Digital Modelling in the Railways

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Abstract. The railways have a quite long modelling history, covering many technical aspects from infrastructure to rolling stock, train movement, maintenance, etc. These models are mostly separate and operated independently by various stakeholders and with diverse objectives. This article presents some of the various digital modelling activities, including formal ones, that are undertaken by the railway industry, for design, development, validation, qualification, and exploitation. It also introduces trends toward regrouping models to obtain more significant results together with a larger scope, prefiguring digital twins.

Keywords: railways, digital modelling, formal methods

1 Introduction

Modelling activities are central to the railways, mainly in the form of separate models of diverse natures. Very early in a development, train manufacturers and operators need to assess and verify that a metro line or a main line will fulfil expectations in term of performance, number of passengers transported, operation costs, power consumed, etc. Most of these models (data and related tooling) are often developed to cover one verification activity, for historical reasons, for regulation reasons (qualification model should be independent from design model), for organisational/political reasons (different services of a same company prefer to develop their own solution), or for technical reasons (models reconciliation/connection requires excessive investment). Initiating a new product line is a good occasion to initiate a new model, distinct from the existing ones, and to contribute to increase their population. Of course, the situation depends on the company developing / operating trains but it is common trend observed during the last decades. However, with the increasing complexity of the systems developed and the competition on the railway market, modelling is going global, including more aspects to obtain more effective results.

Based on a non-exhaustive picture of the use of models for the trains/metros manufacture and operation, this article tentatively outlines what could be the integration of the digital twin concept in the railways. It presents some of the current digital modelling activities, including formal ones, that are undertaken by the railway industry, for design, development, validation, qualification, and exploitation. It also introduces trends toward regrouping models to obtain more significant results together with a larger scope, prefiguring digital twins.

This paper is structured in 6 parts. Section 2 introduces the terminology. Section 3 presents how the infrastructure is modelled. Modelling safety is exposed in Section 4. Section 5 presents some new modelling directions in relation with emerging paradigms. Section 6 sketches some pros and cons arguments concerning the adoption of the digital twin concept in the railways before concluding in section 7.

2 Terminology

This section contains specific definitions, concepts, and abbreviations used throughout this paper.

Formal methods refers to mathematically rigorous techniques for the specification, development and verification of software and hardware systems. [9] identifies a collection of formal methods and tools to be applied in railways.

PLC put for programmable logic controller[21], is an industrial digital computer which has been ruggedized and adapted for the control of any activity that requires high reliability control and ease of programming and process fault diagnosis.

Safety refers to the control of recognised hazards in order to achieve an acceptable level of risk.

Reliability is the ability of a system to perform its required functions under stated conditions for a specified time.

3 Modelling Infrastructure

This section introduces some important notions about the railway elements subject to modelling.

3.1 Categories

Railways are divided into two main areas: metro lines and main lines. Below is a summary of the main differences between the two kinds:

- **metro lines**: installed in and around cities, the lines are tens of kilometres long. Except if the line is circular, trains are operated on a carousel: when they reach the end of a line (forward movement), they fallback using another set of rails associated to the back movement. Metro stations are usually close to the next one (around 500m in Paris): the train spends the same time in station and travelling between stations. The interval between trains is a key performance factor: at rush hour, when a train leaves a platform, another one is going to enter. Only trains from a line are operated on this line, even if the number of trains is likely to vary to match passengers flow. One signalling system is installed on board and on the tracks. The train order is fixed as all trains stop to all successive stations.

– **main lines**: they cover large areas, possibly several countries. Lines are up to thousands of kilometres long. Trains move from point A to point B, with zero / some stops / all stops. Trains may gain / lose cars in station. Additional trains may be injected in the flow, coming from other countries / operated by different companies. Signalling systems change when crossing national borders.

3.2 Rails

Rails are common equipment among metros and main lines. As such they are first class citizens: they are the first elements modelled in a project. The network is called scheme plan or track plan (Fig. 1). These plans contain mainly:

– rails or tracks, made of connected circuits,
– switches, to guide the train from one track to another,
– optical signals, that display instruction or warning to the driver,
– balises/beacons: signals could be duplicated / replaced by electronic equipment in case of (partial) automation.
– axle counters, track circuits to detect the presence of a train,
– interlocking,
– rail crossings.

