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Command and Control 4.0

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Control, command and signalling are at the core of railway operations – they essentially determine safety and performance of the network. With the capabilities provided by new technology in terms of computing power, sensors, networking and connectivity, new possibilities arise – more and more functionality can be moved on board trains (thus reducing fixed cost in the infrastructure), vehicle-to-vehicle communications (including to non-rail vehicles) can enable mitigation of safety risks (e.g. at level crossings), while central traffic management remains significant for network-wide optimisation.

At the same time, interoperability must be preserved (or even enhanced), while advances in artificial intelligence will make possible new forms of automation. With these developments, the silos separating transport modes should disappear and a scenario becomes likely in which all modes become part of a single shared transport system, where journeys are procured digitally using whatever combination best fits the customer's needs and preferences at the intended time of travel. In order to manage evolution towards such a scenario, a representative architecture that describes the key interfaces is necessary.

Introduction

This article is about the future.
It appears to be common knowledge that accurate prediction of the future is impossible. However the opportunities offered by technological progress, the consequences of current and foreseeable decisions, as well as the constraints and restrictions arising from applications within the framework of the shared system, can be captured, and consequential areas of attention and action can be devised. We are not entirely in the hands of developments outside our control, condemned to wait and see; to a certain extent, we can be in control of our destiny.

Despite all advances in communications technology and digital connectivity (the increasing 'virtualisation' of the world), physical transport of people and goods will remain essential. Mobility is not just movement of people and goods, it is shaping society and economy. However mobility brings with it a number of negative side effects such as pollution (including noise), congestion, and safety risks. Today, climate change remains one of the most serious challenges for humanity; transport contributes significantly to greenhouse gases and, unlike some other sectors, the emission situation with transport has not improved over the past couple of years.

Rail on the other hand is a transport mode that is energy efficient, providing high capacity at comparatively high speed, and a significant fraction of rail transport already operates with cleaner electrical energy, so a shift to rail could be an effective strategy to clean up transport [1]. Rail is also the safest mode of land transport [2].

The good environmental properties of rail stem from the low coefficient of friction at the wheel-rail interface, and the lower aerodynamic drag per passenger-kilometre and tonne-kilometre. However, the low friction and the resulting long braking distances of trains have made it necessary to introduce elaborate systems for signalling, train protection, and traffic management, in order to dispatch trains and to avoid derailment and collision hazards. These control, command and communication systems ensure the safe movement and operation of trains on the railway, and so they have a major impact on the performance of the rail system as a whole. The train separation they impose drives route capacity, and speed restrictions determine journey times.

In the 19th century, rail was a major driver of technical innovation, especially in the area of control, command and signalling. Today though, advances in technology are mainly in the fields of information, computing, and communication. Technology in these fields is progressing exponentially in accordance with "Moore's Law" [3].

Furthermore these technological advances can be combined and integrated – innovation by combination, as seen in smartphones (Figure 1). So we are currently witnessing a major transformation of the world, with potentially fatal consequences for rail [4]. In the transport sector, the automotive industry is investing enormous amounts of money in development of autonomous vehicles [5], including truck platooning [6] to improve the efficiency of road freight transport, all based on advances in broadband connectivity, computing power, and artificial intelligence.

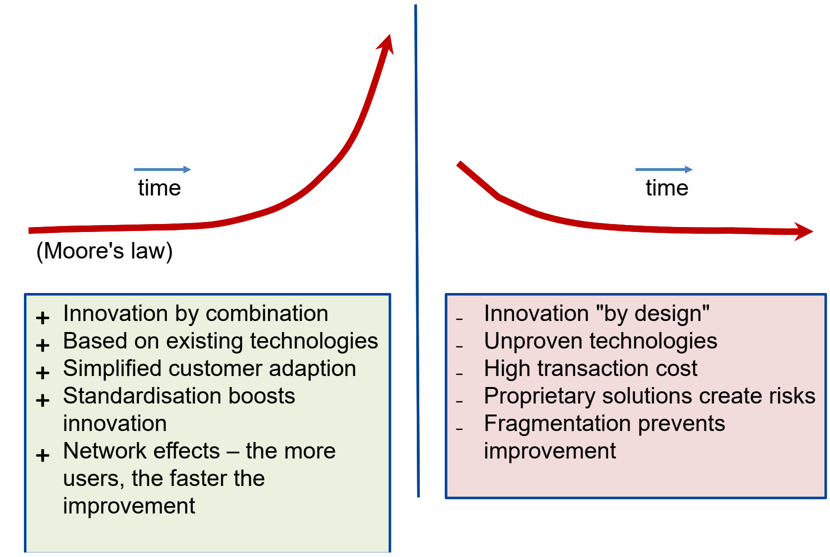


Figure 1 – Combinatorial innovation (left) leading to improvements on an exponential scale, in comparison with the approach often followed in rail (right). Innovation "by design" also means that use of the so-called Vee Model, often called for in safety assessments (as for example in CENELEC EN 50128), is required.

