Developing System Models to Help Railways Embrace Innovative Technologies with Confidence

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Abstract:
Railways are under pressure to become more efficient and cut their costs; innovation has a part to play in achieving these goals. The railway is, however, a complex and closely-coupled system, making it difficult in the early stages of development, to be clear what the system-wide impact of innovation will be. The research covered in this paper stems from the idea that computer-based models of existing systems can help overcome this problem, by providing a framework against which the impact of innovation can be identified. The paper describes a repeatable and objective modelling methodology developed for Great Britain’s (GB) railways, which elicits objective system data from Railway Group Standards and integrates it using CORE®, a powerful system modelling tool, to create system models. The ability of such models to help identify impacts is verified, using as an example the introduction of RailBAM (a new technology that acoustically monitors the health of rolling stock wheel bearings) into the existing hot axle box detection system. Finally, the paper takes an initial look at the structure of railway standards outside GB, to establish whether the methodology can be applied in other countries.

Introduction:
The railway needs to innovate if it is to become more efficient and cut costs. In its recent White paper (EC, 2011), the European Commission set out its vision for a sustainable and competitive transport system, and identified innovation as being an essential part of the delivery strategy. The Department for Transport’s Railway Command Paper (DfT, 2012) stressed the importance of taking advantage of technical innovation, if the railway is to continue to improve its cost effectiveness and performance, and reduce its environmental impact.

The rail system’s complex and closely-coupled nature can, however, act as a disincentive to innovation, because it makes it difficult to see at an early stage in the development process, what the impact of innovation will be on the system as a whole. The railway’s complexity is
manifest in the wide range of infrastructure (track, structures, signals), and train characteristics (high speed passenger, slow freight, frequent stop commuter) present in the system. Close-coupling is revealed in the need for all the sub-systems to interact properly, in order to deliver the timetabled service: for example, localised failure of a switch can result in train delays over a wide area, as well as disruption to train diagrams, train crew rosters and planned maintenance activities.

Model-based systems engineering (MBSE) can help overcome this problem by creating models of the existing system, against which the impact of innovation can be identified. MBSE is defined as the ‘formalised application of modelling to support (system development)’ (INCOSE, 2007); it joins modelling with systems engineering techniques, to create an integrated view of the engineering problem and the proposed solution (Long and Scott, 2011). Model building requires: clear definition of the system boundary; elicitation of system data, ideally from an objective source, and; integration of that data to create the model. A common data integration approach involves linking system entities (and their attributes) such as requirements, functions and components using relationships. An outline of a schema for such an entity-attribute-relationship database is shown in Figure 1.

![Figure 1: Indicative Diagram of an Entity-Attribute-Relationship Database Schema (Attributes not shown)](image)

Systems engineering (SE) techniques are used to support the model building process. They first started to emerge in the 1920s, with work to improve the movement of fundamental scientific discoveries into innovative new products (Kelly, 1950). Further developments in the 1950s played a big part in helping engineers cope with the design complexity of projects such as the U.S.A.’s inter-continental ballistic missile defence system, and the Apollo space projects (Gibson et al, 2007). Essentially, SE is about ‘...creating effective solutions to problems, and managing the technical complexity of the (associated) developments’ (Stevens et al, 1998).

SE is commonly visualised as a top-down process, associated with the design of new systems, during the course of which the system boundary is defined and the system data required for model building is generated. The process starts with a statement of client or user need, which
is developed into a set of capability requirements stating what the system should be able to do. These are worked up into a set of system requirements, describing what the system must do to achieve the required capabilities, but not how it will do it. The ‘how’ comes in the development of the system architecture, or framework, in which functions are derived from the system requirements and assigned to the resources (people, components) that will carry them out. Finally, detailed design and manufacture of components is done, the components are assembled to create the system, and tests are made to check the emergent properties meet the original requirements.

Modelling of existing systems cannot, however, start with the same ‘clean sheet of paper’ assumed for new systems; a different SE approach, called ‘middle-out’, is employed. Middle-out SE is the term given to the process of introducing new sub-systems into existing systems, while taking account of legacy components and interfaces. It begins by modelling the as-built state of the system, to give engineers a better idea of development constraints and opportunities, and is followed by top-down methods for detailed design (Long and Scott, 2011).

Research has identified only a limited number of papers on the topic of middle-out SE, and while they describe specific instances of the middle-out approach, none demonstrates a repeatable and objective methodology. For example, (Dam, 2007) suggests use of carefully selected operational scenarios as a method for helping stakeholders to identify both existing system constraints and new system requirements; however, scenario selection and stakeholder inputs remain subjective. In another example (Logan and Harvey, 2010), middle-out is mentioned, but in the context of needs analysis, rather than modelling of existing systems.

