Rethinking *rail*

How the sector is changing to shape the future of mobility

Capgemini engineering

Introduction

How rail is changing

Around the world, rail offers an efficient and sustainable form of transport for people and goods. As reported by Our World in Data [1], rail travel and freight emit very little — only 1% of transport emissions. Other transport — mainly the movement of materials such as water, oil, and gas via pipelines — is responsible for 2.2%. Rail connects towns and cities and has the potential to generate growth and renewal, connecting people to jobs and family, and goods to businesses. According to Eurostat [2], in 2023, EU rail passenger transport hit its highest level in years, reaching 429 billion passenger-kilometres.

But it faces challenges. Aging infrastructure is often inefficient and costly to replace. Some lines struggle to meet capacity, others don't attract enough passengers to fund their operations. Operators - both private and national - in various countries struggle with profitability and cost control in a tough economic climate. They face unpredictable OPEX expenses related to aging stock and infrastructure, plus legal and practical limitations on how much they can charge. In some cases, they face growing passenger numbers, and increased freight volumes - plus higher expectations around connectivity and convenience that only add to the challenge.

And then there is increasing competition, whether from opening up the market in rail, or from other modes of transportation, like flights or roads – driving and even flying are often considered cheaper and/or easier for human transport, despite their higher cost to society and the environment, just as freight trucking is often chosen for freight rather than rail.

Rail is therefore ripe for reinvention. It must run more efficiently at a lower cost. It must make better use of existing infrastructure, including emerging smart IoT and digitalized systems. It must be more interoperable and standardized. It must improve the customer experience and become easier to use. And, as it evolves, it must become even more sustainable and efficient through better designs, and more optimal traffic management and maintenance. In this, it has a real opportunity, as ecological concerns grow in relation to our Net Zero 50 targets.

How can it do all this? Success depends on all actors in the railway industry mastering innovative technologies, delivering complex digital transformation programs, and building partnerships across digital and technological ecosystems.

In this point of view, we will address these challenges with various approaches which – if tackled correctly and collectively – will transform rail to be fit for the future.

Transforming trains

How digital engineering helps design the trains of the future

Travelers of decades past would recognize the trains of today, even if the design, speed, interiors, and the way people use them are all somewhat different. And today's travelers would probably recognize tomorrow's trains - the fundamental idea of a locomotive running along a track hasn't changed, and probably won't.

But look closer - a time traveler to 30 years from now will see many differences that meaningfully change what a train is. Future trains will likely have much more autonomy, use zero emissions propulsion systems, and be made of new materials. They will be faster, greener, and more autonomous.

The need for development speed

Improvements must be made, even though much of today's rolling stock is required to last another decade (at least). But designing this new generation of trains will impose significant engineering challenges, as more complicated technologies need to be developed and integrated. Yet, even as complexity increases, we will need to do this engineering and manufacturing faster.

A new train takes roughly five years from the initial design stages to qualification. That will likely be more if this train has to integrate brand new technologies. Twenty years ago, car designs also took five years to hit the road, but automotive manufacturers have managed to compress that timeframe to just two years, largely thanks to digital approaches to design, development and testing. Rail has not seen the same time compression yet, though it could. Doing so would speed innovation, lower costs, and help the rail industry meet its net zero goals.

Once a train design is approved, it can be very difficult to alter due to strict safety rules. So, we must also make trains more modular and flexible, for example, through the softwarization of components so that trains are not constrained by their hardware and can evolve through software updates to meet new needs.

Embracing digital engineering for train design

Let's start with an example of train innovations, and the role of digital in making rail greener, better, faster and stronger.

Alstom is developing the Coradia iLint, the world's first hydrogen fuel cell powered train. Another major rail player is developing hybrid propulsion systems that combine diesel and battery power. Both can operate on non-electrified tracks more cleanly.

Such projects can benefit from digital modeling to optimize the propulsion systems for weight reduction and energy efficiency. Moving up another layer, researchers in Korea have used a digital twin to model 30 years of operation of a proposed train operated by solar and hydrogen, showing it would be a good substitute for the diesel locomotives currently operated in South Korea.

Similarly, digital simulation allows researchers to model the behavior of new materials – such as those that are lightweight, stronger, or with greater impact absorption – and predict how they will perform in real-world applications. For instance, the Vehicle Technologies Office at the Department of Energy (DOE) in the United States uses computational materials science to enhance the understanding and development of advanced materials like high-strength steel, aluminum, and carbon fiber composites, supporting the design of lighter and more durable components for a range of vehicles.

Similar modeling approaches support digital crash tests, allowing engineers to simulate the impacts and stresses that materials and components will face during collisions. These can identify potential weak points and help optimize the design to improve crashworthiness.

Digitizing trains

Whilst digital engineering technologies are helping with the physical design, the next generation of trains will themselves become partly-digital thanks to sensors, control software, and algorithms.

These new sensor and connectivity technologies could be highly valuable for getting more from current trains. So, let's start by looking at examples of how technologies could be put to use.

Predictive Maintenance: Various sensors can be installed on trains and tracks to monitor the condition of equipment continuously. For example, vibration sensors and accelerometers on bearings and wheels, temperature sensors on motors, and acoustic sensors for detecting anomalies in the railway track. Data collected by these sensors can be analyzed using machine learning algorithms to predict when parts might fail or require maintenance, allowing trains to schedule repairs before breakdowns occur, reducing downtime and maintenance costs.

Energy Management: Energy consumption sensors can help monitor and optimize electricity use. This can include monitoring the efficiency of the train's propulsion system and the use of regenerative braking systems that capture and reuse energy, as well as onboard systems like lights and doors. Algorithms can analyze fleet energy usage patterns and optimize energy consumption, for example, by adjusting speeds or maximizing the use of regenerative braking.

Safety Enhancements: Technologies like LiDAR, cameras, and infrared sensors can be used for obstacle detection to prevent collisions. Track health monitoring sensors can detect track faults or failures that could potentially lead to accidents. Automatic Train Protection systems can use these sensor inputs to further enforce safe operation.

Passenger Experience: Sensors can monitor onboard conditions such as temperature, air quality, and occupancy. This data can be used to adjust environmental controls automatically, both for comfort and cost efficiency.

Proceed, but with caution

Digital technologies can vastly compress timeframes for engineering design and delivery of new and upgraded trains, without compromising safety and quality, as has been shown by other safety critical industries. And indeed, rail can learn a lot from such industries when it comes to digital engineering, from automation in automotive to simulated testing in aerospace and defense (A&D).

We must, of course, acknowledge that many of these technologies are new to rail. Whilst there are some quick wins to be had, truly transformative technologies like digital twins will take a lot of time. We must be careful to ensure that any such project is managed right, with clear goals and deliverables in mind, to ensure it delivers an ROI, and that we don't end up throwing money into a digitization black hole on the vague promise of some future benefit.

Nonetheless, these technologies' potential is undeniable. Consider one example. US freight railroads test a new locomotive model for 30-50 'locomotive years' before it is certified to use. This means a railroad may need to test ten units for 3-5 years to gain enough data to know whether to accept it or not. But rail is expecting a mandate to migrate away from diesel equipment (California's deadline is 2035), yet there are not enough battery-electric locomotive (BEL) prototypes to test today or in the foreseeable future.

Hypothetically, a BEL manufacturer could create a digital design and have it tested virtually in less time than the physical models could hope to achieve. Based on already developed designs for hybrid battery/diesel electric multiple unit (EMU) passenger trains, we could – with a good case to regulators backed by data – probably reduce the need for extensive physical testing. If we could start collecting data, we could ensure that soon enough to make a difference, and plan for BEL being fully on track by 2030.