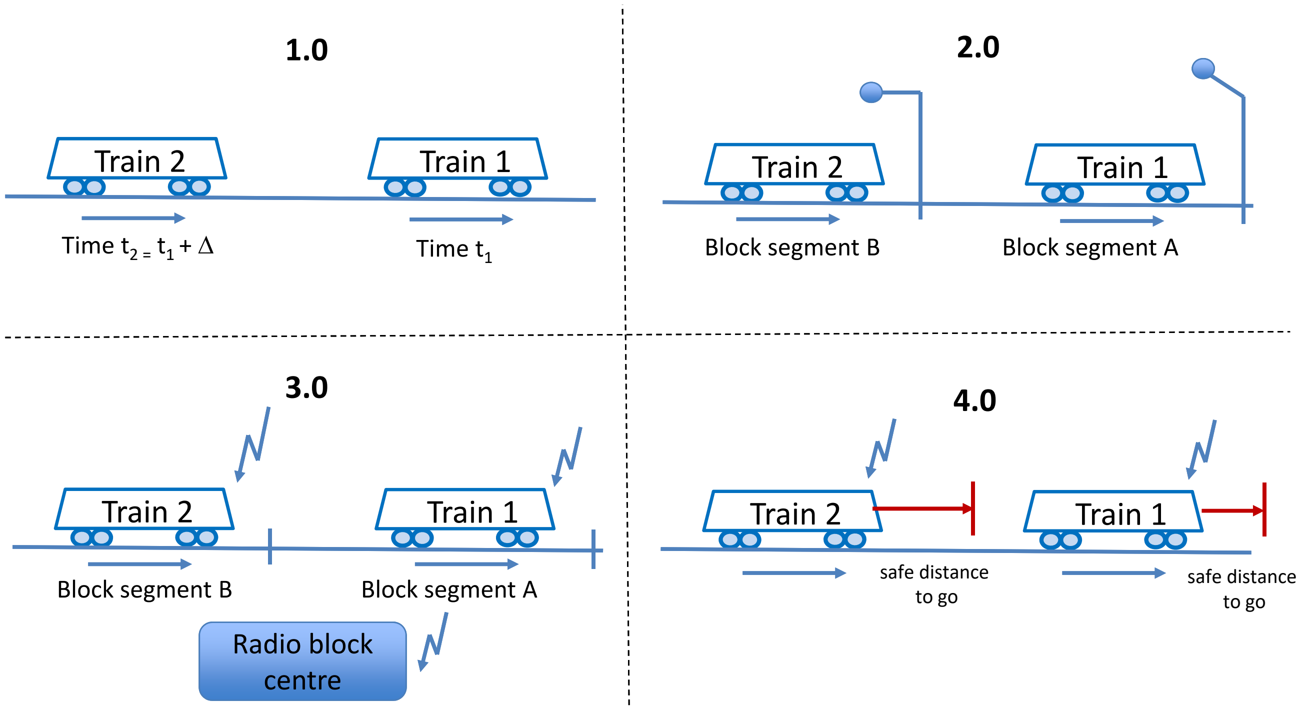


Figure 2 – Four generations of control, command and signalling and their basic principles. The first generation ("1.0", upper left) is based on separation of trains in time. The second ("2.0", upper right) is based on separation in space, by (electro-)mechanical signals. The third ("3.0", lower left), is communication-based signalling, still based on block sections. Finally the fourth generation ("4.0", lower right), has universal geographic safety logic enabled by vehicle-to-vehicle communication.

These new technological capabilities are a threat to rail in its classical form, because they help create cheaper and more convenient alternatives, but they can also be a massive opportunity for rail to become more cost effective and more attractive for users. In the area of control, command and signalling specifically, we have seen time separation; then space separation (the absolute block principle); and finally track to train communication, as in ERTMS. With the new technological capabilities, a fourth generation of railway traffic management system ('Command and Control 4.0') will become possible (Figure 2). In this article, some of the conceptual possibilities, their necessary consequences, and potential issues will be discussed.

From a user's perspective, for both mobility and logistics services, instant updates available for example via smartphones make it possible for the user to be advised of options in real time and to decide on the spot the most suitable way to travel from A to B, taking into account attractiveness and flexibility, and highlighting quality, hassle-free, reliable and safe travel. In freight, intermodality will play a key role in decarbonising transport, drastically reducing the pollution and congestion caused by long-distance road transport. One of the critical questions for rail will be whether it will ultimately be at the core of the multimodal transport chain (the 'backbone'), for integration between the various modes of transport will be critical. In other words, we are confronted with a need to transform the rail industry; just making the current status quo better will not be sufficient.

The interoperability vision

Before we come back to the impact of technology evolution, I would like to briefly discuss some structural issues with rail. Almost all transportation systems