This paper describes a novel approach to overcoming the problems of objectivity and repeatability, developed in the first instance for use on Great Britain’s (GB) railways. It involves: firstly, use of high level, GB Railway Group Standards as the objective source of modelling data, and; secondly, development of a repeatable methodology to identify the standards that apply to the system of interest. The standards cover all aspects of the railway business: from operations through to infrastructure maintenance; and apply to all companies working in the industry: from suppliers through to infrastructure maintainers. The standards have been in place for many years and are regularly updated in the light of operating experience and government legislation; as such, it is arguable that they are a distillation of GB railway knowledge covering functions, components and requirements.

The research is presented in four sections that underpin methodology development. The first defines the boundary of the system-of-interest using Railway Group Standards (RGS) as the objective data source. The second uses top-down system engineering techniques to identify the types of data required for model building, and then elicits the data for the model from the RGSs identified in section 1. The third uses a commercially available system modelling tool (CORE®, produced by Vitech Corporation in the USA) to integrate the data from RGSs to create system models that can help identify the impact of innovation (Vitech, 2012). And the fourth verifies that models generated using the methodology can be used to establish the
impact of an innovative system change. This and the work of the other three sections are illustrated using the example of the introduction of RailBAM technology (Track IQ, 2012) into the hot axle box detection (HABD) system. Additionally, there is a final, fifth section, which investigates in outline whether other railways have standards structures that lend themselves to application of this methodology.

The paper concludes with a summary of the research findings and areas requiring further research.

**Section 1: Defining the System Interfaces and Boundary**

This section of the paper describes the use of Railway Group Standards (RGS) to define the interfaces and boundary of the system-of-interest.

RGSs facilitate the management and operation of the railway by ‘...defining requirements for assets or processes which involve co-operation between two or more duty holders, and assigning responsibility for compliance with these requirements’ (RSSB, 2008). As such, the RGSs relate to one another in a way that reflects the complex and closely-coupled nature of the railway. The diagram in Figure 2, based on information from the Railway Safety and Standards Board website (RSSB), shows the organisational structure involved in the development and maintenance of RGSs.

The stakeholders to the RGS process, such as passenger and freight train operators, are shown at the top of the diagram. RSSB coordinates the activities of the various standards committees, shown in the centre of the diagram. The Infrastructure Standards Committee is used as an example to show the interfaces between standards committees, system interface committees and the European Railway Agency (ERA), which has responsibility for Technical Specifications for Interoperability (TSI). RGSs can act as National Technical Rules (NTRs), which among other things ‘maintain technical compatibility between new assets, which may conform to TSIs, and existing assets or processes that do not’ (RSSB, 2012). They also perform the role of National Safety Rules (NSRs), which ‘provide visibility to any potential open access operators from other countries of the rules that they will need to comply with if they want to operate in [Great Britain]’ (RSSB, 2013).
In general the RGSs are published with a similar format; and in most cases they contain references linking a given standard to other relevant RGSs. This supports the system boundary definition process, which is shown diagrammatically in Figure 3. It begins with a search of the RGSs database, using a term(s) closely describing the system-of-interest, to identify the key standard(s); for simplicity, Figure 3 assumes one key standard has been found, numbered 1. The key standard’s references are identified (2, 3 and 4 in the diagram). The references for those standards are then in-turn identified (2, 5, 6 and 7); this is termed the ‘first iteration’ of the boundary definition process. Not all of the standards emerging from the boundary definition process result in further iterations: for example, standard 2 in the first iteration is a repeat of an earlier standard; engineering judgement is used to conclude that standard 5 is not relevant to the system-of-interest, and; standard 3 does not have any
references. In each of those cases the relevant arm of the diagram can be terminated. Further iterations of the process are made until all of the branches are terminated, at which point all standards on the diagram, except those not relevant to the system-of-interest, are deemed to be the ones defining the interfaces/boundary.

In the case of the hot axle box detection system, one key standard was identified: GE/RT8014 Hot Axle Bearing Detection (RSSB, 2001). The boundary definition process went through seven iterations to identify a total of thirty-two relevant standards. These have been summarised into the nine sub-system interface groups show in Figure 4.

![Figure 4: HABD System Interfaces](image)

**Section 2: Eliciting the Modelling Data**

This section of the paper uses top-down system engineering techniques to identify the types of data required for system modelling and describes elicitation of the data from RGSs.