Since locomotives are complex machines with thousands of parts, and the work has not been done to build such high-fidelity models, this is not realistic today. But could a fully digital design and test regime someday be sufficient to satisfy operational railroad buyers, safety regulators, and emissions authorities? This remains a goal, a hope, and a major market opportunity all rolled into one.

In summary

While the fundamental concept of a train remains unchanged, tomorrow's trains will be more comfortable, more user friendly, faster, greener, autonomous, and more convenient, driven by advanced technologies. The engineering that will get us there will require faster development cycles, akin to that of the automotive industry, delivered through digital approaches that balance rapid prototyping and digital continuity with safety and rigorous testing.

Rail renewal

Using digital technologies to improve rail infrastructure

In it for the long haul

Skerne Bridge in Darlington, England has been used by trains for almost 200 years. According to the UK's National Rail, it was the world's first public railway to use steam locomotives, making it the birthplace of today's modern passenger railway.

The lifecycle of railway hardware is a major challenge. We ask a lot of it. Aging infrastructure, like rail tracks and the structures that bear them must last decades (or centuries, in some cases).

The sheer costs and logistical challenges mean that we can't simply replace infrastructure every few years just because a better version is now available, as we might a smartphone. Outside of the natural renewal cycle, we need to look at doing more with what we have.

That means squeezing as much longevity out of it as possible. Doing so can mean extending the life of tracks. But it is also about improving efficiency, safety and the passenger experience, and by providing increased operational flexibility - for example, making cross-border operations easier.

This can be done through a range of new technologies implemented onto signals and tracks. However, this is rarely as simple as plugging in some sensors. What will this take?

Some of the network is much older than the people who operate or travel on it. Rail operators want to replace old mechanical rail systems with modern digital alternatives.

The idea of a digital rail network is to create a digital model where we can run simulated trains on simulated tracks, so we can quickly test new trains, subsystems and autonomous driving in the 'real world', and work out the best way to optimize routes. It also aims to provide a real time model of the network in which we have an overview of where everything is all the time and can make real time interventions to improve operations.

Digitizing the track

To create a virtual network, we first need to digitize rail infrastructure, and do that efficiently and cost-effectively.

Much of today's route data is currently based on manual observation and record taking, making updates slow. Digitization could markedly improve things, but building a digital model of rail routes means painstakingly gathering data on every slope, curve, signal location, crossing, local wildlife habitat, and so on.

This requires sensors (not necessarily on the train itself) to collect this data at scale. LIDAR (with a lot of processing power behind it) is one common option today, but a range of automatic data collection technologies are also suitable, for example, accelerometer data taken from trains or image recognition via conventional optical cameras. To this end, UAVs are also starting to show promise as a cost-effective way to quickly access and assess infrastructure - being both increasingly economical and highly mobile.

In addition to sensing, this digitization will require Geographic Information System (GIS) technology that combines sensor data with other sources, such as satellite images, to create real-time topology maps. Success will largely depend upon how closely the digital replica adheres to the real network it represents.

That mapping will allow models to be created of the network that support optimal decisions about network changes, like exactly when to replace track components based on real time data on track status, and when to schedule upgrades to minimize disruption. It also enables future decisions – such as increased train capacity or opening new lines – to be simulated to understand their implications on the network.

As ever, these things are not simple. As well as deploying sensors and collecting new data, there is also a vast amount of legacy data, often collected in inconsistent formats (from multiple database types, to Excel, to paper records). A rail digitization project will need to reckon with this, through data discovery, cleaning, and centralization of all data, backed by robust data governance and cloud-based database management tools.

Digitizing the signals

This is the process of ensuring that every signal – some of which are still purely mechanical – is electrified and connected and can be observed and controlled from a central system. Digital signals bring many benefits, allowing for more optimal route management.

An example of utilizing signals to deliver value is the US's Positive Train Control (PTC), which can automatically stop or slow trains where there is a risk of collision, derailment, unauthorized movement, or passing through switches left in the wrong position. PTC uses on-board GPS and data communication systems that relay information between trains, signal and trackside sensors, and railroad back offices – allowing remote monitoring. The European Rail Traffic Management System (ERTMS) - more on this later - is preparing the ground for something similar in Europe,

through a standardized pan-European approach that will work across borders.

Digital signals can also help underpin Virtual Block Signaling (VBS), a promising approach that allows trains to be controlled and monitored digitally. Rather than dividing the track into blocks, regulated by signals, where only one train is allowed, virtual blocks move with the train defined by its longest stopping distance at its current speed. That allows more trains to be safely put onto tracks.

Ultimately, digitalized signaling systems could eventually evolve into non-physical, in-cab signaling. This already exists on some high--speed lines today, because, for example, physical signals can be difficult to read at hundreds of kph.

Once all signals are in-cab, we can envision a faster progression to fully automatic train operation (ATO) on more lines. Such systems require seamless connectivity both on the train and on the track. In Europe, further work is being done on ATO-enabling technologies, like train-to-train communication.

The eventual aim is Grade of Automation 4 (GoA4) - the highest level, in which the train is unattended (controlled without any staff on board). There are several metro lines in various countries already operating at this level, and the eventual aim would be to deploy this on a larger scale, and on other types of line.

Benefits of digital signals

- Optimized route planning: Detailed information of where everything is, all the time, allows optimal route planning using sophisticated algorithms.
- Dynamic route management: Dynamically adjust train speeds or routes based on traffic conditions, track work, and other factors, reducing delays and increasing overall throughput.
- Enhanced safety: Digital signals improve the accuracy of train control systems, reducing the risk of collisions and derailments.
- Increased efficiency: Real-time data monitoring enables more trains to run on the same tracks without delays, increasing network capacity.
- Better passenger experiences: Providing passengers with real-time information about schedules, delays, and platform changes.

The challenges of signal connectivity

However, digitizing whole networks of signals, spread across nationwide networks of rail tracks – much of it in remote places – is tricky. Moving from physical to virtual signals means relying completely on radio communication systems between trains, and between trains and the wayside.

