are irrelevant to him. All diagnostic data is available to both the operator and the supplier of the vehicle.

These and other aspects are an essential part of optimizing the overall system of vehicles, infrastructure and operation. Apart from practically continuous redundancy and many other infrastructural optimisations, a number of stops are also being pulled out in the operational sense. In future, the Core will, technically speaking, be defined as a station area in Germany so that, for example, in the event of serious disruptions, it will be possible to clear the track with simple verbal communication without ETCS train protection as a shunting movement [43]. To avoid increasing the inherent high degree of complexity any further, additional technologies that are not absolutely necessary for the initial commissioning, such as ATO GoA 2, will be deliberately implemented downstream and put into operation little by little once ETCS L2 only has proven itself in operation and has been further optimised at

a high level. In turn, it remains a challenge to maintain a high level of competence when dealing with disruptions, although these are likely to occur very rarely once teething problems have been overcome.

Operability, driveability and maintainability

Special attention was and continues to be paid to the operability, driveability and maintainability of the retrofitted multiple units. Ultimately, this also plays a large part in creating a pleasant and therefore attractive workplace.

Essential parameters were defined back when the specifications [44] were drawn up, also on the basis of mediocre findings from other equipment projects and operational observations. A core point here is that usability of the vehicles must not be restricted and process times (such as when starting up or changing direction) must not be made any longer because of the new equipment. Based on the rapid EVC-3 and its in-depth integration into the vehicle, Alstom's on-board equipment was also optimised accordingly in close consultation with DB Regio. Generally speaking, for example, the train driver and train number need only to be entered once (on the DMI). These are then transferred to the train radio, the electronic timetable system in the driver's cab and the passenger information system. The train length and brake status are determined automatically and submitted only for confirmation. The time specifications for processes such as starting up or the technical preparatory service were checked in tests and undercut.

A great deal of attention was also given to maintainability. Many details were improved during the FoC design sessions, for example the routing of new cables was planned in such a way that they do not get in the way of maintenance. The planned maintenance of the on-board equipment was also synchronised with the maintenance intervals that had been planned anyway. Assemblies must be able to be replaced without the need for special tools, and the replacement of any one component must not take longer than two hours, which also has to be demonstrated within the scope of trial maintenance. Less maintenance is expected as compared to the previous equipment.

ETCS braking curves are another key issue. The restrictions encountered in Switzerland in particular (such as "creeping runs") will not occur in the DKS for the following reasons: braking curves are calculated according to the harmonised braking models for ETCS baseline 3 (instead of baseline 2); these have been optimised in some respects and are also transparent to the train driver

(ETCS mode "Full Supervision" instead of "Limited Supervision") [45]. In order to counteract jumps in the permitted speed curve, a guidance curve is parametrised with inclination-dependent correction factors [46, 47]. In ATO-GoA-2 operation this brake curve is not used, and unwanted beeps ("S_info") are also suppressed whenever the ETCS movement authority is extended when following in close proximity to a train ahead [48]. However, it remains to be seen how a release speed of 5 km/h, which happens in some cases before the target point and is strictly supervised, will actually be achievable.

Benefits

Modernisation and therefore also "digitalisation" of the control and safety systems, including on-board equipment adapted to it, is not an end in itself.

Arguably its most important benefit lies in the opportunity to run trains more densely and with a much better foresight. An important but by no means the only element here is block division: thanks to the formation of optimised [49] 30 to 75 m short blocks in platform areas on the Core, the minimum headway can be cut by almost half a minute. Short system delays, optimised ETCS braking curves, localisation accurate to within a few metres as well as an initial, conservative use of ATO GoA 2 are also deemed to be achievable and in the process of being implemented. Altogether, this is expected to cut minimum headways by around 45 seconds, which is around 35 % lower than if the system were equipped with ESTWs, Ks signals and PZB. For the future this means that instead of a few seconds, there will be a buffer of almost one minute on the Core with no initial change to scheduled train intervals. This can, for example, compensate for almost all extended dwell times during operation, since it enables subsequent trains to follow much closer behind.