The introduction summarised the top-down systems design process; based on that, the data types involved in the creation of new systems and required for system modelling are:

- User requirements (user needs);
- Capability requirements;
- System requirements;
- System architecture;
- Functions, and;
- Resources (including components and people).

The first three types of data are requirements: user, capability and system (Hull et al, 2011). Requirements define what stakeholders want from a new system, and what the system must do in order to satisfy that need. User requirements (often called user needs or mission requirements) are the most basic; they do not result from a rigorous analysis and often
contain woolly expressions of need mixed with descriptive material: for example, ‘a new tool is required to help cut the number of hot axle box detection system false alarms. Capability (or originating) requirements provide more detail; they are statements about what the system should do (but not how it should do it) and ‘...define the constraints and performance parameters within which the system is to be designed’ (Buede, 2000). They are characteristically written in the form ‘The system shall be capable of...’. System requirements are the most detailed type of requirement; they describe what the system must do in order to deliver the capabilities to satisfy user needs. They are characteristically written in the form ‘the system shall...’. The three types of requirement form a hierarchy with the top level, basic user requirements being decomposed to form first capability requirements, and then detailed system requirements.

HABD system key standard GE/RT8014 was analysed for examples of the three types of requirement data described above. No instances of user or capability requirements were found, which is not unexpected bearing in mind that those types of requirement relate to the development of new systems, whereas the standard is describing the existing system. Consistent with this thinking, numerous examples of system requirements, describing what the system has to do, were found.

Moving on to system architectures, there are three principal types in system design: the physical architecture, which defines the system’s physical resources (components, people) that will perform the system’s functions; the functional architecture, which defines the system’s functions (verb-based descriptions of what the system must), and; the operational architecture, which maps functions to resources (Buede, 2000). For the physical architecture, RGSs GE/RT8014 Issue 1 and GE/RT8000/TW5 (RSSB, 2008) were analysed to determine whether they contained the necessary data. Many examples of resources were found; however, they were distributed through the document as required by the narrative, rather than presented in a tabulated form. Therefore, identifying the data and organising it hierarchically required a systematic approach on the part of the modeller. The sample results in Figure 5 show four high-level resource groups, with each group decomposed to lower levels of detail, including the component level.

For the functional architecture, analysis showed that some standards were better than others in presenting function data: for example, RGS GE/RT8250 Issue 2 ‘Reporting High Risk Defects’ (RSSB, 2007) uses functional flow block diagrams to identify some of the functions and the relationships between them. However, many of the RGSs do not and in those cases it was necessary to elicit the functions by reading through the standard, looking for characteristic ‘the system shall...’-type sentences. Guided by the standard, functions then had to be ordered hierarchically, and linked sequentially, to create descriptions of the
processes that the system carries out. Therefore, again, a systematic approach was required on the part of the modeller to gather and organise the data effectively. An example of linked functions is shown in the diagram of Figure 6, and described in more detail below.

In the case of the operational architecture, analysis of the standards found strong evidence of functions being mapped to resources. For example, GE/RT8000 TW5 provides many examples of tasks assigned to signallers and train drivers. Figure 6 shows functions relating to the ‘inspect bearings’ task. The diagram is drawn to illustrate the operational architecture involved: the upper strand of functions starting with ‘Contact signaller’, has to be carried out by the driver; while the lower strand starting with ‘Instruct driver to inspect’, is all carried out by the signaller. The last four functions of the upper strand also involve other resources such as the train itself and the diagram could be developed further, if need be, to show this.

Section 3: Integrating the Data to Create the System Model
This section of the paper describes how Vitech Corporation’s CORE® system modelling tool is used to integrate the system-of-interest data elicited from RGSs to create the model.

Figure 1 shows an outline schema for an entity-attribute-relationship database, similar to the one on which CORE® is based. It shows how a selection of entity data classes (for example, function and requirement) can be linked using relationships; some of the most common relationships are shown as examples. The CORE® schema contains a predefined set of relationships, which have been developed over many years of modelling experience in a range of industries. Additional relationships can be added if the circumstances demand, but care has to be taken to ensure any changes do not disturb the logic of the schema.

The HABD system was too big to model in its entirety; therefore, modelling was restricted to the part of the system dealing with activation of the HABD and inspection of the train out on the track. Data for modelling was elicited from two standards: GE/RT8014 Hot Axle Bearing
Detection, and; GE/RT8000-TW5 Preparation and Movement of Trains: Defective or Isolated Vehicles and On-train Equipment. The data used was from entity classes: document; component; function; requirement and item (inputs and outputs). The relationships describing the various links between the entities were selected by the modeller from the menu provided by CORE®, rather than being elicited from the RGSs. Functions were ‘partitioned’, or allocated, to the components that carry out the activity, and were also linked together to describe some of the system processes. Items (inputs and outputs) were added to the functions to show the flow of data through the processes.