Modelling items have attributes like position, length, gradient (slope), maximum speed.

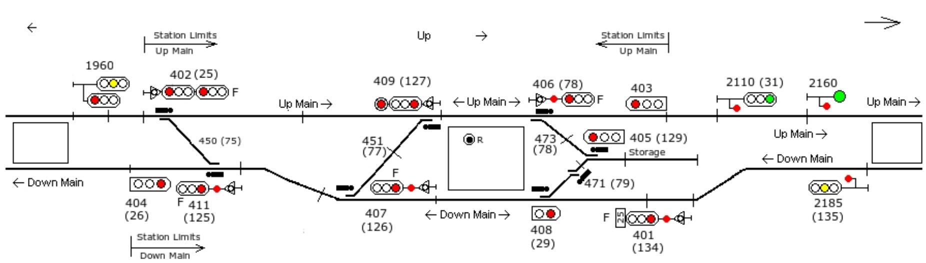


Fig. 1: Scheme plan of the Taita metro station, New Zealand.

Many track plan editor tools are available. Some examples are given below. They are either developed by:

– train manufacturers (SIGART by Alstom, TMDS by Wabtec),
– software/services companies (ERSA traffic simulator, iFrank by iRFP, Ferrovia by CGS Labs, Anylogic, Track Editor Tool by SA Transurb, OpenRail by Bentley, OpenTrack),
– or universities (SafeCap by University of Newcastle).

These tools have specific GUIs with different graphical representations. For data persistence/exchange, they rely on either:

– RailML[5]: based on XML to describe tracks and signalling equipment, timetables, vehicles (rolling stock) and signalling routes (interlocking),
– RailTopoModel[13]: promoted by the International Union of Railways, is a systemic, general, standard model for describing the topology-based railway infrastructure, able to take into account many non-standard descriptions needed for addressing specific needs.

Other proprietary formats (mostly closed specification) are also available like Siemens Infrastructure Format, Infraspeed Infrastructure Format, Bentley Rail Track, or OpenTrack.

The modelling of the tracks and related equipment is central as it provides a basis for forthcoming engineering activities. An overall system deployment is in five steps:

– capture of the railway environment and infrastructure,
– develop railway infrastructure data and generate track plan,
– prepare and compile data necessary for configuration of equipment (beacons, telecommunication, PLCs, interlocking, etc.),
– validation of data by check or automatic methods (Section 4.3),
– validation by simulation including train environment.

The drawing of the track and the positioning of the equipment have to comply with rules (issued from the train manufacturer, from the train operator, and from regulations). Engineering also includes the design of the technical rooms (where equipment is installed), the cable layout and its estimated length.

3.3 Dynamics

Modelling the rails and related equipment provides a static view of the network. The dynamic view is obtained with:

– **a model of the driver**. The driver is able to accelerate, decelerate, and brake (as well as open and close doors). The driving behaviour has to be somehow optimal by complying with several, sometimes antagonist, requirements:
  - the time to travel from one station to another has to be minimal,
  - the train speed has to be lower than speed limits,
  - the train speed has to be lower than its braking curve, taking into account the minimum train braking capability,
  - train acceleration/deceleration has to be kept within bounds, ensuring a comfortable travel to passengers.

  Such an acceleration profile is given in Fig. 2.

