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Case Study: Achieving System Integration through Interoperability in a large System of Systems (SoS)

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Abstract. This paper provides a case study on system of systems engineering (SoSE) being performed in a multi-billion-dollar program – the California High-Speed Rail System – viewed from the systems integration perspective. The paper discusses why the subject program of projects (PoP) can be viewed as a system of systems (SoS), identifies the SoSE challenges faced, describes the SoSE activities performed, and summarizes the achieved outcomes and conclusions as of today.

Specific SoSE challenges discussed include SoS authority, leadership, architecting, collaboration, integration, and emergence. The paper reviews how decision-making in independently operated and managed constituent systems (projects) resulted in unanticipated SoS emergent behavior, which is one of the key challenges in the engineering of SoS.

The paper further discusses the performed SoSE activities, including an international best practice review, the tailoring of SoSE to the specific SoSE challenges, and provides examples where SoSE principles are being applied to perform successful SoS integration.

Brief Introduction: System of Systems

A system of systems is a system-of-interest (SOI) whose elements are themselves systems. A SoS brings together a set of systems for a task that none of the systems can accomplish on its own. Each constituent system (CS) retains its own management, goals, and resources while coordinating within the SoS and adapting to meet SoS goals (ISO/IEC/IEEE 15288, 2015).

SoS Characteristics: SoS are characterized by **managerial and operational independence** of the constituent systems, which in many cases were developed and continue to support originally identified users of the constituent concurrently with users of the overall SoS. In other contexts, each constituent system itself is a SOI, with its existence often predating the SoS, while its characteristics were originally engineered to meet the needs of their initial users. As constituents of the SoS, their role is expanded to encompass the larger needs of the SoS. This implies added complexity particularly when the systems continue to evolve independently of the SoS. The constituent systems also typically retain their original stakeholders and governance mechanisms, which limits alternatives to address the needs of the SoS (ISO/IEC/IEEE 15288, 2015).

SoS Types: SoS have been characterized into **four types** based on the governance relationships between the constituent systems and the SoS (Dahmann, 2015):

Table 1: System of Systems Types & Characteristics

SoS Types	Governance Relationships between SoS and CS
Directed SoS	• SoS created to fulfill specific purpose • Dedicated SoS manager • Subordinated constituent systems
Acknowledged SoS	• Recognized SoS objectives • Designated SoS manager & resources • Independent constituent systems
Collaborative SoS	• Agreed upon central purpose • Voluntary interaction • Independent constituent systems
Virtual SoS	• Lacks central management • Lacks agreed upon purpose • Large scale emergent behavior

SoS Emergence: Emergence is a key characteristic of SoS – the unanticipated effects at the systems of systems level attributed to the complex interaction dynamics of the constituent systems. In SoS, constituent systems are intentionally considered in combination, to obtain and analyze outcomes not possible to obtain with the systems alone. The complexity of the constituent systems and the fact they may have been designed without regard to their role in the SoS, can result in new, unexpected behaviors. Identifying and addressing unanticipated emergent results is a particular challenge in engineering SoS (ISO/IEC/IEEE 15288, 2015).

The California High-Speed Rail System (CHSRS) Program

One of the largest and most ambitious public transportation programs in U.S. history, the California High-Speed Rail System Program will allow passengers to travel from Los Angeles to San Francisco at speeds of up to 220 miles (354 kilometers) per hour, making the trip in just 2 hours and 40 minutes, compared to almost 6 hours by automobile. The system will connect California's mega-regions, contribute to economic development and a cleaner environment, create jobs and preserve agricultural and protected lands (WSP, 2019).

Using federal and state funds, including Cap and Trade auction proceeds, the California High-Speed Rail Authority (Authority) plans to begin high-speed operations in the Central Valley by 2028, eventually connecting San Francisco to Los Angeles in under three hours by 2033. Eventually, the system will extend to Sacramento and San Diego, totaling 800 miles with up to 24 stations. The Authority is also working with regional partners to implement a state-wide rail modernization plan to improve local and regional rail lines (WSP, 2019).