Figure 6: Diagram Showing Decomposition of the ‘Inspect Vehicle’ Function and Operational Architecture

Figure 6 shows an example of output from the CORE® model for the ‘inspect bearings on track’ process. The diagram is referred to as an ‘Enhanced Functional Flow Block Diagram’, because it shows the movement of data in addition to the functions linked sequentially to describe the processes: for example, the driver’s first task is to give the signaller the train head code, which triggers (denoted by the double arrow head) the signaller to instruct the driver to inspect the train. The diagram also shows ‘partitioning’ of functions (allocation of functions to the components that will actually carry them out): the functions in the top half of the diagram are carried out by the driver, while those in the bottom half are carried out by the signaller. Although not shown in Figure 6, CORE® can also model the interfaces between the HABD system and the related systems shown in Figure 4.

Section 4: Methodology Verification

This section of the paper demonstrates how the CORE® model of the HABD system can be used to identify the impact of introducing new RailBAM technology.

Current HABD equipment monitors the infra-red signature of bearings and can produce false alarms by detecting heat from brakes or other sources. False alarms are expensive, because the operating rules require the affected train to be stopped and inspected, during which time
adjacent lines are closed to traffic. RailBAM on the other hand monitors bearings acoustically and can indicate what the remaining life of a bearing is, as well as warning when the bearing has failed. This research focused on the latter capability and used the model of the existing hot axle box detection system to explore what the impact of introducing RailBAM on the wider system might be.

As already described above, modelling was restricted to the part of the system where a warning of a hot axle box is received and the train is stopped and inspected. Two views from that model are shown in Figures 7 and 8.

Figure 7 shows the system is built from the hot axle box detector (HABD) component and

![Figure 7: Part View of HABD System](image)

![Figure 8: Part View of Monitor Bearing](image)

that the system cannot be considered in isolation, but must be viewed in a wider context (built in HABD context) as shown earlier in Figure 4. Information about the HABD is documented in RGS GE/RT8014 and the system performs two functions: monitoring of bearings, and; inspection of bearings. Figure 8 provides a view of the ‘monitor bearings’ function, referred to in Figure 7. It shows the task of monitoring bearings is allocated to the HABD component, which is part of the HABD system. It also shows that the task of monitoring bearings can be decomposed to give two more detailed functions: ‘scan passing bearing’ and ‘detect hot bearing’. Finally, it shows that the requirement to monitoring bearings is documented in RGS GE/RT8014.

The model is very simple, but it is still possible to see how it can help to identify the impact of replacing existing HABDs with RailBAM. It shows the HABD system context (Figure 4) that must be considered, and it shows the functions, documents and components affected. It does not say what the effect of making the change will be; that activity still remains with
engineers. It does, however, help engineers objectively to identify the components, documents and processes they need to concentrate on, and show them how they relate to one another.

Section 5: Can the Methodology Work on other Railways?
The structure of railway standards in the United States of America was investigated, to establish whether it can support the modelling methodology proposed in this paper. Starting at the top and working down, the Federal Railroad Administration (FRA) is responsible for railroad-related regulations passed by the legislature (Federal Railroad Administration, 2012). The regulations constitute the top-level set of requirements which all railroad undertakings must comply with. The regulations relating to railroads are collected in Title 49: Transportation. Title 49 is divided into Parts covering the principal safety topics such as: operating rules; communications; locomotive safety; and braking systems. Parts are further broken down into sub-Parts containing the individual regulations.

In an arrangement similar to that for GB RGS, the Parts are organised into fourteen high level divisions; Figure 9 contains a table showing how the Divisions relate to the ten Categories of GB RGS. It can be seen that all of the Divisions bar one (Passenger Rail) have corresponding RGS Categories: this apparent anomaly is perhaps explained by the standards reflecting the mixed traffic nature of GB’s railway, whereas the USA is predominantly freight, with passenger traffic being seen as something of an add-on.