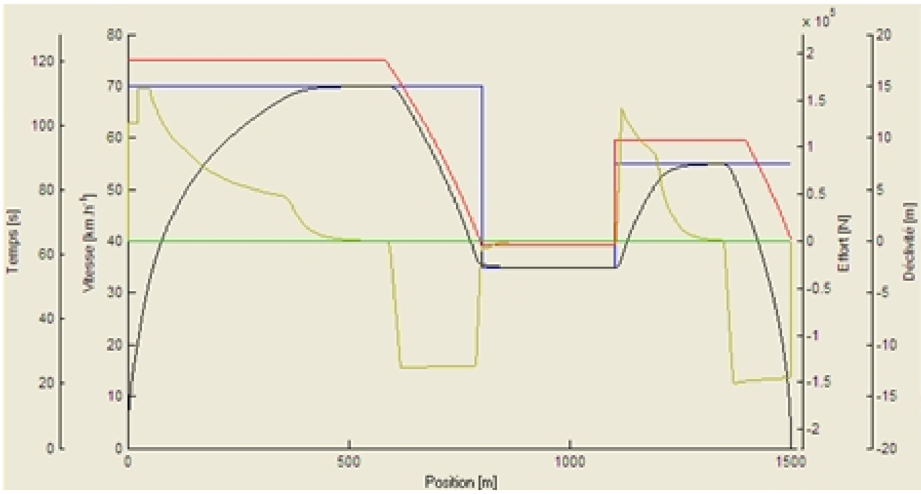


Fig. 2: An example of speed profile. X axis represents the train position, red curve is breaking curve, blue curve is speed limit, black curve is train speed, beige curve is train acceleration.

– **a model of the train**. Reacting to the acceleration/braking of the driver, this model includes technical characteristics like tractive effort/speed diagrams, load, length, adhesion factor, and power systems. It also takes into account track gradients (Fig. 3) that make the computation of the train dynamics more complicated [2]:
  - positive gradient slows down the train and reduces travel performances,
  - negative gradient has to be taken into account for the safety braking curves in relation with the minimal braking capabilities,
  - bathtub curve gradient combines both effects. In case of a train at standstill in such a place, an oscillation movement could be observed.

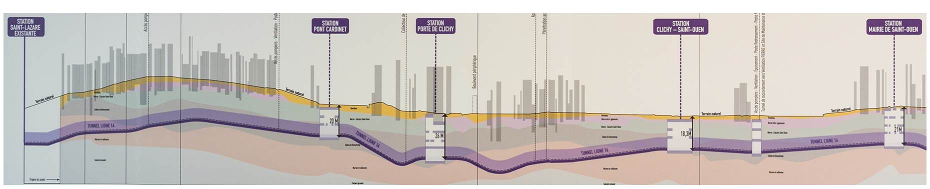


Fig. 3: Paris Metro line 14 tunnel depth.

The wheel-rail interface is also a complex domain to model [1][15]. Wheel slipping occurs when tractive effort exceeds adhesive weight whereas sliding occurs when braking effort exceeds adhesive weight. In both the situations, it is the adhesive weight playing the most important role. When tractive effort is more than adhesive weight, difference in power accelerates the wheel which results into grinding action on the rail. In the similar manner, when braking effort exceeds the adhesive weight, extra braking force prevents its rotation but with continuation of linear motion which results rubbing of wheel at one location on the circumference and called development of wheel flat. Both these conditions create unsafe situation. Weather and environmental conditions, including dry leaves, play a vital role in reducing adhesion.

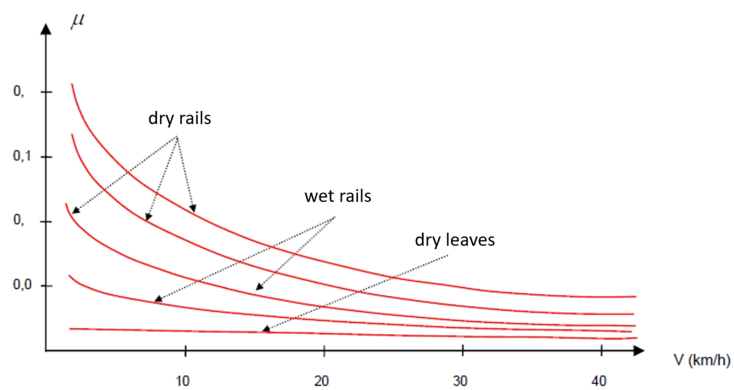


Fig. 4: Maximum actionable adhesion in function of speed and rail state.

Slipping and sliding have a dramatic impact on the safety:

- braking distances may be greater than expected, leading to a potential collision with a train.
- train position is deduced from a number of inputs sources (beacons, odometer, GPS). In a tunnel, the position between two beacons is estimated with the rotation of the wheels - sliding may bias the precision of the position and lead to a collision if the train is ahead of its estimated position.