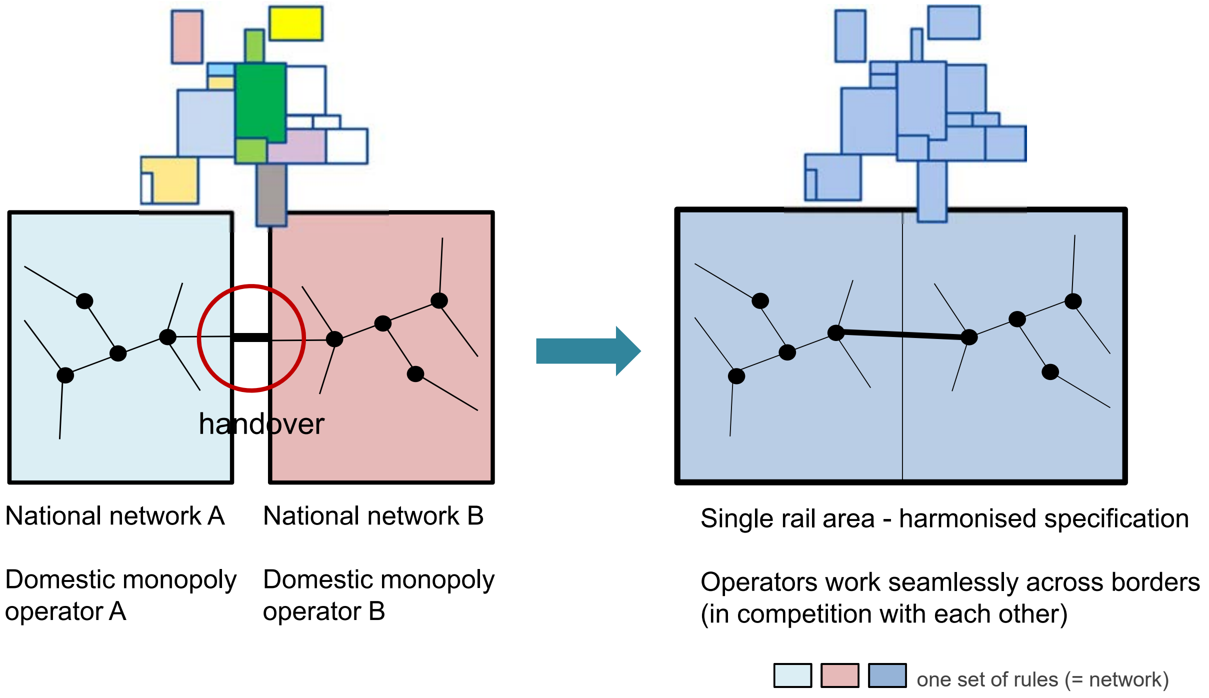


Figure 3 – The interoperability vision for rail: fragmented national systems (left) versus single rail area (right).

have rules which are globally valid: roads (apart from the issue of driving on the right or the left); aviation; and maritime. Rail is the exception. Historically, technical and regulatory requirements and operational rules on the railway have been fragmented, mostly along national borders (see Figure 3). Control, command and signalling is one of the areas where there is the greatest diversity; although all signalling systems are based on the same block principle, every infrastructure manager adapts this principle to its own operations concept, resulting in different technical specifications for both mobile and fixed equipment. As a result, even with the introduction of the European Rail Traffic Management System ERTMS [7] full interoperability across national borders has yet to be achieved.

The consequences of this diversity are high costs for operations, maintenance, and investment, lack of opportunity for economies of scale, and being locked into a thirty to fifty year cycle of obsolescence. This fragmentation is a major competitive disadvantage for rail against other transport modes; it needs to be rectified if rail is to play the role of the backbone of the future multimodal transport chain, both in order to remove barriers for seamless transport across borders and to improve return on investment for innovation. Creating a Single European Rail Area has therefore been one of the policy objectives of the European Union.

Within such a legal framework, it is important to apply principles that are well established in other transport modes, such as 'user first'. This means that it should not be for the infrastructure manager to define restrictions on rolling stock that it allows on its network, but for the railway undertaking (as the user) to demand capabilities from the network that it needs in order to fulfil its core purpose of supporting optimum operation of trains. (Ultimately, this principle should lead to the definition of categories of trains, to be matched with categories of infrastructure capabilities, with appropriate system version management linking them). The new legal framework of the Fourth Railway Package in Article 23 of the Interoperability Directive [8] reflects this principle.

In order to make railway operation more economic, the infrastructure needs to be made cheaper and more efficient. To optimise the financial viability of the assets used generally, there should be a shift from fixed cost (in the infrastructure) to variable cost, with most of the intelligence moved on to the train. This reduction of fixed cost is obviously more important on routes having less dense traffic, as in rural areas. The mobile assets should then be able to roam freely in an integrated rail area. Needless to say, in such a single, global railway area operating rules should also be global.

Operational procedures are based on the need for efficiency but, more importantly, on the necessity for safe operation. This constitutes another structural problem for rail, with severe consequences for the cost and complexity of introducing new technologies. Railway safety results from the combination of functional and technical safety of assets, control of route-train compatibility, and operational rules. Any change in one of these will have an impact on the other two which must be considered in the authorisation procedure, making this repetitive procedure complex, time consuming, and expensive. In line with the interoperability vision and the 'user first' principle, technical and functional safety needs to be encapsulated and follow a universal design logic [9], whereas operational procedures should mostly be covered by the railway undertaking's safety management system in order to ensure conformity with the system's operational rules [10]. This aspect is crucial; if this deadlock situation is not resolved, rail will essentially become decoupled from the mainstream of technology.

The railway system of the future and how it will be operated

The exponential development of technology mentioned above means that, within a couple of years, computing power will continue to drastically increase, digital storage will be practically unlimited, broadband connectivity will be available at unrestricted bandwidth, a variety of sensors will collect information on virtually every aspect, big data-based algorithms will enable the effective processing of enormous amounts of data, and artificial intelligence will compete with human brains on decision making. It is unlikely that railways will survive if they remain in a closed corner, using expensive niche technology, decoupled from and outpaced by the tide of mainstream development.