Other elements have a purely operational quality effect, in particular faster running with delayed trains. Furthermore, this leaves a range of potential, which also includes DKS module 3, such as further reduced system delays, particularly by means of FRMCS or driving closely below the emergency brake intervention (EBI) curve in anticipation of the movement of the train running in front (using, among other things, the traffic management system CTMS). Insofar as it is possible to harden and raise potentials in stages, then a reduction of 50 % (and more) in minimum headways is well within reach [46, 48, 50, 51]. Seen in practical terms, this would mean that approximately at the moment when the train in front has cleared the

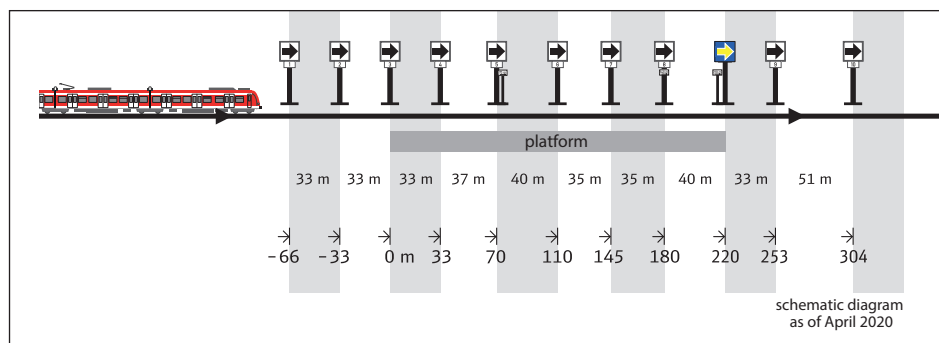
roughly 220-metre-long platform, the following train reaches the start of the platform at full speed and begins to decelerate.

In all this, it is – incidentally – not a question of squeezing as many trains as is technically possible into the system, but initially of creating opportunities with the new technology that for technical and operational reasons do not exist in the current system. With an initial continuation of 24 scheduled trains per hour and direction, the core area of the S-Bahn Core (Schwabstrasse to Mitnachtstrasse) is expected to see a significant improvement in operating quality from 2027 onwards, and consequently in customer and employee satisfaction, too. Once the expected teething troubles have been overcome and operating experience has been acquired, the aim will be to run more trains while exercising caution. Factors unrelated to signalling and safety systems CCS, such as quality of stay for travellers on the platform and platform clearance times, must also be considered.

It is also only possible to run additional trains on the Core if they can be sensibly incorporated into the adjoining (mixed transport) network. CCS modernisation which is necessary regardless and intended as part of the DKS module 3, has great potential for increasing capacity. The combination of multifaceted CCS optimisations and straightforward conventional upgrades (such as fast speed when switching to a branch line) could make it possible to overtake S-Bahn trains during their scheduled 30-second stops [46, 52]. If the planned journey times remain unchanged, then speed increases in the existing system, as are also being pursued within the framework of the DKS [53], could serve as an additional "buffer" and as an opportunity for a forward-looking traffic management system. This could be the key to what the S-Bahn system intends to be in the long-term, gradual transition from 15 to 10-minute intervals. A consistently anticipatory driving style that largely avoids unnecessary operating stops may also be expected to cause noticeably lower energy consumption and less wear and tear.

Precise localisation and safety via ETCS, train control via ATO GoA 2 and broadband radio communication with FRMCS/5G are some of the essential principles on which automated driving (ATO GoA 3 / 4) will be based. Within the scope of the "Automated Train" project, further foundations are currently being developed for fully automated moving between station track and siding [54]. To this end, a trainset operated by S-Bahn Stuttgart (vehicle number 430 236) is also being equipped, among other things, with sensors for obstacle detection in order to commence operations starting from the end of 2025. Demonstrations of fully automated moving between station track and siding are now being planned in Esslingen in the absence of timely ETCS lineside equipment. Fully automating these processes and the associated journeys up to a speed of 40 km/h will be a key step on the way to implementing ATO GoA 4 in a few years' time, initially for stabling and later for track-side operations.

While equipping vehicles will become significantly more complex with ETCS and



Schematic diagram of the block division on a platform of the S-Bahn Core (drawing: DB).

other technology the infrastructure can be simplified considerably. On-board equipment designed with the overall railway system in mind not only paves the way for ETCS L2 only, but also for further major simplifications in infrastructure, including a simplified radio network or considerably streamlined track vacancy detection system (via TIMS) [5, 24]. Some simplifications will only succeed in conjunction with fundamentally revised operational rules, for example with regard to dispensing with light signals for shunting or a future moving block operation.

Costs, financing, coordination

As previous experience in the DKS has blatantly shown, cleverly designed digitalisation in the overall railway system brings about an uneven distribution of benefits and costs in the overall railway system. While infrastructure can be simplified considerably – far beyond simply dispensing with light signalling –, the on-board equipment will become much costlier. Dual infrastructural equipment is not only considerably more expensive than ETCS L2 only equipment, including (!) precursory vehicle equipment [55], but also leads, among other things, to considerably lower possible increases in capacity and ultimately even to a greater susceptibility to failure [17].