Many other aspects, not listed here, have an impact on the behaviour of the train. For example, strong wind (Mistral wind in Provence) implies a speed restriction because of important windward grip (strong side wind may lead to train rollover [18]).

3.4 Timetables

With several trains being operated on a line, a timetable specifies where each train is located at given times over a certain period and is often presented as a graphical space-time diagram (Fig. 5). That the timetable is feasible means that it should be free of conflicts between trains and satisfy certain functional constraints given by the railway system, such as the track capacity resulting from the physical infrastructure and the signalling system.

The timetable stores information for each train at each station, including arrival and departure times, minimal stop time, and connections to other trains. It can be computed from the static model (routes) and from the dynamic model.

Simulation tools (like OpenTrack or SafeCap) could be used to evaluate timetables by introducing random delays. Predefined trains run according to the timetable on a railway network. During the simulation, train movements are calculated under the constraints of the signalling system and timetable.

Traffic is:

– cyclic (or not): all train services are operated with some fixed interval time
– homogeneous (or not): trains have the same profile (speed, running time, stop patterns).
– passengers traffic or freight traffic or mixed.

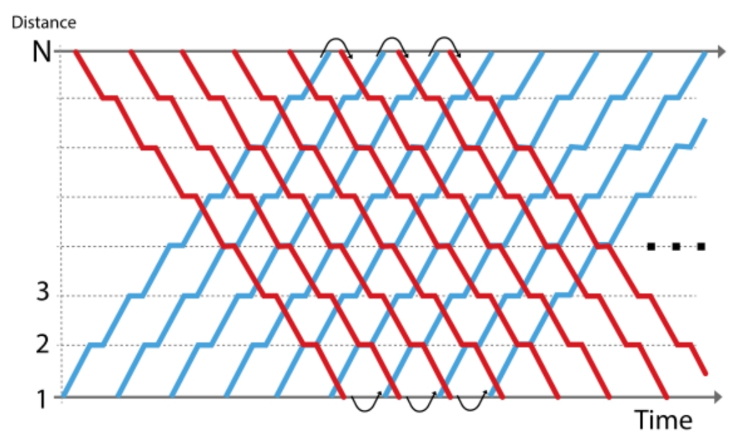


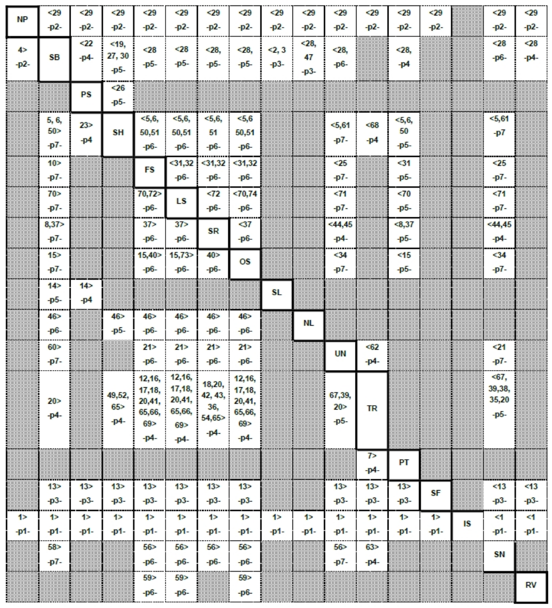
Fig. 5: Diagram of a single route timetable [20]

After a simulation run, train graphs, occupation diagrams and statistics are used for assessment. In particular, the headway between two successive trains is used to identify critical block sections. Simulation may be used to:

– compute real-time optimum strategies for traffic flow,
– explore the design space by modifying the track plan and the signalling parameters,
– minimise energy usage: when employing rheostatic braking, a train could provide energy to the network that could be used by another close accelerating train.

In [8], the automation of a large part of the ETCS rail track planning process is addressed by the algorithmic sequencing of formalized planning rules based on the knowledge and some best practices obtained from experienced track planners.