The California high-speed rail system is the first truly high-speed system to be planned, designed, built, and soon operated, in the nation. In taking on this challenge, the Authority has broken new ground and set a precedent for other high-speed rail systems in the US. This presents atypical challenges compared to other complex infrastructure projects that have been delivered under more developed state and federal regulatory guidelines and mature technical standards, including (WSP, 2019):

- Funding and Financing
- Environmental Clearances
- Right-of- Way Acquisition
- Long, Deep Tunnels through Seismic Areas
- Increasingly Complex Technical System Integration

Figure 1. California High-Speed Rail System (WSP, 2019)

California High-Speed Rail as a System of Systems

From a systems integration perspective using the managerial and operational independence as a litmus test, the California High-Speed Rail System can be considered a SoS on multiple hierarchical levels, including:

- **CHSRS External**: The CHSRS as a constituent system within a larger SoS (Figure 2),
- **CHSRS Program**: A program of projects (PoP), whereby the program presents the SoS and the projects present the constituent systems (Figure 3), and
- **CHSRS Program Organization**: An organization of organization branches, whereby the program organization presents the SoS and the individual organization branches present the constituent systems (Figure 4).

CHSRS External: Figure 2 presents the CHSRS as a constituent system within a larger SoS. Other interfacing constituent systems and organizations included, but are not limited to adjacent railroads and highways requiring intrusion detection and protection, utilities providing high-voltage power, potential interfaces with U.S. Geological Survey (USGS) for the earthquake hazards program, shared track operation in existing rail corridors in the San Francisco area (Caltrain) and Los Angeles (Metrolink), irrigation canals, local counties, cities, businesses, property owners, and many more.

Figure 2. CHSRS as a Constituent System within a Larger SoS

CHSRS Program: Figure 3 presents a simplified life cycle view. The CHSRS program will be procured (acquired) in form of several projects (supplied). Each project is managed and operated independently by a design-build (DB) or design-build-operate-maintain (DBOM) contractor. Additionally, each contract is overseen by an independently managed and operated project and construction manager (PCM), supported by independent checking and site engineers (ICE/ISE), reporting both to a local Authority (program) representative.

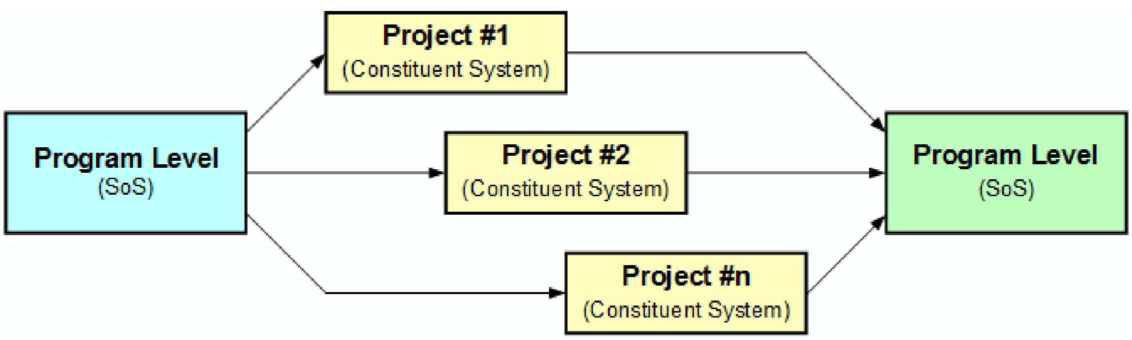

Figure 3. CHSRS as a Program (SoS) of Projects (Constituent Systems)

CHSRS Program Organization: The California High-Speed Rail Authority organization can be characterized as a matrix organization, with three main vertical **program delivery pillars** (strategic delivery, infrastructure delivery, rail systems delivery), supported by horizontal **functional support groups** and **executive support functions**, as presented in Figure 4 below. The **network integration** section, part of the **rail systems delivery** branch, is led by the deputy director of network integration and program compliance responsible for managing the process for integrating all aspects of the rail system and for developing and retaining documentation related to systems engineering, including requirements management, configuration management, interface management, RAM (reliability, availability, maintainability), and system certification (CHSRS, 2018). The **systems integration lead** position reports to deputy director of network integration and program compliance (CHSRS, 2018).