<table>
<thead>
<tr>
<th>Federal Railroad Administration: Safety Divisions</th>
<th>Railway Safety and Standards Board: Standards Committees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railroad Safety Program Management.</td>
<td>Administration.</td>
</tr>
<tr>
<td>Railroad Safety Information Management.</td>
<td></td>
</tr>
<tr>
<td>Safety Regulation Analysis.</td>
<td></td>
</tr>
<tr>
<td>Rail and Infrastructure Integrity; Track.</td>
<td>Permanent way, structures and construction safety;</td>
</tr>
<tr>
<td></td>
<td>Inter-company infrastructure activities;</td>
</tr>
<tr>
<td></td>
<td>Electrification.</td>
</tr>
<tr>
<td>Signal and Train Control Division.</td>
<td>Train control and communications</td>
</tr>
<tr>
<td>Operating Practices; Hazardous Materials</td>
<td>Traffic operations and management;</td>
</tr>
<tr>
<td></td>
<td>Inter-company activities.</td>
</tr>
<tr>
<td>Motive Power and Equipment.</td>
<td>Rolling stock;</td>
</tr>
<tr>
<td></td>
<td>Plant (fixed and mobile).</td>
</tr>
<tr>
<td>Railroad Safety Technical Training Standards.</td>
<td></td>
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<tr>
<td>Risk Reduction Programme.</td>
<td></td>
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<tr>
<td>Highway-Rail Crossing and Trespasser Programs.</td>
<td></td>
</tr>
<tr>
<td>Industrial Hygiene.</td>
<td></td>
</tr>
<tr>
<td>Passenger Rail.</td>
<td>Health and safety.</td>
</tr>
<tr>
<td>Nil</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9: Table Showing the Relationship Between USA Federal Railroad Administration Divisions and GB Railway Safety and Standards Boards Categories
Each Division has a corresponding compliance manual for its Parts. This lists each regulation and provides guidance on definitions and situations in which the regulation will apply. Often the guidance for a specific regulation will make reference to other regulations; therefore, there is potential for compliance manuals to perform functionality similar to the GB RGS, in terms of helping systems engineers to identify those parts of the existing system relating to a specific system of interest.

In the case of hot bearing detectors, Chapter 16 of the Motive Power and Equipment Division compliance manual discusses wayside detectors, including hot bearing detectors, in some detail; however, there are no references to specific regulations on wayside detection (FRA, 2012). Similarly, Part 215 (Railroad Freight Car Safety Standards) of Title 49 has a number of sub-Parts governing the entry of bearings into service, but does not say anything about wayside detection.

This suggests a significant difference between GB RGS and USA regulations: namely, that while GB RGS do in certain circumstances specify how certain requirements (hot bearing detection in this case) will be met, regulations in the USA specify what is required but not how it should be done. The Author believes that standards and guidance issued by the American Association of Railroads (AAR), and operating standards developed by individual railroads, provide more detail on the application of hot bearing detectors; however, these documents are not publicly available, therefore it has not been possible to confirm this.

Conclusions and Further Work

The research described in this paper has developed a repeatable and objective methodology for modelling existing rail systems, the outputs from which can be used to identify the impact of innovative technologies and processes at an early stage in the development process.

The research has identified the principal types of data required to model a system: namely, the user, capability and system requirements; the system architectures; the functions, and; the components. It has made the argument that Railway Group Standards (RGSs) relate to one another in a way that reflects the closely-coupled nature of the railway, and can act therefore, as high-level, objective repositories of system data. It has shown that the data types required for modelling are available in, and can be elicited from, RGSs. The case of the introduction of the new wheel bearing monitoring technology, RailBAM, has been used to demonstrate the feasibility of system boundary definition, data elicitation and model building using the CORE® system modelling tool. The research has demonstrated the model’s ability to help identify those parts of the existing system that will be affected by the introduction of new technologies or processes. Finally, research into standards in the USA, suggests that their structure may support application of the modelling methodology; however, it may not be possible to build the high level models without access to ARR standards and guidance.

The work has shown that input from domain technical experts is still needed in the modelling process. Engineers with experience of the system-of-interest are required to help ‘order’ the data elicited from the RGSs, select the appropriate relationships and link functions to create processes.
Although not discussed in the main body of the paper, the research has raised a question mark over whether efforts currently underway to rationalise the RGSs, could weaken many of the links between them, reducing their ability to contribute to model building.

Further research is planned to verify the model building process against the results of recent work by the Technical Strategy Leadership Group to create a railway system functional architecture. An interesting opportunity to use the methodology to assist Network Rail in its efforts to streamline its own technical standards has been identified. Further research is also required to confirm that the modelling approach can work in USA; the Author would welcome collaboration with fellow systems/railroad engineers who have access to AAR and railroad company standards. And finally, it would be interesting to explore the feasibility of linking system models with cost breakdown structures, as a first step towards being able to estimate more accurately the cost impact of technology and process change.

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Axiom

Bibliography:


RSSB, http://www.rssb.co.uk/Pages/Main.aspx