Even though this article is mainly about control, command and signalling, to assess the impact of new technology we need to consider the entire rail system and its integration with the overall transport system. Starting from basics, localisation (that is, determining the positions of trains) is a key factor in rail operation.

Currently rail-specific coordinate systems are used; for example, ETCS uses balise-based coordinates.

In the future, rail should rely on a coordinate system that is used by the rest of the world too. All data should be expressed in these coordinates. (These data could then be used by third parties, such as shippers, to trace a train via Internet maps). As will be discussed below, geographic localisation will also become the basis for the new universal safety logic.

The obvious source of localisation information is satellite positioning, complemented by other means such as balises and tags in places where satellite positioning does not work such as tunnels. Complementary to localisation, information on train integrity (completeness) can be provided by position sensors plus appropriate connectivity.

By definition, railways remain constrained by tracks, meaning that tracks remain the essential element of a railway system. Even on the well proven rail/wheel interface, technology could bring about a change. Mechatronically controlled wheels could provide an alternative to the constraints of conicity.

As for problems with the track itself: inspection of the track for damage and defects can impact availability. Sensors on railway vehicles could turn every vehicle into an inspection vehicle. With big data algorithms operating on location-correlated datasets, deteriorating infrastructure can be detected and maintained appropriately.

Track switches and crossings will remain essential elements of the future railway system; changing direction, splitting and merging of routes will always be required for rail operation. The reliability of switches will therefore continue to determine the performance of the rail network. However sensor technology and wireless connectivity will increasingly facilitate continuous monitoring of switches, including weather conditions, and condition-driven maintenance.

From a safety perspective, switches must not move under a running train, and switch locking must therefore be provided. Whether switches will best be centrally controlled from an interlocking or train controlled (route protection versus train protection) will most probably evolve over time. In any case, with precisely known train location and train speed the efficiency of releasing switches can be maximised.

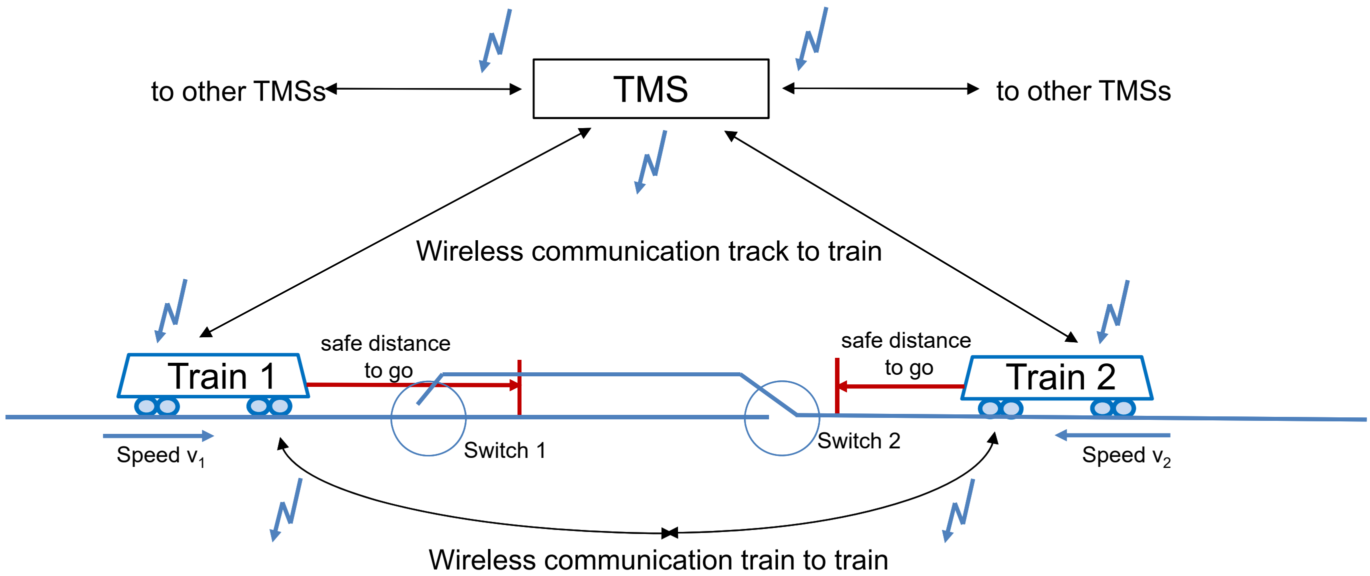
I fear that road level crossings will also remain, at least on secondary lines; however, control of these devices will shift more to the vehicles. Vehicle-to-vehicle communication (including rail to road) and integrated traffic management between road and rail will offer additional mitigation for safety hazards at level crossings.

From a control and command perspective, the future railway system will look as shown schematically in Figure 4. Immersed in a wireless communication network, each train will calculate its safe distance to go continuously and adjust its speed accordingly, on the basis of its physical location (as expressed in geographical coordinates), and of information derived from various sensors (such as speed and health check), communicated from track to train from the traffic management system (TMS), or communicated from train to train. This will be the new universal, dynamic and geometric safety logic of 'Command and Control 4.0'.