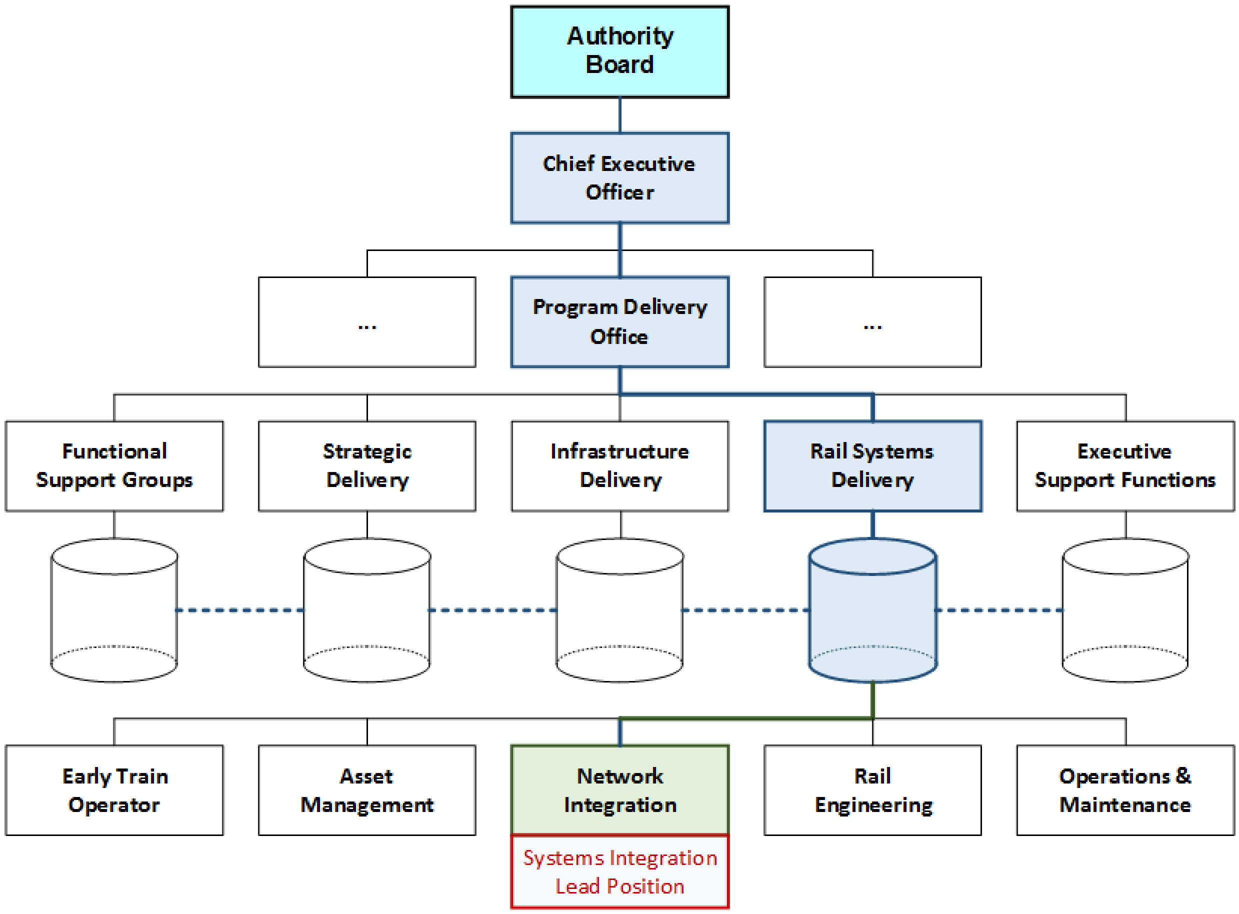

Figure 4. CHSR Program Organization as an Organizational SoS

The project management institute (PMI) identifies an organization where the project manager works in a staff position as part of a functional unit as a **weak matrix organization**, with the project manager having **limited power and authority**. The same can be argued for the systems integration lead position, even for the deputy director position of network integration and program compliance.