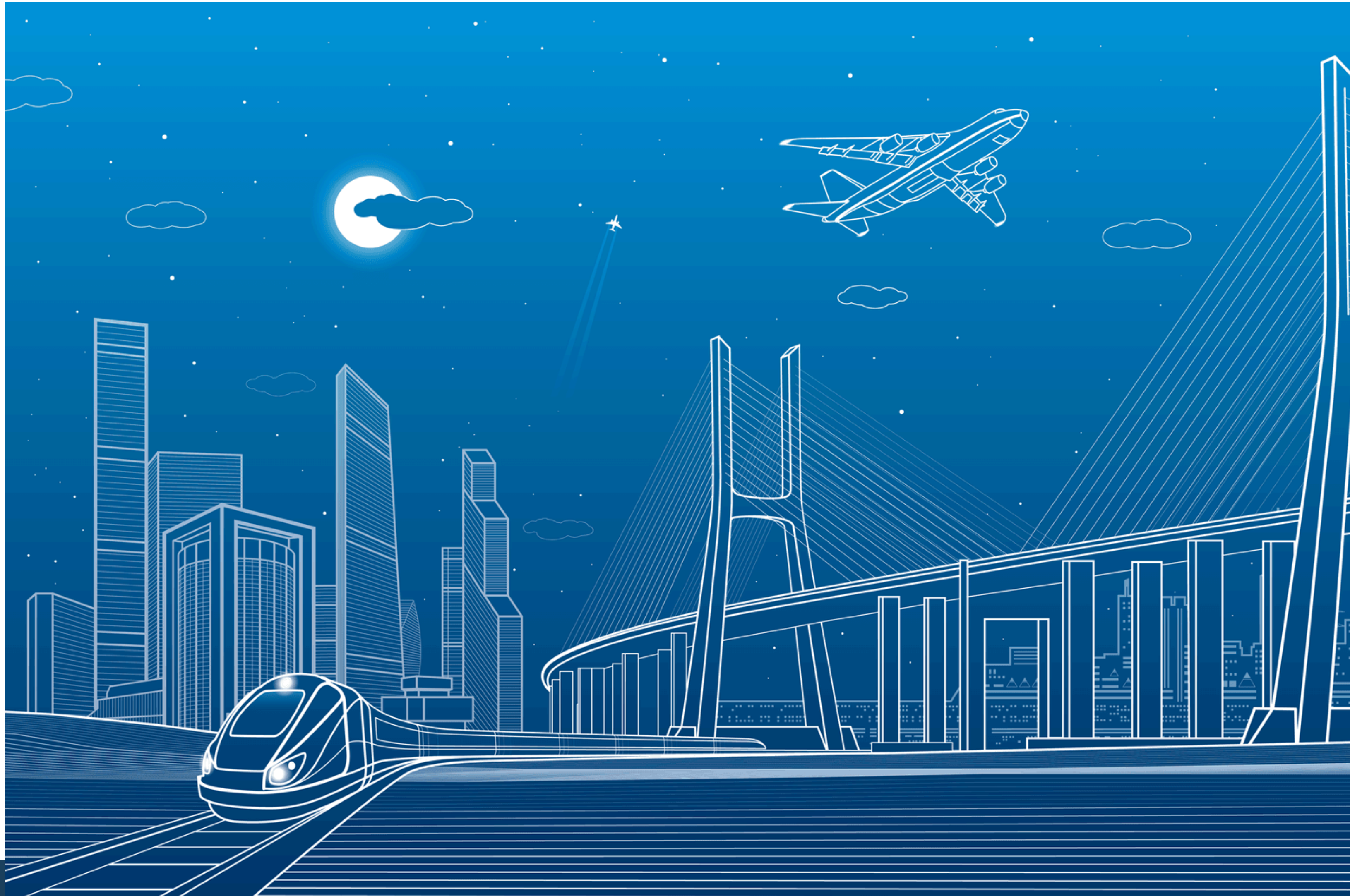
In Europe, though less so in North America, the main blocker right now is the lack of good communication infrastructure. Most current rail connectivity was built with 30-year-old 2G technologies.

As such, many railways are looking to move to 5G, under the new FRMCS standard, which is due to be implemented fully circa 2035 (though that date is flexible). That should provide the level of connectivity required for reliable networks of digital signals, and all the services that can be built on top of them.

This is coming, but it is a technically complex upgrade, involving the deployment of new 5G technologies and architectures. Rail also presents some unique challenges to rolling out a communications network, such as mapping different communications technologies to a geographically vast physical network, and ensuring security is adequate throughout.

Innovation in digital signaling is also hampered by an excess of standards - meaning each country has a different way of doing things, making innovation harder to do at scale. To solve this in Europe, the ERTMS was developed to overlay or replace existing national systems and also includes a standardized digital communication system (FRMCS) between the trains and the control centers.

That should speed innovation by allowing rail operators to learn from cutting- edge projects in other regions, and by boosting supply chain innovation by allowing companies that currently operate nationally to develop solutions for operators across the EU. If you'd like to learn more, read our FRMCS whitepaper [3].



Operational optimization

Harnessing tech to make day-to-day operations more efficient

Running a network of trains involves more than managing their routes from A to B. It needs a whole infrastructure to check and maintain trains and tracks, ensure trains can leave on time, and to respond to problems quickly.

Here, again, technologies can help ensure efficient incident management and improve traffic flow. Transforming rail operations is less about complete transformation, and more about hundreds of incremental gains that add up to big cost savings. In this article, we'll look at three, before drawing some broader conclusions on setting up organizations to continually use digital approaches to optimize operations.

Predictive maintenance (PdM)

Probably the most talked about digital solution for operational efficiency is predictive maintenance.

Predictive maintenance uses data to proactively detect anomalies and predict equipment failures before they occur. That allows maintenance to be scheduled at convenient times to repair issues before they become a more complex or expensive problem.

An example could be a door sensor that shows incremental slowing of the closing mechanisms that would not be detected by the human eye until it became an issue, or a sensor that detects subtle vibrational patterns that indicate a flattening of the wheel, or defects on the track. By establishing normal work conditions for assets, PdM can compare the actual infrastructure state to baselines, thus detecting the start of any drift, and so plan targeted maintenance to address the issue.

Further algorithms can be used to predict when this will actually become a problem. A wheel flat may affect safety, by damaging tracks and switch needles, and by reducing comfort (through extra noise and vibrations) and thus need to be corrected as early as possible - whereas a slowing door may still have weeks of usable life before it actually affects the customer experience. Predictive algorithms can tell you with greater accuracy what is failing and when the required intervention is needed to avoid such failure.

This can be backed by whole systems that optimize that scheduling - to ensure appropriate maintenance, at the right place, at the right moment, by the right people.

Implementing predictive maintenance can be a long process, which requires an understanding of each maintenance type, and the possible solutions. In each case, the first step is to set up systems to collect historical data to set the baseline, and live data to analyze failure patterns. We must also digitalize the whole maintenance process - from fault detection to maintenance scheduling, repair tracking and updating the parts history book.

Making day-to-day tasks easier with AI assistants

Thousands of rail engineers work around the clock to maintain vast and complex railway networks, so that passengers are safe, and the railway operates smoothly. Behind every operational procedure they conduct, are a slew of minor processes that take time. Some are burdensome but safety-critical, some are there out of habit. New technologies could be applied to streamline many of these processes, and make engineers' lives easier.

Having the right crew at the right time and with the right skills is critical - so predicting resources, crew availability and resilience is an important capability. AI can be used to help with this kind of activity by anticipating sickness rates based on seasonal data, and

potential service disruption or the lack of particular competence for an anticipated repair work can help to optimize resource use and network efficiency.

According to a 2023 Capgemini Research Institute survey [4] across 800 organizations, 67% of executives see the most potential for generative AI in the IT function to drive innovation and create value.

Gen AI's ability to parse human language also means it can be used to analyze day-to-day interactions and propose improvements. For example, it can be used to analyze emails or transcripts of phone calls between engineers – thousands of which happen every day – and to identify whether they met guidance for being clear and concise when providing safety critical information. Capgemini is currently working with major rail operators to develop a proof of concept for auditing maintenance safety- critical phone calls – with appropriate consent of course – to learn such lessons.

Tracking and inventory management

Running a railway involves a lot of physical 'stuff' that moves around, from tools and technologies for maintenance, to freight that needs to be loaded onto and off of trains. A surprising amount of time can be lost just looking for things. Tracking technologies, backed by digital management technologies and digital ledgers can bring some much-needed order.

For freight trains, there is a need for yard optimization to facilitate efficient loading and unloading of freight. That starts with knowing where everything is, all the time, through tagging freight, and having connected trains. For example, every crate has an RFID tag and unique ID that can be scanned when it leaves a customer's premises (like a factory or grain facility). When it arrives in a yard or boards a train, it pairs with the train's GPS. All of this is tracked in a digital ledger - so there is a live view and record of where everything is at all times.