In other words, in Command and Control 4.0 we will see a risk-based approach to controlling train movement. Each train's speed envelope is to be calculated based on knowledge of location, track topography and switch positions, traffic ahead (known through wireless communication), and other relevant information (such as wind, rail adhesion or snow) and additional factors that might inhibit safe speed.

'Safe software', meaning software that conforms with Safety Integrity Level SIL 4 according to CENELEC EN 50128, should be used only where justified by the need to maintain proportionality of cost and risk in comparison with all the other elements of the system that ensure safety. Other functions can be provided

Figure 4 – Schematic representation of trains operated under Command and Control 4.0. TMS is traffic management system. Each train calculates its own 'safe distance to go' (shown in red).



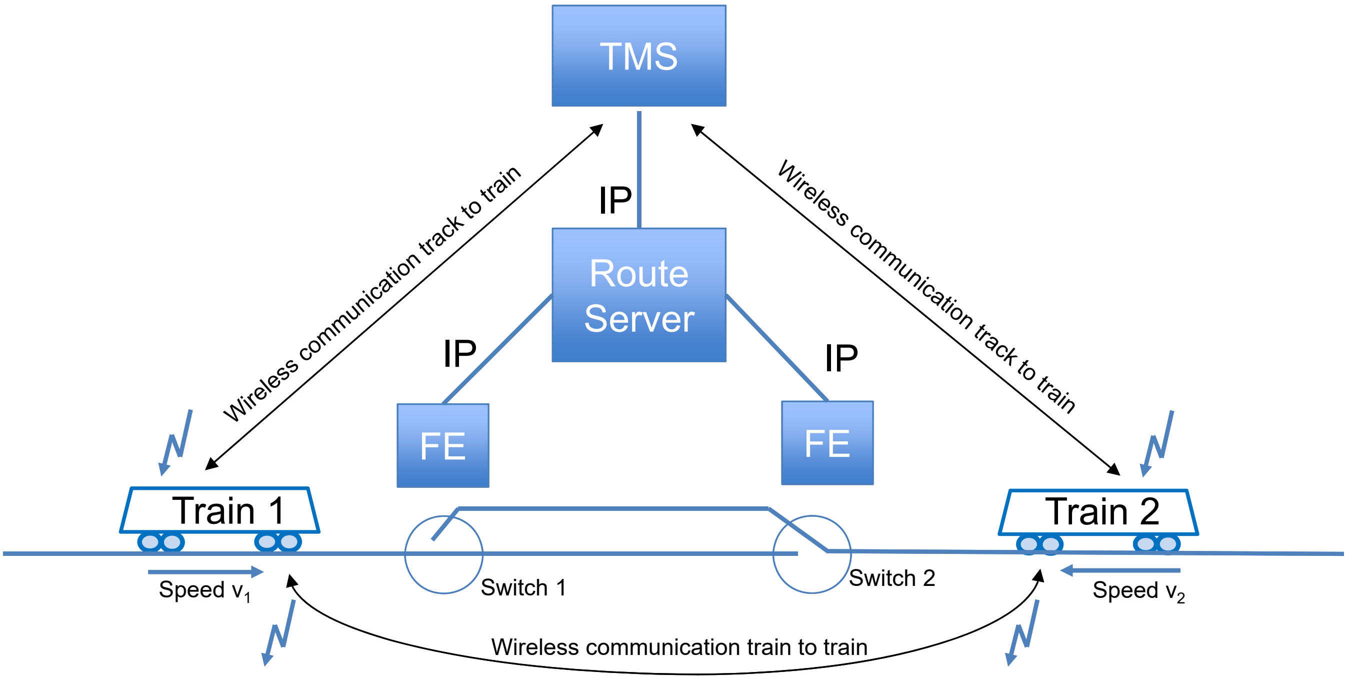


Figure 5 – Architecture of a future Command and Control 4.0 system. Smart wayside objects (field elements, FE) have open interfaces and powerful degraded modes. On the train, clearly only one interface is necessary, the communication interface between the rail vehicle and the external world.

in the form of applications that are 'safe enough' without achieving SIL 4. In all cases, the tolerable safety levels must be balanced between the elements of the rail system, and consistent with other modes of transport. In addition, technology might further be used for risk reduction by taking into account information for example about evolving degradation of equipment.

One of the key questions to be resolved remains the optimum distribution of functionality. On the basis of intelligence on each train and on bidirectional communication, both TMS-to-train and train-to-train (see Figure 5), there are several possible control loops. The innermost of these loops can be considered to be individual train protection (for example against collisions and derailment, but possibly also against obstacles), based on sensor fusion and the known weight, length, speed, and position of the train.

The next level can be collective action by a number of trains in close vicinity, the highest level in turn being centralised traffic management. More complex track layouts, as in larger stations, may possibly require station-wide control – the function currently performed by signal boxes or interlockings could be taken over by a 'route server', a function that does not necessarily have to be local to the station, but could equally be an 'interlocking in the Cloud'. The expected increase in computing power will permit calculations to be done on line that today have to be done off line because of long response time. In any case, there must be quick reaction to external events at local level, while retaining responsiveness to emergency commands from the centre. (Please note the similarity of this architecture to the way in which vertebrate animals – including humans – control their movements: local sensors and reflexes in the limbs, coordination by the spinal cord, and finally high-level management by the brain).