From an SoS perspective, the vertical delivery branches, horizontal functional support groups and executive support function are operationally and managerially independent from the rail system delivery branch. Additionally, the Authority organization is an integrated organization of state personnel, occupying primarily the key positions (Figure 4, highlighted in blue), and supporting consultant personnel from contracted architecture and engineering (A&E) firms (highlighted in green). A case can be made that both the state personnel and the supporting consultant organizations are managed and operated independently, and that both the vertical and horizontal matrix organization presents the Authority as an **organizational SoS**.

Traditional Industry Approach to Systems Integration

This section provides a brief overview of the traditional approach to systems integration in the U.S infrastructure and transportation industries, using the prevailing project delivery methods as they are applicable to the CHSRS program.

Functional Organizations: The acquiring owner organizations (e.g. state department of transportations, transportation agencies) have historically been highly functional organizations, organized into civil, structural, mechanical, electrical, communication and signaling, operations, maintenance, safety, and other departments. For example, the CHSRS design criteria manual (requirements document) is comprised of 35 different chapters, of which 33 represent design criteria (requirements) from different engineering disciplines.

Silo Engineering & Stovepiping: Conway stated in 1967 that "*organizations which design systems ... are constrained to produce designs which are copies of the communication structures of these organizations.*"). Following **Conway's law**, a functional organizational structure therefore results in designs that replicate the functional organization, for example a civil department creates civil designs, the structural department produces structural designs, and so on. Integration during design is limited and typically occurs in form of informal coordination, with a more formal cross-discipline review after completion of the design.

Design-Bid-Build (DBB) Delivery Method: For decades, DBB was the traditional U.S. project delivery method typically involves three sequential project phases: (1) the **design** phase, which required the services of a designer who will be the "designer of record" for the project; (2) the **bid** phase, where a (construction) contractor is selected; and (3) a **build** or construction phase, when the project is built by the selected (typically low bid) contractor. This sequence usually leads to a sealed bid, fixed-price contract. There are two separate contracts: (1) between the owner and designer, and (2) between the owner and the contractor/builder (Hoehne, Russell, 2018).

DBB Disadvantages: The functional organizations often created independent designs that were **not optimally integrated** before putting them out to bid, for example an electrical lighting design conflicted with a fire suppression (sprinkler) design that again conflicted with a mechanical heating, ventilation and air-conditioning (HVAC) design, all of which were to be installed in the same physical locations. Those conflicts were frequently not noticed before actual construction, requiring rework (re-designs), thereby resulting in schedule delays and costly **contractor claims** (cost overruns).

Design-Build (DB) Delivery Method: The industry eventually reacted with a **risk transfer**, requesting the (build) contractor to perform the (final) design activities. As (build) contractors were typically specialized in construction, the builders had to acquire design expertise, typically by hiring a designer or forming a joint venture in form of a DB entity (contractor). Owners would now focus on developing scope, results oriented ("performance") requirements and high-level conceptual (preliminary) designs, only. The key advantage – from an owner's perspective – is that design and construction integration are the full responsibility of the contractor, and that only one contract between the owner and DB entity is required. The DB project delivery method is advertised by the Design Build Institute of America (DBIA) as encouraging collaboration and innovation, and thereby saving time and money (DBIA, 2015).

DB Consequences: The DB project delivery method resulted in several fundamental changes that have a significant impact to systems integration:

- **Reluctance to be Specific**: With the risk transfer of the design to the contractor, owners are very cautious not to provide any detailed means and methods (how-to) in regards to required contractor activities – including systems integration – as this may be interpreted as the owner giving directions to the contractor, possibly resulting in **additional work order claims**.
- **Unknown Systems Integration Scope:** With the contractor performing the final design, an owner has limited knowledge of the final system design and resulting systems integration scope (i.e. the system architecture, system elements, and system interfaces) at the time of bid. Owners are therefore very hesitant to provide a list of specific interfaces in the contract, as any interface not provide in the list may be subject to **additional work claims**.
- **Innovative Design & Construction**: Fast, cheap, good – pick any two. With the intent of the DB delivery method to save time (fast) and money (cheap), the emerging design and construction solutions may be an unanticipated "innovation" by the contractor that was not desired by the owner, potentially requiring **additional change orders** to meet the owner's original needs and/or intent.
- **Owner Experience & Expertise**: One additional consequence of the DB project delivery method is the slow but steady loss of design and design integration experience and expertise on the owner side.