This approach can be applied to the entire freight transportation value chain, where a unit of freight is tracked from its point of origination (eg. factory, mine, grain facility) through its various transport modalities (eg. truck, train, ship, air cargo) - all the way to its final destination.

Such tracking provides customers with an answer to the common question 'where's my stuff?', which provides reassurance and supports efficient planning of loading/ unloading. Similar tagging and tracking systems are also hugely valuable right across networks for quickly locating the tools needed to perform upgrades or fixes. We could also use AI to optimize the order of the carriages and wagons that constitute the train - tailoring them exactly to the needs of the journey, the kind of cargo being transported, and so on.

Whilst the immediate benefit is organizational efficiency, over time such systems gather rich data on which to design better systems. For example, historical data about grain transports will show patterns of transport needs linked to harvest season, which can be mapped to market demand models, and other forecasts about seasonal and event-based train demand, which allow long term schedules to be designed to maximize train use.

In summary

Today's rail maintenance and operations centers often rely on aging applications and technology.

Once again, the theme here is joined-up systems, which consolidate various legacy systems into a single, standardized approach, with an effective set of tools to draw data and inform the relevant workers of where things are, and what needs doing in the most efficient way possible.

Digital solutions like Enterprise Asset Management (EAM), Computerized Maintenance Management Systems (CMMS) or Asset Operation Management (AOM) all play a vital role in planning and scheduling. But true optimization relies on connecting everything up – from sensors, to management software, to engineer's mobile devices – all joined by a cloud-based system, applying the right analytics, and designing the right user interfaces.

All of this must balance efficiency with keeping people safe, and respecting people's security and privacy. But with the right approach to people and technology, there is lots of room for small improvements across the board that will add up to big improvements and savings for rail companies.

Contented customers

Improving the user experience to make rail travel more appealing and competitive

You and a colleague are traveling cross country for work. Before you leave your house, you bring up an app that plots out your route, booking a driverless cab to take you to the train station, and the train and metro that will take you to your client's office. Once you arrive at the station, a hidden scanner detects your phone's unique identifier, proving you have a ticket, and you waltz onto the train.

On the train, you enter a 'pod' that you booked in advance. At the push of button, an acoustic screen built around your seat creates a private meeting room where you and your colleague can do your weekly catch up in privacy. You set the lighting and air conditioning to your perfect comfort level via your phone.

Unfortunately, the train stops unexpectedly. But it's of some comfort that the train's built in AI, accessible via your phone, can bring up the details of the delay, the steps currently being taken to remediate it, and predicted remediation time based on past experience. No matter, you let your taxi and client know the updated arrival time, and use the time to pop on your VR glasses and join a virtual meeting – with no interruption to the connection – where your engineering team in India give you a hands-on walk through of the latest product design.

We are, of course, quite a long way off from this reality, but the technology to make it happen is mostly already available. The work now is to integrate, test and certify this technology.

Why take the train anyway? The competition problem

The first question might be, 'why bother with all these expensive upgrades?'. Though many operators are nationalized, railways still operate in a transport marketplace where they compete with many forms of transport. Rail is often just one of the various available options. It struggles to compete with cars for convenience and planes for speed. But it can be better at both of these than it is now, whilst also offering greater comfort and – critically in a busy world – the gift of time to be productive as passengers sit uninterrupted in a comfortable, connected seat. It is also far more environmentally friendly.

We reckon that, when the journey time is roughly ±30% more than the length of a car of plane journey, most customers could be convinced to choose rail as an option.
Trains can also get you from city center to city center, which isn't true for planes, and can be highly challenging for cars, due, for example, to traffic congestion and the logistics of parking.
We also envision a model where a train traveler can seamlessly rent private transport (eg. electric car, electric bike) for the 'last mile' to their destination.

By leaning into its natural benefits, and getting better at making the entire journey smoother, trains can attract many more customers, which is good for rail companies and good for carbon emissions.

But what will it take to achieve this?

The user experience

Comfort will need to be at least equivalent to car travel, though rail can (and should) aim higher. Though a staple of good service in days

gone by, the food and drink cart is not as important today - a consequence of the COVID-19 pandemic and better food options at stations.

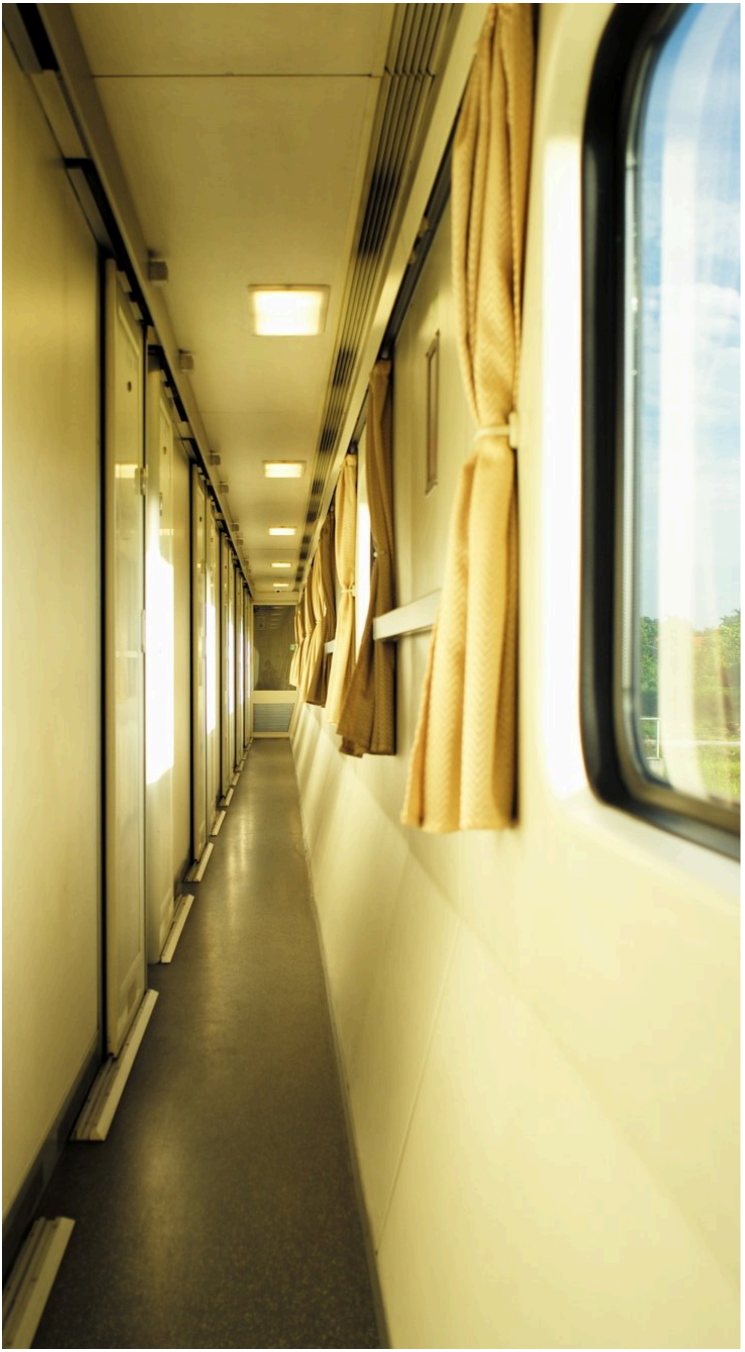
Instead, here is what rail users care about.