Simulation may also be used to assess compliance to standards. For example, the ERSA traffic simulator implements the ERTMS principles[1] that are explained in 700 pages (Fig. 6).



NP	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-	<29 -p2-		<29 -p2-	<29 -p2-
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Fig. 6: Transitions between ERTMS driving modes (matrix 17x17 !). White cells represent conditions and priorities for feasible transitions. Priorities enable avoiding conflict between simultaneously actionable transitions.

4 Modelling Safety

Models are also developed and used to ensure safety.

4.1 Automatic pilot - braking

The automatic train protection (ATP for the metro) is a system on-board the train which continually checks that the speed of a train is compatible with the permitted speed allowed by signalling, including automatic stop at certain signal aspects.

If it is not, ATP activates an emergency brake to stop the train. The braking curve is calculated based on the track topology (including gradient), the distance

[1] https://www.era.europa.eu/content/set-specifications-3-etcs-b3-r2-gsm-r-b1_en

```
variables :(types &
    properties &
    properties_train &

    (loc_trainLocated = TRUE =>
        0 <= loc_locationUncertainty
        & kine_kineInvalid = FALSE
        & loc_train_track /= {}
        & first(loc_train_track) = loc_ext2Block |-> oppositeDirection(loc_ext2Dir)
        & !ii.(ii : 1..size(loc_train_track)-1 => loc_train_track(ii) : dom(sidb_nextBlock))
        & !ii.(ii : 1..size(loc_train_track)-1 => sidb_nextBlock (loc_train_track(ii)) = loc_
        & #aa.(aa : 1..size(loc_train_track) & prj1(t_block,t_direction)(loc_train_track(aa))


        & loc_rearBlock = { c_cabin1 |-> loc_ext2Block, c_cabin2 |-> loc_ext1Block, c_none |-
        & (loc_rearBlock = c_block_init
          =>loc_rearDir=c_up)
        & ( not (loc_rearBlock = c_block_init)
          =>  loc_rearDir   = { c_cabin1 |-> oppositeDirection(loc_ext2Dir), c_cabin2 |-> c
        & loc_rearAbs   = { c_cabin1 |-> loc_ext2Abs, c_cabin2 |-> loc_ext1Abs, c_none |-> 0
        & loc_frontBlock = { c_cabin1 |-> loc_ext1Block, c_cabin2 |-> loc_ext2Block, c_none |
        & loc_frontDir   = { c_cabin1 |-> loc_ext1Dir, c_cabin2 |-> loc_ext2Dir, c_none |-> c
        & loc_frontAbs   = { c_cabin1 |-> loc_ext1Abs, c_cabin2 |-> loc_ext2Abs, c_none |-> s
    ))
```

Fig. 7: Top-level specification of an ATP main loop (excerpt) written in B. For each cycle, the software has to verify all conditions to either enable a permissive behaviour or stop the train.

to go to the next red signal (including a safety margin), the guaranteed train braking capability and the estimated train localisation (section 3.3).

Around 30% of the automatic metros ATP specification are modelled with the B language (Fig. 7). Their implementation are proved[3] to be correct refinements (no contradiction wrt specification). The model is huge, representing more than 50,000 lines of specification. The overall model requires to mathematically demonstrate 23,000 proof obligations to ensure its correctness.

4.2 Estimating maintenance periods

The rail integrity is a critical subject for train control as well as for maintenance strategies. Over all the possible rail flaws, a broken rail is obviously the most sensitive point. Typically, flaws are detected with special ultrasound monitoring trains and with unusual noise reports from drivers.

Two facts have a strong influence on the availability and safety of the railway system:

- the occurrence of critical defects of infrastructure subsystems,
- false alarms for instance triggered by monitoring devices designed for the defect detection.

For these two points, the railway operators need a degradation model of the rail and, as accurate as possible, an estimated rate of good detection of defects by their measuring devices. Then, various maintenance strategies can be simulated and their impact on the broken rail monitoring process can be completely estimated. In [4], dynamic Bayesian networks theory are introduced for the rail degradation and for the broken rail monitoring process model. The objective is keep (or improve) the ability to detect flaws when automating metros (the driver's feedback is not available anymore).