Industry Approach to Systems Integration: In summary, the preferred approach to systems integration in the U.S infrastructure and transportation industry from an owner's perspective is to "leave it to the contractor". Systems integration is typically described only in the form of contractor scope, without the identification of specific interfaces, interface requirements, or interface designs. The use of terminology varies, with interface management, integration management, and systems integration often used interchangeably.

Systems integration is commonly understood and practiced using "**coordination**" during design and construction by forming interface coordination teams that use interface coordination workshops to discuss open questions and/or resolve conflicts as they arise – a rather reactive instead of a proactive approach. Common contractor systems integration scope consequently requires the "contractor to carefully coordinate" all technical and managerial matters to achieve a "fully coordinated design and construction". Contractors are expected to manage all internal (i.e. design and construction) and external ("third party" stakeholder) interfaces, including utilities, agencies, regulators, sub-projects, railroads, adjacent geographical areas and contracts, etc. Coordination efforts include organizational coordination (e.g. communication between entities), managerial coordination (e.g. handover of milestone deliverables), and/or technical coordination (e.g. making spatial provision for future equipment provided by others).

Typical systems integration tools and deliverables include interface management plans (IMP), interface coordination teams (ICT), interface coordination workshops, interface control documents (ICD, documenting interface agreements), coordinated design drawings (e.g. combined services drawings [CSD], interface demarcation drawings), and interface status reports.

Description of the Challenges Faced

Using the background information provided above, this section provides an overview of the key systems integration challenges the CHSRS has faced, provided from an SoS perspective.

SoS Authority: While the CHSRS as a whole could be classified as an acknowledged SoS, the systems integration function has rather limited power and authority (see Figure 4). For example, the three active CHSRS civil works contracts (constituent systems) are overseen by the Authority infrastructure delivery branch, not the rail systems branch which is responsible for systems integration. The infrastructure branch then oversees the three design-build contractors, who are managed by independent project and construction managers (PCM).

SoS Architecture & Leadership: There is a lack of recognition and acknowledgment in the industry that the program manager becomes the de-facto SoS architect, as conceptually depicted in Figure 5. By decomposing a program into contract/procurement packages (projects), the program manager effectively creates large-scale constituent systems with numerous interfaces in between that require careful management throughout the life cycle as a precursor for successful system (program) integration at a later stage.