Comfort

"Freezing", "cramped", "people chattering in the quiet carriage". These are just some of the complaints routinely found on rail review sites.

Much of this could be solved quite easily. In many cases today, a train's onboard heating and cooling systems are set before departure and cannot be modified once the train is in transit. This isn't good enough for today's passengers. They need localized heating and cooling options, and windows that, on demand, can create electronic blinds to protect against excessive sunlight.

Seats may require a rethink too. These seats need legroom and comfortable, ergonomic designs - though this is more of a requirement



for longer trips, and less so for short stop metro journeys. All seats require USB-A and USB-C sockets and power outlets.

On board privacy and value added services

For many passengers, one of the major downsides of public transport might be having to deal with other members of the public. What if you didn't have to (or, at least, not as much)?

The idea isn't entirely new. First class carriages and sleeper trains have offered enclosed carriage spaces for decades, and offered additional services. Airlines have some excellent offers here for those who can afford it - some first class 'suites' come with everything from HD screens, shower suites, luxurious beds and high speed internet.

Few trains are likely to offer such extravagance, but simpler options could provide the privacy needed for a private meeting or conversation, and attract a premium, particularly from business travelers where travel eats into their working day. This would, ideally, be a private environment - a kind of cocoon or pod. Physical barriers could descend to create a 'room', or speakers use noise cancellation technology (similar to what is found in some high end headphones) to decrease background noise. A rail operator in Norway offers a carriage where passengers can book a private 'phone booth' via an app to take phone calls (familiar to those who use modern shared office space), which can be unlocked at the pre-booked time via a QR code.

Real time, high quality connectivity

Then there is connectivity. For a comfortable journey, users want to stream HD films and join meetings. The bandwidth required to allow, say, 1000 train passengers to simultaneously stream video with a high quality of service (QoS) is significant. That could increase exponentially if real-time VR takes off.

Current systems fall well short, but this kind of connectivity is the target of 5G FRMCS, or Future Railway Mobile Communication System. Like other 5G networks, FRMCS operates through a series of cell towers that cover geographic areas. These towers connect to devices on trains and along tracks, enabling continuous communication even at high speeds. This infrastructure supports both the uplink (from train to tower) and downlink (from tower to train) communications essential for railway operations. That means it can offer high-speed data transmission, low latency, and the ability to connect many devices simultaneously.

It also offers much greater security, since it is a fully digital system that brings much greater control over how data is encoded and transmitted, allowing more robust security mechanisms to be put into place vs today's analog systems.

Nonetheless, this is a technically complicated upgrade and so the transition will occur gradually over several years to allow for rigorous testing, certification, and integration without disrupting current railway operations.

Flexibility, reliability and resilience when taking the train

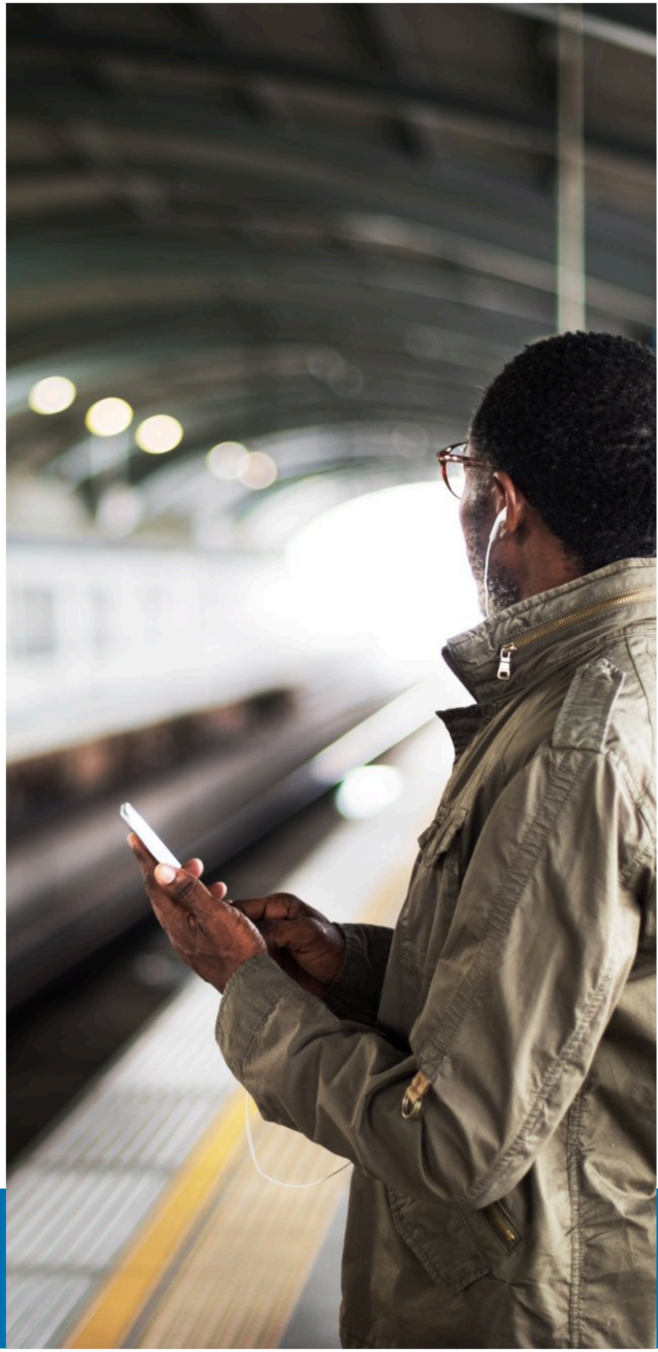
Ultimately, we must tackle perceptions of unreliability in rail by making trains more reliable. We can do this by building increased resilience and flexibility into trains – making them better able to tackle the incidents that will be inevitable, regardless of how technologically sophisticated trains become.

Today, timetables and routes are fixed. This is what you can see printed in the stations for the next six months, or via the operator's app as you book tickets online.

Tomorrow, we may imagine that additional trains or reduced service could be done 'on the fly', meaning, for example, that more trains go to and from a city on the day of a major sporting event at that city – or reducing train frequency when there is a bank holiday.

Doing so means higher flexibility and more capability management (also requiring crews to be more flexible to react to fluctuating demand). When routes are compromised due to traffic or an incident, there should be a way to divert a train from its original plan, take a secondary route (deviation) and transport people with less disruption than an outright cancellation.

The goal is a train that continues its route to the destination regardless - one that never stops operating completely, even, for example, when no power is available on the overhead catenary, or the original route isn't available. In other words: a journey should *never* be canceled (ie. passengers have other options, like bus transfers in worst case scenarios), delays are limited to less than 10 minutes, and service is frequent (eg. one train at least every 20 mins). If train integrity is high enough, a single failure could, ideally, never prevent the passengers from getting to their destinations within a few minutes of their planned arrival.



All of this requires extensive redundancy and increased support for operation in emergencies or degraded modes of working, a complete failure analysis of train operations to better understand (and mitigate) everything that could possibly go wrong, and highly connected services, supported by connectivity everywhere.

A better experience from start to finish

Finally, there is everything around the journey that makes it seamless end-to-end, from the moment you book a ticket, to getting to the train, getting on it, and arriving at your destination.