The costs involved in first-of-class equipment for Class 423 and 430.0/430.2 trainsets are around EUR 30 million each, while the serial equipment costs come to around EUR 350 000 per multiple unit. Roughly ten percent of the costs of the series equipment can be attributed to elements such as

Multi-purpose area redesigned in the course of the redesign process (photo: DB Regio / Niemüller).



optimised brake curves, FRMCS and TIMS, in which a railway undertaking has little interest as such, but which are very useful in the overall system [25]. Then there are associated costs, such as those for project management and transfers, necessary content changes during the course of the project and the redesign.

The on-board equipment is being financed to a large extent by DB Regio and the VRS, and funded to a lesser extent by the EU. As part of the DKS pilot project, the German federal government is subsidising the on-board equipment for vehicles at the core of the rail node for the first time. The funding (for multiple units) is subject to 24 technical conditions [6], which go beyond the minimum requirements imposed by regulations and network access as well as by the railway undertaking perspective – and thereby pave the way for a much simpler and, at the same time, more efficient infrastructure in the future.

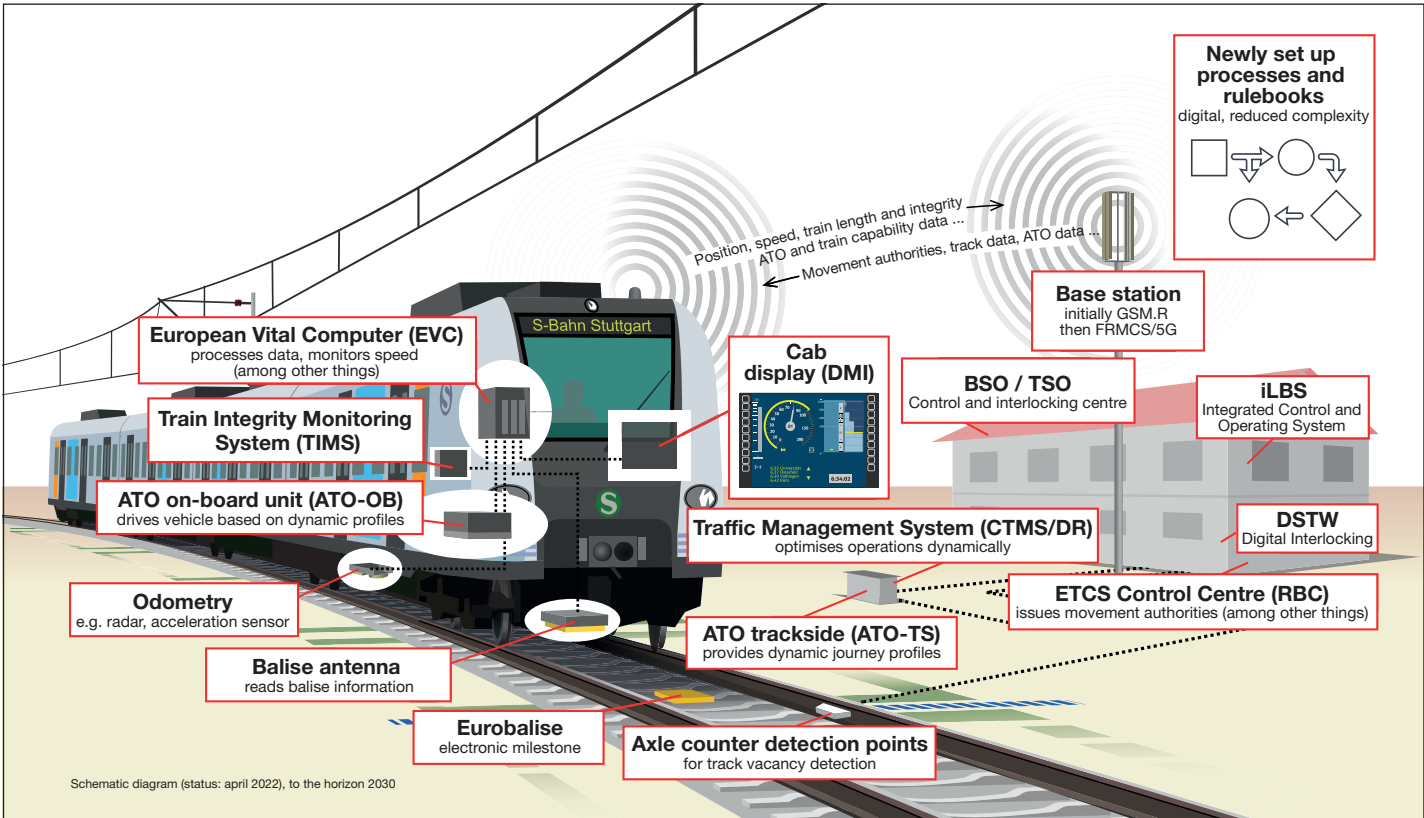
The findings and experience gathered from the DKS were also incorporated into an