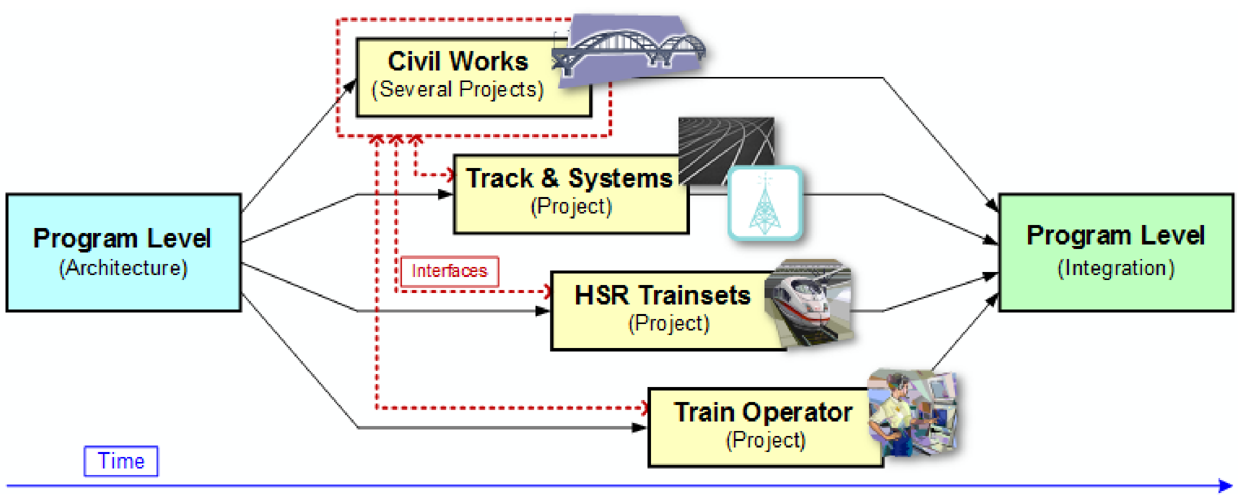

Figure 5. Program Manager as the SoS Architect

SoS Collaboration & Integration: While the traditional U.S infrastructure and transportation industry approach to systems integration may work in a single project/contract environment with all interfacing parties present and available for coordination, the same approach does not work in an SoS/program environment such as the CHSRS, if one or more of the interfacing projects/contracts are not available for coordination. For example, Figure 6 presents a typical CHSRS tunnel cross-section, highlighting several key interfaces between the civil works (tunnel) contract and the future track and systems, HSR trainset, and train operator contracts. As tunneling takes a long time, a tunnel contract would be issued years ahead of the follow-up contracts, creating a significant challenge in identifying the applicable interfaces, associated interface requirements, and interface implementation in the early civil works contracts.