4.3 Formal data validation

Data validation consists in the verification and validation of the static data (section 3.2) against railways signalling rules (that are specific to every country or even each company in a single country), on rolling stock features (constant or variable train size or configuration) and operating conditions. By data validation, we mean the validation of the parameters (i.e. constants) that determine a specific behaviour of a software/system over a wide range of possible sets of values. Microsoft Excel defines data validation in terms of type checking: a cell may contain a date, an integer, a string or a floating point number. In our case, the data to validate are not only scalar but also represent more complex structures like graphs. A metro line is seen as a graph, made of connected tracks with distributed signals and switches implementing signalling rules. Graphs are encoded through a large number of tables.

```
FOR
        sig
WHERE
        sig : sys_sud_er::Signal &
        sig : dom(sys_sud_er::Signal__dptId) &
        sig : dom(ic::sys_sud_er::signal_geopoint) &
        ic::sys_sud_er::signal_geopoint(sig) : ic::sys_sud_er::zone_GPZone
(sys_sud_er::IXL_Core__singleZone(ixl))
THEN
        VERIFY
                sys_sud_er::Signal__dptId(sig) : ran(sys_sud_er::IXL_Core__signal(ixl))
        MESSAGE
                «The signal %1 belongs to IXL_Core %2 territory but is not referenced
                among its signals.»
                ARG sys_sud_er::Signal__name(sig) TYPE STRING
                ARG sys_sud_er::IXL_Core__name(ixl) TYPE STRING
        ENDVERIFY
ENDFOR
```

Fig. 8: Example of verification rule. Signals belonging to an interlocking territory are searched (clause WHERE); such signals have to be linked to this interlocking (clause VERIFY). If not, an error message is displayed for each faulty signal found (clause MESSAGE).

Formal data validation consists in:

- formalising the verification rules,
- formally proving that the data to verify comply with the formal rules.

In [14], rules are formalised with the B language (Fig. 8) and the proof is performed with the ProB model checker. Formal data validation has been applied to complete metro lines / main lines interlocking systems, demonstrating its applicability to large systems. In [17], configuration rules for interlocking are specified by temporal logic formulas interpreted on Kripke structure representations of the interlocking configuration.

4.4 Proving interlocking (model-checking, installation-based)

An interlocking is the safety-critical system that controls the movement of trains in a station and between adjacent stations. The interlocking monitors the status of the objects in the railway yard and allows or denies the routing of trains in accordance with the railway safety and operational regulations that are generic for the region or country where the interlocking is located. Verification of correctness of control tables has always been a central issue for formal methods practitioners, and the literature counts the application of several techniques to the problem. It is a well known fact that interlocking systems, due to their inherent complexity related to the high number of variables involved, are not amenable to automatic verification, typically incurring in state space explosion problems. Model-checking[10][11] has been exercised with considerable success for specific implementation and up to a certain complexity measured by a number of managed Boolean equations.

4.5 Modelling Design Reasoning

A railway system is often huge and very difficult to assess as structural modelling is not able to scale up properly. For example, a RER A regional train simulator modelling all track-side equipment (including wires, relays, etc.) contains more than 2,000,000 variables and requires seven computer to simulate simplified traffic scenarios on the central sector of the line. In [16], structural formal modelling is applied to an existing interlocking specification, but the results are a single error ("well known" by the customer) and an Event-B model refined 15 times, unreadable/unusable by the recipients.

A different formal methodology was then invented[19][6] where the design reasoning is modelled and proved against properties, based on assumptions admitted by all experts. Fig. 9 below illustrates its different stages, which can be called "the ideal formal world" and which makes it possible to obtain a system that is guaranteed to be zero-defect:

- The left side of the diagram represents the "formal proof of correct interoperability". The aim is to ensure that if the individual sub-systems making up the overall solution are implemented in accordance with their specifications, then the safety of the overall system is guaranteed. This proof enables the entity responsible for the integrated system to ensure that there are no hidden safety bugs in the subsystem breakdown.