A train app could allow you to book the entire journey based on your preferences, eg hiring a bike for a short journey to the station in the sun, or an Uber for a longer one in the rain. A single ticket could give you access to everything. Theoretically, there is no need to scan at all on trains, a device at the station could detect your phone's identifier and link it back to your journey, or a camera linked to your phone's face ID algorithm could detect you as you walk by – though, obviously, data privacy would need to be very carefully managed here.

This has an additional security benefit; people can always jump barriers – London's transport operator TfL says people who jump the barriers cost it £150 million per year. An identifier based system could provide a clear view of who has paid and who hasn't, and allow them to be directly approached, or barred in future.

This holistic journey approach also extends to updates on board. Customers don't want to be kept in the dark when things go wrong. A large proportion of complaints are related to punctuality and reliability - 2023 data from the UK Department for Transport [5] finds that a lack of punctuality and reliability were the main cause of complaints. Being made to wait without an adequate explanation can make the situation worse.

As in the example at the beginning of this article, this could take the form of a 'live view' of the train's location on an accessible website,

backed by an AI chatbot that can quickly and accurately provide answers to questions like 'what has caused the current delay?' or 'what the best route to X is if I miss my connecting train?' or warn customers if they may be running late.

Frontline employees reporting a superior experience can also have an impact on customer satisfaction. Our research reveals [6] that 89% of frontline employees say their organizations have improved their employee experience, leading to an indirect positive impact on customer experience. Additionally, 82% say that their organizational leadership listens to and learns from employee interactions with customers to improve the customer experience.

This notion of a joined up journey needs significant integration behind the scenes. This requires integration between different transport companies to allow multi-modal routes to be suggested based on criteria, booked in one payment, and payments split between companies. Many booking sites already allow train tickets that span more than one train network, so adding in bike, bus and taxi companies doesn't seem farfetched.

It also needs backend systems in the cloud that can track a single identifier – say an app or a credit card number – through the journey, so the user can be validated at each checkpoint without needing separate tickets for each. Finally, it needs all information systems from train locations to maintenance systems to be connected and fed into purpose-built analytics software, and presented through well-designed user interfaces (likely harnessing Generative AI) such that the user can access the information they need, when they need, in a way that is meaningful to them.

We believe that trains can remain relevant and competitive well into the future, and play a major part in the move to **MaaS (Mobility as a Service)** - an aspirational vision of future transport that "*integrates various forms of transport and transport-related services into a single, comprehensive, and on-demand mobility service… one that aims to be the best value proposition for users, societies, and the environment*" (the MaaS Alliance) [7].

Expectations are rising, service must follow

The continual rise in passenger expectations of comfort and convenience cannot be ignored. Rail also has some stiff competition; other industries are working to make their modes of transport more attractive.

But rail also has a lot of things working in its favor. It is generally cheaper, more ubiquitous and more comfortable than air travel, and it provides more space than air, car or bus travel. In most cases – especially when electrified – it is far greener and emits less per passenger than most of its competition.

In some cases, its uptake is held back by perceptions of unreliability, crowded or cramped conditions, inflexible ticketing and a lack of amenities. Broadly speaking, these are all things that can be fixed with some of the interventions outlined above.

Ultimately, travelers are more likely to choose rail over other forms of transport if:

- There is frequent service - including early mornings and late evenings - and this service is consistently reliable
- Trains offer high quality connectivity and comfort - and there is the privacy to work or relax
- There is a clear green incentive to travel by rail
- The first and last mile are easy to organize, book and pay for
- There is confidence in the reliability of trains and their ability to easily overcome incidents

Today's rail industry has a chance to make itself more appealing and grab a larger share of the market. It will do so by embracing technology and IT architecture that will allow it to deliver a connected, joined up and comfortable service.

Technology transformation

The enabling technologies for rail transformation

In the previous pieces, we discussed the digital transformation of rail, from engineering design and manufacturing, to digitizing trains and track, to optimizing maintenance and operations and creating new digital customer services.

Whilst we have looked at these from the point of view of innovation across various areas of the rail industry, these areas require overlapping technologies and IT infrastructure, and will benefit from different rail divisions working together. Sensors will help automate train schedules, but also provide valuable data to help engineers design a new generation of trains built around the reality on the track.

Designing these solutions will rely on a range of similar digital technologies and approaches, which must often be joined up and designed to talk to each other. This final article explores the enabling technologies that will deliver rail transformation, and how to approach them.

Digitize your world - Sensors

In order to digitize, trains are going to need to deploy a wide range of sensors. Imaging such as LiDAR and cameras will collect the data that allows the digitization of the train and the track. Movement sensors, like GPS and accelerometers, will provide real time information about the train and allow real time responses to emergencies and generate data from which to build AI models that optimize driving for safety and efficiency. Vibration, temperature, and door sensors will detect early signs of problems that can be flagged to predictive maintenance systems.

That is to name but a few of the myriad sensors that future digital trains will deploy.

Deploying sensors at scale will come with costs and skills implications. Rail companies need to decide on the right sensors for their fleet – which will contain trains of varying ages and uses – looking at cost/benefit before rolling out.

But they shouldn’t rush into connecting everything for the sake of it. There are workarounds if you know what you are doing. For example, data from cheap vibration sensors can be used to infer a great deal of detail about train and track conditions, without the need for pricier systems like LiDAR on every train.

Most importantly, deployment should be done with scale in mind, ensuring all sensors work to the same standards so data can be combined, and future upgrades can be added or swapped out without needing to upgrade the system.

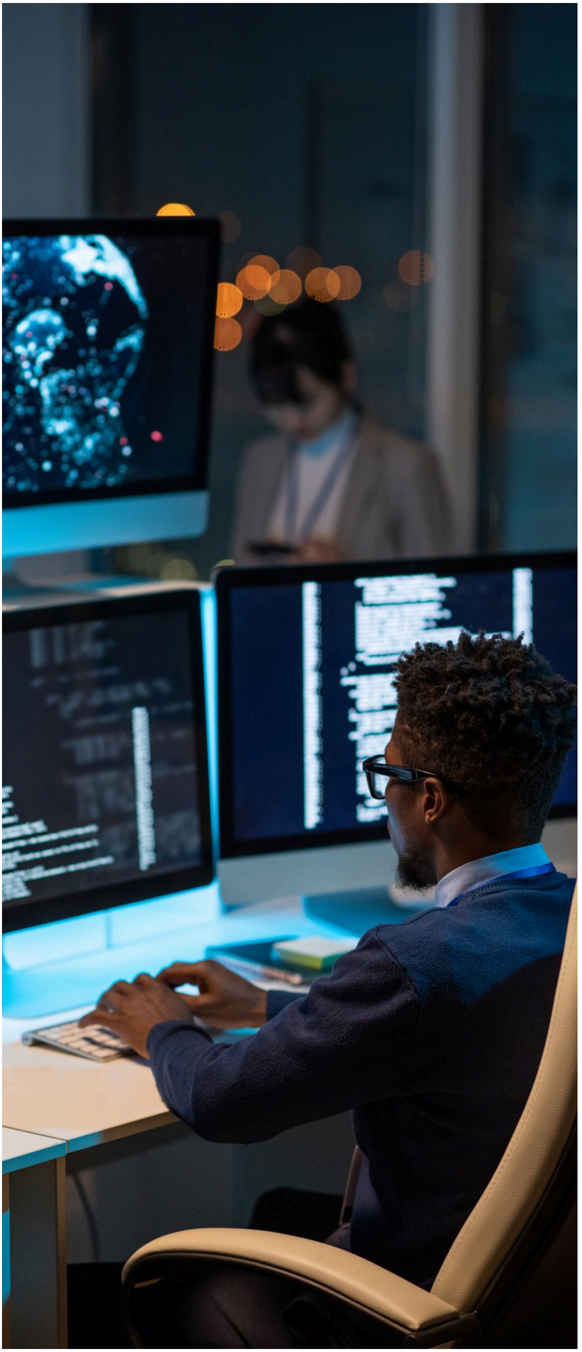
Bring everything together - Cloud storage

All of this data will need to be processed and analyzed to generate insights. Some will be fed straight into real-time systems like braking or driver assistance. Some will be directed into predictive maintenance systems back at the depot. Some will sit in databases for analysis by engineering and data teams looking for new opportunities for optimization.