In this future configuration there is no need to keep the distinction between routes (in stations) and blocks (between stations). The route server will obviously combine the functions of the current interlocking and the radio block centre (RBC).

The only essential field elements in the track that will remain will be switch controllers and level crossing controllers. The controllers for these devices will have to be connected via an Internet based interface (that can ultimately be wireless) to the route server and the rest of the world (see Figure 5). Signals and track circuits or axle counters will no longer be needed, except in the transition period or as fall-back in degraded situations.

A number of sensors of various kinds will complement the basic system, each sensor being connected to the Internet (thus becoming an application of the 'Internet of Things'). In such an arrangement, with the ability to handle large amounts of data efficiently, additional asset management functions such as predictive maintenance can be integrated. Used intelligently, by this means system reaction can collectively be anticipated, and reliability and punctuality of the service improved. In an extreme case such sensors might include, as in a recent proposal from China, devices for supervising the brain activity of the driver, able for example to detect fatigue.

Naturally, with an architecture as shown in Figure 5, gradually more and more tasks can be automated – avoiding human factors, including language. Automation has a long history in rail so generally speaking, further automation should be achieved more easily on the railway than the roads, as fewer variables need to be controlled than for autonomous cars in cities for example. Automation will again contribute to better reliability, because driver behaviour is stochastic; with automated train

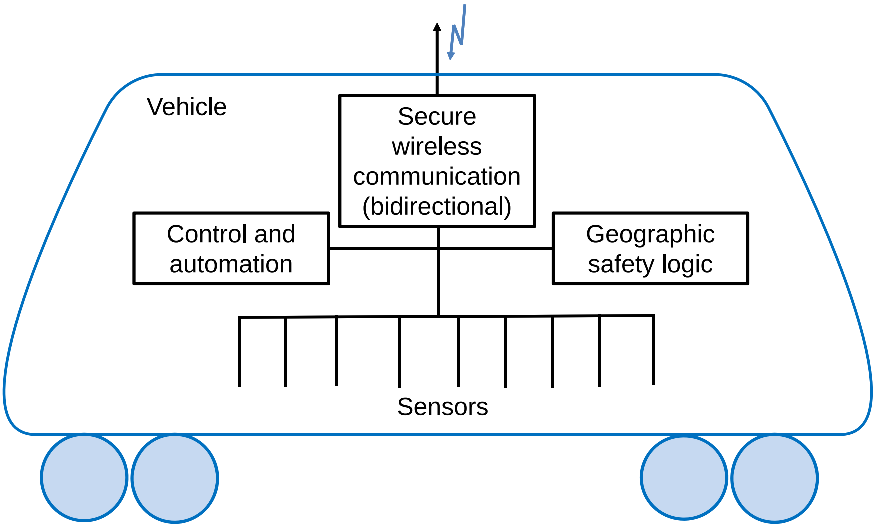


Figure 6 –Representative architecture of the on-board system with Command and Control 4.0.

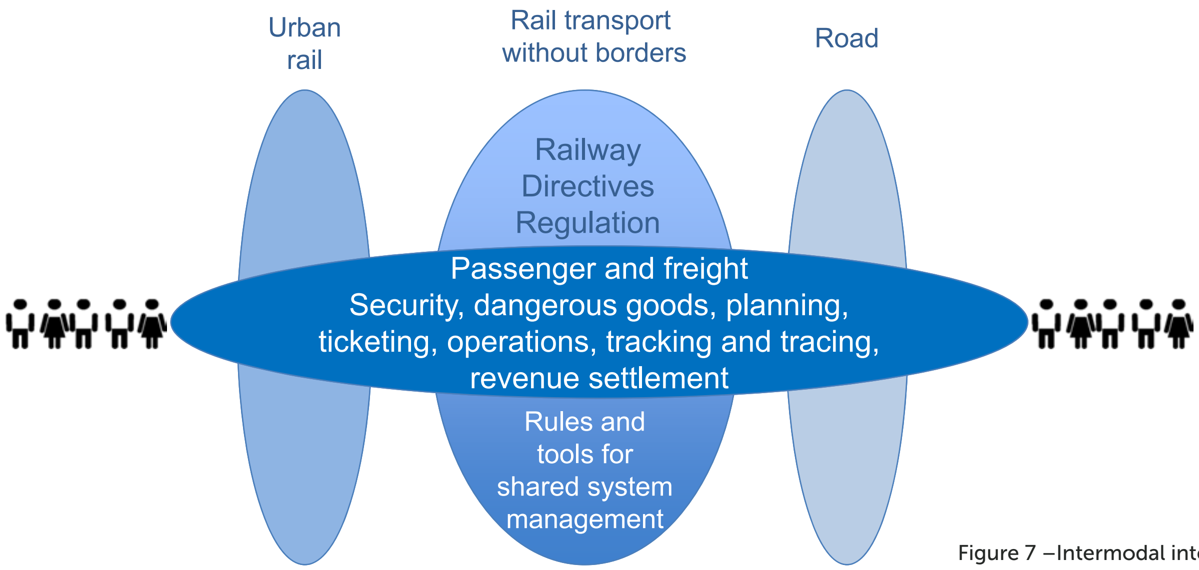


Figure 7 –Intermodal integration between main-line rail, urban rail and road.

operation (ATO) no big variations are to be expected (and in addition, the working environment will be healthier and safer). With advances of artificial intelligence (AI) an unprecedented variety of opportunities might open up here. Autonomous systems will evolve from recipients of a 'movement authority' to vehicles able to calculate their own safety envelope (risk based). A more detailed representation of the system on board is shown in Figure 6.