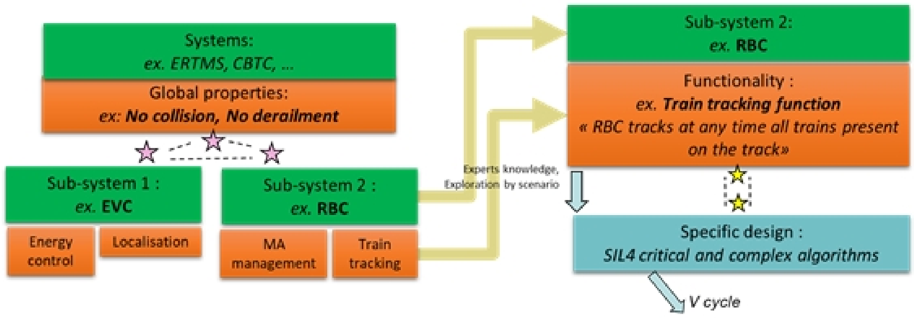

Fig. 9: The complete picture of the formal approach for safe systems).

– The right side of the schema could be named "formal proof of correct design". It is a question of guaranteeing that a given implementation is designed in such a way that the safety expectations expressed in the specifications are effectively met.

The by-product of this methodology is a book, written in natural language, providing an irrefutable mathematical demonstration that the various subsystems meet the expected refined properties[7].

5 Convergence and Relevance

The previous sections show that many railway activities are now subject to modelling. The complete picture of the situation is difficult to obtain as many of them are not publicly disclosed, for various reasons (competitiveness, secrecy, insufficient maturity, etc.) or are more a marketing by-product unable to survive the demonstration/prototyping phase.

Several initiatives to combine / associate theses modelling activities have been launched in order to address larger engineering problems or new paradigms like AI, hybrid modelling[2], and model-in-the-loop. Among them, we may notice:

– MegaM@RT[3] project, with the analysis of traces at execution time by comparison with system-level models (search for patterns, AI)
– Shift2Rail[4] improved train localisation with the formal modelling of the forthcoming Moving Block specification and the fusion of diverse data (GPS, odometer, kinematics, digital maps) to get rid of most track-side signalling.
– Simulating ERTMS Hybrid level 3 specification [12], a novel approach between ETCS level 2 fixed blocks and full moving blocks. Fig. 10 shows the formal B model being executed in real-time, along with a visualisation of the model's state: over 40 issues were identified.

[2] The combination of continuous and discrete models to associate a logic controller to the physics of a controlled system described with differential equations.
[3] https://megamart2-ecsel.eu/
[4] Call for Project 2R-OC-IP2-01-2020

– SNCF Réseau[5] is developing a digital mock-up of its network to provide valuable input for scheduling predictive maintenance operations, foresee behaviour, train teams and test-drive strategic solutions.
– Alstom[6] develops a rail network digital twin for railway yard design and predictive fleet maintenance based on AnyLogic.
– On-going autonomous train projects[7] are integrating AI for decision and diverse sensors for detection, while ensuring a human remote control in case of unexpected situation.