This needs a place to store data, and the capabilities to process it, draw insight from it, and deliver those insights to the people and automated systems that need them. The most obvious way to do that is a hosted cloud environment, such as those offered by Tech companies – a single space where everything can be stored and managed, and where there are readily accessible analysis tools to build models. These can then be connected to onward systems – such as engineering design tools, maintenance scheduling, or enterprise resource planning software.

An alternative could be to build such an environment on your own servers, which is harder to do, but brings greater certainty over where your data is stored, which may be valuable for sensitive data.

These environments need to be carefully set up with standard approaches to data management, to ensure data can be easily found, and different data feeds can be easily combined - a 'Single Source of Truth' in IT parlance. Ultimately, as data collection and model building increases, this will become a digital twin of the train and the rail network.



Real time responses – Embedded software

Some onboard devices – such as emergency brakes - will need to react instantly. They cannot afford even the brief delay of sending data back to the cloud, or the risk of a momentary loss of connectivity. These devices will need their own onboard processor and embedded software – programs designed to take data, run it through a model, and deliver a resulting instruction on the device.

These will need to be carefully designed and tested in their own right according to the high standards of safety critical industries. But again, they should be designed with the whole ecosystem in mind, since away from emergencies, such data can be immensely valuable to other applications – from predictive maintenance to engineers designing new braking systems - and so needs to be able to easily flow between joined up systems.

Smart decisions, accurate insights: Analytics, AI and Gen AI

If you do the above right, you will find yourselves with rich repositories of data, from which you can draw insights and design intelligent software, using analytics and AI. These tools allow you to analyze vast amounts of sensor data for complex patterns, beyond human comprehension, to do things like predict maintenance needs, and optimize train schedules and routes.

Generative AI offers a whole new suite of opportunities. It can be used to absorb vast amounts of uncurated information – such as video and instruction manuals – that would not traditionally be thought of as data, and understand its context. This allows teams to develop tools that can quickly propose a set of useful answers – how to fix a machine for example – or even intuit the right answer from different pieces of information, or apply one solution to a different problem, even if the question is not specifically addressed in its training material. Of course these tools need guardrails and governance structures to ensure they are used appropriately in a context that demands precision and rigor. We recommend a Hybrid AI approach [13].

Not everything needs to be hyper intelligent, but now things can be. Doing this well is about having the right people who can choose the right (and most cost-efficient) tool for the job.

A report [8] recently produced by the International Union of Railways (UIC) in partnership with McKinsey concluded that increased AI adoption could add roughly $13 to $22 billion of value a year to the sector. That report found that about 20 AI use cases were currently being explored, and concludes that AI could present an opportunity of around €700 million a year for a €5 billion rail company.

On a related note, the European Infuture Institute, said the following in a recent article in International Railway Journal: [9] *"AI is already transforming the rail industry through the automation and optimisation of every aspect of operations, including traffic control and maintenance. It is also a great tool to enhance the efficiency and reliability of rail transport since it strongly supports the development of intelligent rail infrastructure management systems."*

Think global and local

New trains will have to better serve the global environment. But these trains, for infrastructure reasons, must also live with existing local rules and technology - even in cases where some regions (eg. the EU with its ERTMS signaling rules) are trying to standardize aspects of rail operations. In many cases, today's trains are too country specific.

Instead, these trains must be designed as a more generic, modular product that can be easily modified to meet the diverse requirements of different regions, operators and roles. As such, flexibility in the design and the ability to adapt to change is key to success.

Connecting the train – 5G

Finally, the onboard devices need to connect directly and continuously to the cloud. The onboard wifi needs to have a reliable, high bandwidth connection to enable the kind of services customers increasingly expect, such as high-definition video calls, and in future, perhaps VR.

Right now, most trains are not able to deliver such connectivity. The solution will be the Future Railway Mobile Communication System (FRMCS), the upcoming global standard designed to replace the existing 2G-based GSM-R (Global System for Mobile Communications - Railway) system. FRMCS is based on 5G technology and utilizes 5G's high data rates, low latency, and increased connection density to deliver enhanced voice and data communications on trains – for people and IoT devices – and seamless data exchange between trains and railway infrastructure. It is highly scalable, setting trains up for ever higher data demands from passengers and digital trains.

Transforming rail through technology

Technological visions are all very well. But the reality is that these are technically complicated, especially when retrofitting to a safety-critical industry, with a wide variety of moving and fixed assets, all around the country (and often crossing borders), of varying ages, most of which were not built with all this digitization in mind.

It is therefore important to tread carefully. Work with companies that have 'been there, done that' and learned the lessons along the way. Take advantage of battle-tested methodologies for rail technology selection, deployment, and systems integration. Utilize frameworks for software development to ensure both speed and consistency in the development of the myriad different software systems that will be needed, both embedded on devices and in the cloud.

In doing so, engage with all country regulatory and homologation bodies. The future of rail needs to be consistent and trans-national. When a new train rolls onto the production line, we want to know all its systems will work anywhere in the world, and any future technologies can be easily implemented into its IT architecture so that they seamlessly work with everything else on the network. That needs standardized approaches – or at least reliable ways of connecting different systems – not just across the company, but across all companies, in all countries.

All of this needs to be wrapped in excellent project management. Keep your eyes on the goal, and break down progress into incremental steps with small wins along the way. Rail is safety-critical infrastructure and rightly conservative, so we need to go slowly, and prove concepts rigorously with attention to safety. But we also need to show that – through digital technologies – there are better answers out there that make rail safer, more efficient, more sustainable and more attractive to customers.

Changing culture

Creating a culture to take rail companies into the future

To deliver the technology-led digital transformations discussed in this paper, rail companies will need a change of culture. They will need to move from companies building assets, to companies creating digital, multi-modal, mobility-as-a-service offers. They will need to move from national champions to organizations that operate – individually or collaboratively – across borders, networks, and company boundaries – to provide users with seamless journeys. To do all this, they will need to become more innovative and more collaborative.

This can be seen as somewhat akin to the mindset of innovative tech companies, which foster innovation, create spaces to experiment and fail, and take a digital-first mindset. But let's not get ahead of ourselves: Rail is not tech. It is a safety-critical industry that predates digital technology. Cultural change must work within those constraints.

Previous Capgemini research [10] found that 62% of respondents considered culture to be the number one hurdle to digital transformation - but there are proven ways to address it.

Experiment, please: encouraging innovation

At the heart of cultural transformation in the rail industry is the need to develop an innovation culture. Traditionally, rail companies have focused on reliability and safety, which are undoubtedly vital, but this focus can sometimes lead to a conservative approach that rejects or defers promising new ideas.

The challenge is to maintain these essential standards while also promoting a more dynamic approach to new ideas and technologies. Companies should encourage experimentation, allowing for a certain level of failure within safe boundaries. We can learn a lot from autonomous car testing. But we can even see successful examples in rail, such as the world's first fully autonomous freight train, which was developed in Australia, and was a bold experiment, backed by years of rigorous testing.