Command and Control 4.0 will allow for highly automated (re-)scheduling and precise real-time control, enabling real-time traffic management. Interruptions and disturbances (such as door closing problems) can be taken into account, and cascading of interruptions can be avoided. In turn, this will enable the reduction of buffers in the timetable; the more accurately the position of a train is known, the less buffer is needed, leading to an improvement of line capacity. It will no longer be necessary to resort to the worst case assumption, unless accurate information is lacking.

Collective action after first solving problems locally will help increase the efficiency of the rail system. For road, such systems already exist (an example being Waze [11], the world's largest community based traffic and navigation app, with which drivers of vehicles share real-time traffic and road information in order to find the best route for each), and integration across modes could be an interesting option. (Note that such intermodal integration will rule out having a specific, dedicated wireless network for rail). With the architectural possibilities of the new command and control architecture, level crossing closures could be factored into the calculation of car journey times, possibly preventing risk-taking on the part of car drivers.

New arrangements may arise, in turn, for the relationship of infrastructure managers, train operators (railway undertakings), and traffic management, ultimately with a central, European instance in charge of overall optimisation ('Eurocontrol for rail').

Digitalisation will promote multimodality and integration between industrial sectors. With vehicle to vehicle communication, a vehicle-centred approach to safety, and the need for rail to become the backbone of the multimodal transport chain, intermodal integration in the transport ecosystem and in the area of traffic management will become relevant (Figure 7). Interoperability across all sectors is also desirable in order to make possible sharing of components and functions (sensors, network interfaces); this should be particularly attractive for the rail sector, as it could profit from the higher volumes in for example the automotive

Innovation	Locality	Soft/hard	Comment
From **steam** traction to **diesel** traction	largely local	soft	Provided sufficient fuel is available, both steam and diesel locomotives can run anywhere on the network.
Electric traction	network	semi-soft	Diesel and steam can continue to run under catenary. Unless trains have batteries ('fuel on board'), electric traction depends on the provision of an adequate energy supply infrastructure
Air conditioning in passenger coaches	local (to coach)	soft	Practically no impact on the network, apart from weight and electromagnetic compatibility.
New materials for car bodies	local	soft	Passive safety? Fire safety?
Self-steering trains – no moving parts in switches in the infrastructure	local + network	very hard	Saves maintenance cost for switches in infrastructure massively. BUT ALL trains need to be converted – a 'normal' train can no longer run once the first switch is converted
Automated train operation (ATO)	largely local	semi-soft	ATO has existed for quite some time in closed (urban) rail networks
Universal geographic safety logic	local + network	semi-soft	Migration necessary, including regulatory framework

Table 1 – Some examples of innovations in rail, categorised by their location and impact ('soft' or 'hard' – this concept relates to the time delay for an innovation to take hold). Note that moving most of the functionality on board the train will help in making innovations local.

sector. Shared technology could, in turn, lead to shared regulation between modes and sectors.

Migration

The cost of the railway system needs to be systematically reduced by eliminating costs caused by existing diversity, and the performance of the rail system needs to be improved by introducing new capabilities, that is by innovation. In order to achieve this goal it is necessary to define a consistent vision of the future target railway system, and the evolution to it.

In the European Union, the joint undertaking Shift2Rail fosters research and innovation in the railway sector [12]. Its innovation programme IP 2 should support rapid and broad deployment of advanced traffic management and control systems, by offering improved functionalities and standard interfaces, based on common operational concepts, without impacting the ERTMS core.

In a shared network such as rail, for every innovation it is necessary to consider whether the change can be kept local to one element or whether the entire network needs to be changed. Likewise, the consequences of introducing a new capability can either be 'soft' or 'hard'; some examples are shown in Table 1.

The railway system has to remain in service, it cannot be stopped for the duration of a system upgrade. Also, the connected nature of rail infrastructure only allows compatible evolution; the cost of either building a new system in parallel, or of taking out of service the existing system, are prohibitive. On the other hand, a migration that involves the coexistence of old and new will have an impact on the safety concept.

A fourth-generation control and command system architecture as described above, specified in a modular way with common interface specifications, must deliver 'migrateability' followed by continuous upgradeability. As the railway system will remain a system shared between many actors, migration needs to include technical, operational, and regulatory aspects. Naturally, the evolution toward the new generation should be based on ERTMS. The 2016 Memorandum of Understanding on ERTMS in particular contains the compatibility definition that will be essential: "A compatible onboard can safely operate on any compatible section of infrastructure, with acceptable performance." [13].