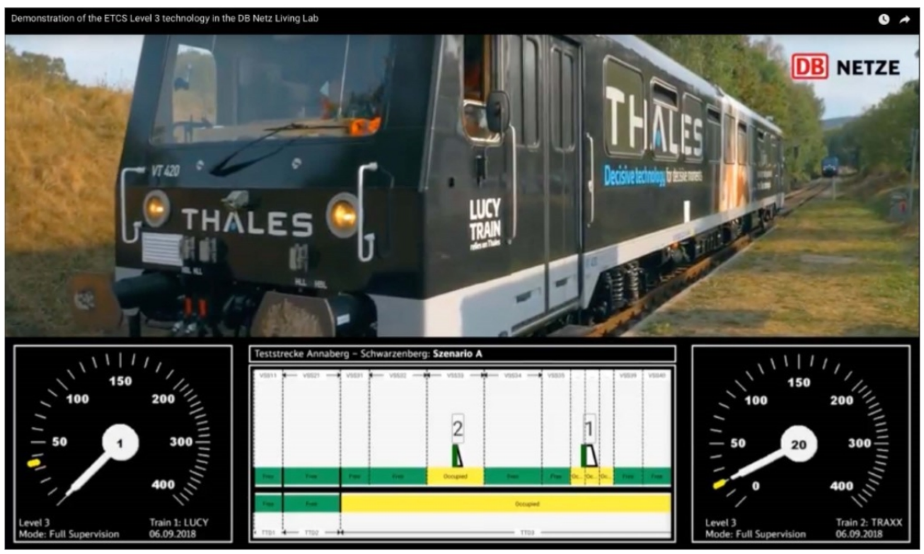

Fig. 10: Formal B model of Hybrid Level 3 Principles running in real-time.

Besides the fact of using state-of-the-art techniques, how relevant the concept of digital twin is in the railways ? Due to the different domains, timescales, and objectives[8] covered by the modelling activities listed above, having a digital twin of a whole railway system does not seem much adequate.

A digital twin would probably find a more suitable usage for a restricted domain/timescale/objective combination like training simulation or validation test bench [9]. More precise results are expected with the integration of addi-

[5] https://www.sncf-reseau.com/en/entreprise/newsroom/sujet/the-digital-twin
[6] https://www.anylogic.com/digital-twin-of-rail-network-for-train-fleet-maintenance-decision-support/
[7] https://tech.sncf.com/dossier/train-autonome/
[8] For example, respectively functional vs safety, seconds for slipping vs thousands years for rail maintenance, and development vs certification.
[9] SNCF test bench BATIR enabling the real-time functional simulation, including HiL, of full high speed trains to validate embedded software.

tional modelling dimensions. However tool/model integration costs are a high barrier as there are many tools, specific to a line/model/plant, for which source code / (design, interface) documentation is often hardly available. The combination of these tools/models, developed separately, would induce extra effort to validate their semantic and pragmatic consistency, especially if used for safety certification. Moreover developing new tools/models for legacy systems already in exploitation requires a sound justification (exploitation/maintenance costs saving, solving design issues uncovered lately).

Digital twin is probably more adequate to address newer systems (new baseline) or new themes like:

- ERTMS: its evolving specification and the lack of feedback (compared to historical national signalling which have been designed over decades/century), difficult to deploy[10] and enabling the late discovery of errors through hybrid modelling[12].
- Cyber security: critical transportation infrastructure is facing increasing security risks given that many systems are (going to be) connected to the Internet, while related standards are as of today being written (hence not ready for deployment). In particular, joint security and safety modelling are closely related and are good candidates to populate a digital twin.
- Terrorism: At the highest level, there is a clear need for the combination of models from different transportation systems[11], to take into account multimodalities, especially with respect to the terrorist risk and the way independent transportation infrastructures will manage security.
- Autonomy: automating trains requires to consider more aspects than for automated metros, as the environment is more complex with more elements, interfaces, and interactions. The variety of scenarios and situations met requires precise models of the system and its environment to ensure AI consistency.

6 Conclusion and Perspectives

Railways are heavy modelling providers and users. Most models are:

- separate;
- have different natures and objectives: logic, physical world, performances, safety, etc.
- have different subjects: infrastructure, rolling stocks, environment;
- used for different activities (specification, development, validation, qualification/certification, exploitation/maintenance);

[10] "Bring in the disruptors to drive rail innovation", Stuart Calvert, Digital Rail, TransCityRail North conference, London, 06/10/2017

[11] H2020 Call SU-INFRA-01-2020: Prevention, detection, response and mitigation of combined physical and cyber security threats to critical infrastructure in Europe

The on-going tendency is to support more engineering activities with modelling or cross-modelling (either by combining modelling to obtain an augmented one, or by exercising modelling with the support of another one). For example, slipping/sliding physical modelling provides outputs (i.e. tables) for the estimation of the train localisation precision, but is not included into train traffic simulation per se.

However it seems unreasonable to imagine a model of a complete railway system (a metro line) shared among different stakeholders, as the range of uses is quite large and the systems considered made of many equipment/subsystems/parts.

Applications to new themes (AI for autonomy, cyber security, terrorist risks, etc.) might constitute a suitable entry point for digital twins in the railways.

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