evaluation, the results of which have been published in full. By way of summary, it can be seen that, in addition to access to the railway network (minimum requirements) and funding (subject to conditions), what is needed above all is credible and reliable planning and coordination, transparency on benefits and differentiation in track access charges, in particular on the basis of the extremely heterogeneous “digital” capacity consumption [25, 56]. Without such a cleverly designed framework, the modernisation and “digitalisation” of CCS would foreseeably not only be much more protracted and costlier procedures, but also significant increases in capacity would be unlikely to be achievable [57].

Summary and outlook

After more than five years of intensive work, three Class 430.0 / 430.2 trainsets were approved for passenger service equipped with PZB (C2T) on 20 February 2025. They were used in passenger service for the first time on 3 March 2025. This represents a

Simplified representation of the overall architecture of vehicles, infrastructure and regulations (drawing: DB).





Above: Retrofitted and newly approved multiple units have been in passenger service since 3 March 2025, although the built-in ETCS has not yet been activated. Here, 430 231 + 070 + 217 EMUs can be seen passing the Oberesslingen track construction depot under the Esslingen vineyards. The middle multiple unit 070 will receive the new livery later (photo: DB Regio / M. Sauer).

Below: The 430 084 multiple unit, which was retrofitted at the DB Fahrzeuginstandhaltung (Rolling Stock Maintenance) workshop in Hagen, is being transferred to Plochingen at the Glens cross over on the Mannheim – Stuttgart high-speed line. This multiple unit too has now been re-approved and can operate self-powered once again (photo: A. Bickel, 1 March 2025).



However, there is also a need for more pragmatism and ways to simplify the now hugely complex authorisation procedures. Ultimately, in the retrofitting of existing rolling stock, first-of-class and series retrofit need to be decoupled and organisational interfaces that are not absolutely necessary should be avoided as far as possible.

Vehicle retrofitting and equipping was and is a major motivating factor for Alstom in the development of the EVC-3 platform, which is now also being deployed in other projects such as the S-Bahn system in Cologne and new regional multiple units destined for Luxembourg and Sleswick-Holsatia. Future projects will benefit from the experience gained in the DKS and will be able to draw on a platform that has already been tried and tested.

In February 2026, a first section of the DKS, stretching from Stuttgart-Feuerbach via the new Central Station to Wendlingen, is to begin pre-run operations with no passengers [5]. For the first time, suburban trains will then also run equipped with ETCS in the Stuttgart node. From October 2026, S-Bahn passenger services will run with ETCS in the north-east approach to the Core. In April 2027 the airport branch will follow, in July 2027 the Core. After a lead time spanning one decade, high-performance operation with ETCS is becoming a reality; further technologies (such as ATO) and optimisations will then follow step by step.

milestone for the vehicle project and the DKS. Some 1000 people were involved in this project: engineers, technicians and craftsmen, engine drivers and maintenance staff, dispatchers, lawyers, business people and several more.

However, vehicle retrofitting for the DKS also proves how time-consuming and difficult such a conversion programme is. It means that the FoC vehicles are taken out of service for around three years and retrofitting each series vehicle takes several weeks. Vehicle retrofit projects are extremely complex and require close collaboration between the operator, vehicle manufacturer, maintenance provider, owner, signalling technology manufacturer and series supplier. Due to the fleet expansion that had been planned anyway in conjunction with the DKS (Class 430.2), at least there was no need to procure replacement vehicles to maintain train services during the retrofit programme [16].

There is no alternative to modernisation and therefore digitalisation of the railways in Germany. The project shows only too clearly how important it is to shape this. It became clear right from the 2017/2018

feasibility study that this can be achieved only if digitalisation is more than ever designed in a whole-system approach. Only in this way can comprehensive capacity gains actually be achieved; only in this way can infrastructure be simplified in many respects and thereby satisfy customers, employees and taxpayers. The on-board equipment is and has been an integral part of the DKS from the outset – alongside infrastructure and optimised operational regulations. It is a deliberate strategy that far exceeds the mere “just some” ETCS equipment (in accordance with standards and network access conditions), which consequently creates far-reaching benefits in a much simpler, more efficient and safer overall railway system while keeping additional costs at a moderate level.

In many ways, the DKS shows how digitalisation of the railways in Germany can succeed. But for thousands of traction units and tens of thousands of track kilometres to be equipped, there needs to be a stable technical basis, a clear, credible and reliable strategy, along with secured financing and coordination, as well as transparency and price differentiation in the infrastructure.

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