On the hardware side, the following scenario leading towards Command and Control 4.0 seams feasible: the existing lineside and on-board equipment can be migrated from control by existing interlockings to control by new control mechanisms by changing the path of control from the current system to the new one. Object controllers for trackside equipment and virtual on-board balises are examples of tools that allow this migration to happen. The system needs to allow mixed traffic of both fitted and unfitted trains.

The importance of software will be predominant in the future, as the amount of software will grow exponentially. Migration of the software side is more difficult: it firstly requires modularity and concentration and, if it cannot be avoided, isolation of SIL 4 functionality, strictly limiting what has to be SIL 4 to the smallest possible amount; and secondly an evolution of the mechanism for authorisation, from certification of the product to certification of the design organisation. Functionality and safety levels must be flexible enough to be appropriate for the risk and the economic burden associated with each type of service. In the future, testing of new solutions should be possible in 'light tower implementations', for example in closed systems (metros) or on secondary lines. Thereby, a staged authorisation system could be introduced, as is known from sectors such as pharmaceuticals.

Definition of manageable software modules with precise interfaces will be paramount not only for SIL4. A train operating system with clear application programming interfaces (APIs) will be necessary, either defined by industry, or imposed by standards and regulation. Such an API will enable an ecosystem of developers to provide added-value functions that are not necessarily developed for the railway market by the historical rail suppliers, such as mobility services, real time information, and multimodality.

Conformity with standards (drafted by industry actors) confers a presumption of conformity with the essential requirements. Where deemed by the regulation to be in the public interest, third-party verification of conformity with the essential requirements is required.

Open interfaces will also make it possible to avoid supplier lock-in.

Challenges

The most important challenge for rail is obviously its low speed of innovation, leading to a dramatic disadvantage in the competition with other modes of transport. The new concepts presented here can be seen as a positive response to the innovation challenge, but there are also some intrinsic issues that need to be resolved.

Apart from the need to carefully manage migration in a shared system, with a new safety logic based on geography, independent of track layout and operational rules, there is the fundamental need to know securely where the trains are. Secure and precise localisation and secure communication therefore are the critical conditions for Command and Control 4.0 to work. Cybersecurity will be a design requirement of the system, with a modular design allowing for easy upgrades. As there are cybersecurity threats related to 'GPS spoofing', it might be necessary to build an additional cellular network for secure localisation in parallel with GPS. In other words, even if functions can be moved into the Cloud, safe operation has to remain solidly rooted in physical reality.

Another challenge is related to the capabilities of artificial intelligence: to what extent should we permit programmes to reprogramme or upgrade themselves?

Summary and conclusion

Exponential progress in technology (computing, communication, localisation, sensors, big data, artificial intelligence and so on) will allow optimisation of command and control for railway operation. Shifting functionality to the vehicle will allow a reduction of fixed cost by reducing the number of physical assets on the track. Interoperability considerations demand standardisation of vehicle-to-ground and vehicle-to-vehicle communication interfaces, supporting the 'user first' principle whereby this standardisation should not stop at the boundaries of rail since interaction across modes will become more and more relevant.

A new safety logic based on geography, independent of track layout and operational processes, will be necessary in order to provide 'migrateability' (and the ease of upgradeability required for cybersecurity). This new logic will, at the same time, provide an opportunity to leave behind the legacy of national rules for signalling.

Confining the 'safe' SIL 4 part of the software and introducing a staged approach will make authorisation more efficient. With these measures, innovation in rail might receive a significant push.

There is however the need to break with some traditions in rail. In the spirit of "building windmills on top of the walls" [4], state-of-the-art technology and components should be imported from other sectors into rail, instead of re-inventing the wheel. 'Mainstreaming' rail on the technology side could make the sector more attractive for suppliers outside the circle of classical incumbents. In addition, opening up markets and mobility of assets could enable increased levels of private financing for rolling stock; as the number of vehicles of a certain type will increase as compared to today, suppliers will rely less on customisation. Globalisation of rail technology, regulation, and standardisation can lead to huge efficiencies (and to a level playing field in competition with other modes of transport): the technology challenge to rail can equally turn into an opportunity.

I also draw an important conclusion for today's existing '2.0-world', on its way to ERTMS through legacy system replacement ('ERTMS Deployment') programmes. The exponential progress of technology could not be anticipated at the time when ERTMS with its different levels was conceived 25 years ago. However the ERTMS deployment philosophy must be reviewed, in order to take the evolving technology opportunities best into account. In particular the vision of reducing the number of physical assets in the track significantly requires a rethink of the acceleration towards Level 3 from the current ERTMS Level 2 planning. In view of the long duration foreseen for the deployment of ERTMS in Europe it could be a very interesting economic option to upgrade and redefine ERTMS Level 3 to a '4.0 Level'. Railways could then – as far as is feasible – migrate directly to a system in the described way without producing sunk costs for technology investments now which would need to be migrated (and paid for) again to a 4.0-system in the future. Some railways are already thinking in this direction [9]; the European Union Agency for Railways will continue to monitor and carefully steer this development.

Acknowledgements

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What do you think?

Do you agree with the view of the future that Josef has described in his article? Do you think that something else will happen, or that we are already heading down a different route? Do you think that we need to exploit technology to do things differently in the future, or is our current approach good enough? Perhaps you think that disruptive technology we can't currently imagine is just around the corner. We'd love to hear from you, email us at irsenews@irse.org.