Creating a supportive environment where employees feel empowered to suggest new ideas is critical. This means establishing formal innovation programs and ensuring that there is space to safely develop innovative proof-of-concepts – eg. digitally, or within dedicated rail testbeds – and a path from idea generation to execution. Capgemini calls this 'applied innovation'. Leaders within rail companies must champion these efforts, providing the resources and support needed to turn creative ideas into tangible products and services.

Change your mindset: embracing 'digital-first'

As first reported in Digital Culture 2026 [11], employee experience (EX)-led transformations focus on the needs of employees. Progressive organisations adopting new technology can use opportunities to integrate the views of their people from the outset, ensuring the 'humancentricity' of the solution. This includes using personas to see how the combined impacts of many projects can be navigated. This lens informs the appropriate pace of change and enables training requirements to use micro-segmentation and multiple communications channels, enabling employees to best digest and absorb the information.

Digital technologies offer vast opportunities for the rail industry, from enhanced data analytics for predictive maintenance, to passenger apps that improve the travel experience. Embracing a digital-first mindset requires a cultural shift towards ongoing learning and adaptability. Rail companies must integrate digital skills across all levels of the organization, ensuring that employees are not only comfortable with technology - but are also proactive in leveraging digital tools to enhance their work. Digital must be considered an essential skill and function, just like HR or business development.

This shift also means updating legacy systems and processes that can hinder digital integration. It's about more than just adopting new technologies; it's about rethinking processes so that digital solutions are at the forefront of every decision and innovation, and redesigning IT systems so that digital products can be quickly built on top of them, without creating technology debt or impacting a plethora of inflexible legacy programs.

A lesson comes from a leading US innovative car manufacturer, which has singlehandedly reinvented the nature of cars and how they are made, from the ground up, by embracing a digital-first approach. By integrating advanced software and connectivity into its vehicles and production processes, and pioneering over-the-air updates, the US automotive player ensures continuous vehicle improvement post-purchase. In production, it utilizes automation technologies and extensive data analytics, optimizing manufacturing efficiency and quality. Robotic automation and AI-driven processes streamline assembly lines, reducing costs and increasing precision. This digital integration enhances user experience, vehicle performance, and production efficiency.

Transcend silos: working across teams

Innovation in rail products often requires expertise from various fields, including engineering, data science, customer service, and cybersecurity. Traditional departmental silos can limit the exchange of ideas and slow product development. Cultivating a culture that promotes collaboration across different functions is essential. This can be facilitated by creating cross-functional/interdisciplinary teams that combine expertise from very different disciplines.

These teams should operate with a high degree of autonomy and accountability, empowered by leadership but free from micromanagement. This approach not only speeds up the innovation process but also helps inculcate a sense of ownership and pride in the results.

‘Be the change’: leadership and vision

Leadership also plays a pivotal role in cultural transformation. Leaders must not only articulate a clear vision for the future of the company but also ‘walk the talk’.

This involves being visible champions of change, demonstrating a commitment to the new culture through their actions and decisions. It is also crucial for leaders to communicate effectively, ensuring that all employees understand not just the 'what' and the ‘how,' but most importantly, the 'why' behind the cultural shift. The digital transformation shouldn’t be seen as something that is being ‘done to’ staff, it should be understood as an opportunity for everyone to work better and for the company.

Leaders should also be accessible and open to feedback, creating a two-way communication channel that helps build trust and buy-in among the workforce. They need to recognize and reward contributions to innovation and digital initiatives, setting a clear precedent that these are valued activities within the organization.

Conclusion

What success looks like

The French **Light Train project** [12] is an example that combines both train and transport system innovation. Small French railway lines are experiencing renewed interest, which requires rethinking the system to make it more attractive and less expensive. The project aims reduce to operating costs by 30%, thanks to advanced technologies and a whole-systems approach, making the lines profitable again.

The project involves designing a light train built around a modular platform that can be adapted to the needs of passengers. It uses an electric motor powered by batteries and hydrogen fuel cells to reduce transport costs and limit its carbon footprint. It offers a modular interior layout in order to adapt to as many needs as possible. This new train is designed to run on the existing rail network and requires less maintenance.

As well as train design, this systemic project includes signaling, command and control systems, and infrastructure monitoring. The train uses sensors and driving aids to optimize routes, and efficient signaling, which could ultimately evolve towards autonomous driving.

To conclude

Technology evolves more quickly than in the past - some of today's trains are older than the first iPhone. New technology for trains must be flexible. Thus, building an open, adaptive, high-bandwidth environment on our trains, tracks and operations is a prerequisite to using them even more efficiently in the future.

All of this is a steep path that can be difficult to climb without the right resources, knowledge, or assets and methodologies to make the right choices. Many digitization programs (not just in rail) fail because of a lack of experience, consistent approaches, or attention to detail.

Finding the right partner for your journey is essential to your success. You should seek one with deep experience in rail digitization and other safety-critical industries. In addition, look out for those with a track record of putting skin in the game by making technology investments like AI and Gen AI to accelerate industry transformations and are prepared to bring transformative technologies to the rail sector at large, both operators and OEMs. Capgemini meets these criteria.

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References

1. Our World in Data, *"Cars, planes, trains: where do CO_2 emissions from transport come from?"* https://ourworldindata.org/co2-emissions-from-transport

2. Eurostat, *"Railway passenger transport statistics - quarterly and annual data"* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Railway_passenger_transpo_quarterly_and_annual_data

3. Capgemini Engineering, *"FUTURE RAILWAY MOBILE COMMUNICATION SYSTEMS"* https://prod.ucwe.capgemini.com/wp-content/uploads/2023/04/FRMCS_position-paper_April-23_final.pdf

4. Capgemini Research Institute, *"Turbocharging software with Gen AI"* https://www.capgemini.com/wp-content/uploads/2024/07/CRI_Turochanging-Software_Final.pdf

5. UK Department for Transport, *"Rail factsheet: 2023"* https://www.gov.uk/government/statistics/rail-factsheet-2023/rail-factsheet-2023

6. Capgemini Research Institute, *"THE PEOPLE EXPERIENCE ADVANTAGE"* https://prod.ucwe.capgemini.com/wp-content/uploads/2022/07/People-Experience-Research_Report.pdf

7. The MaaS Alliance, https://maas-alliance.eu/

8. International Union of Railways (UIC), *"The journey toward AI-enabled railway companies"* https://uic.org/com/IMG/pdf/uic_layout_web_05032024.pdf

9. International Railway Journal, *"Megatrends: what the rail sector needs to know"* https://www.railjournal.com/opinion/megatrends-what-the-rail-sector-needs-to-know/

10. Capgemini Invent, *"CULTURE FIRST!"* https://www.capgemini.com/de-de/wp-content/uploads/sites/8/2022/08/Culture-First-Capgemini-Invent_web.pdf

11. Capgemini, *"Digital Culture"* https://prod.ucwe.capgemini.com/gb-en/wp-content/uploads/sites/5/2023/08/Capgemini_A_Digital_Culture.pdf

12. Capgemini, *"TELLi, redynamiser les territoires en relevant les défis ferroviaires"* https://www.capgemini.com/fr-fr/actualites/cas-clients/train-leger-innovant/

13. Gen AI is not enough https://www.capgemini.com/solutions/elevate-gen-ai-with-augumented-engineering/

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