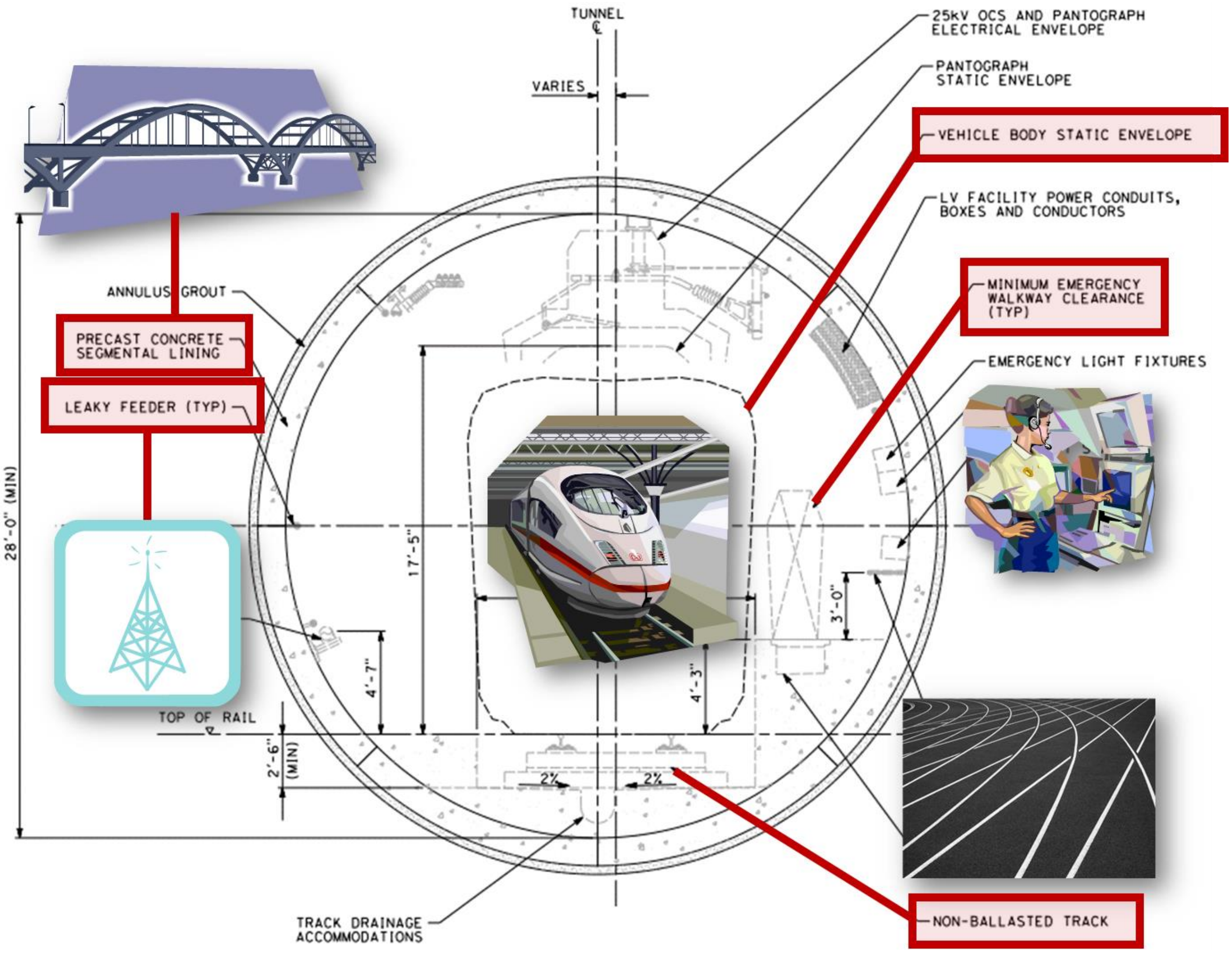

Figure 6. SoS Interface Requirements for Civil Works (Example: Tunnel)

The problem is exacerbated due to the fact that owners have become very reluctant to specify implementation (here interface) details out of concern of providing incomplete, incorrect and/or inconsistent information to the contractors, possibly resulting in contractor claims and change orders. Consequently, contracts often lack interface specifics such as well-defined list of interfaces and/or interface requirements. As contracts are commonly procured using fixed-scope and fixed-price contracts, there is also a significant risk that any interface requirements discovered during the project may be claimed as additional out-of-scope work.

SoS Autonomy & Emergence: As CHSRS contracts are individually procured, managed and operated, there are no contractual relationships between each other. By using the design-build project delivery method, contractors are deliberately encouraged to develop innovative solutions meeting the contract requirements. For example, the CHSRS conceptual design included an aerial structure (bridge) for a specific track/guideway area, and was later changed by the contractor during final design to an earthen embankment using retaining walls, with the intent to save construction costs. The same area, however, included a future wayside power supply station to be provided by the follow-up track and systems contractor. Changing the civil works design clearly impacted the interface with the track and systems contract (i.e. on how to run the power lines to the track/guideway area and how to provide maintenance access). The design-build method effectively encourages the prioritization of short-term gains in projects (constituent system) over longer-term program (SoS) benefits, thereby creating large scale SoS Emergence.

SoS Constituent Systems: The concept of interface coordination teams and workshops assumes that interface conflicts can be resolved applying an "interface management by talking about it" process. However, some of the CHSR systems involve far more complex data interfaces, for example the functional interface between the command & control location (track & systems contract) and the HSR trainsets, which may take years to develop and mature. Consequently, contractors prefer to offer their established standards as part of their proposal. By avoiding interface specificity in the contracts, contractors may provide (data) interface standards that are not compatible with each other, resulting again in rework, delays, and costly change orders to remediate.

International Best Practice Analysis of HSR System Integration

Prior to defining and tailoring the CHSRS SoS integration approach, the CHSRS program performed an international best practice review, analyzing existing in-service HSR systems and their approach to system integration. The most applicable and best documented approach was the one for Trans-European High-Speed Rail Systems, which is described on a high-level below.

The European Union wanted to move towards a single European railway system and establish an internal market for railway services and equipment. However, the railway system could not be fully competitive without the prior removal of technical and operational barriers to trade in trains and to their interoperability, defined as their ability to run on any interoperable segment of the European high-speed network. Significant differences remained between the networks in Europe (see Figure 7), most of which were built from a national perspective and which had long played on these differences to protect their own interests or those of their national railway industry (European Commission, 1996).

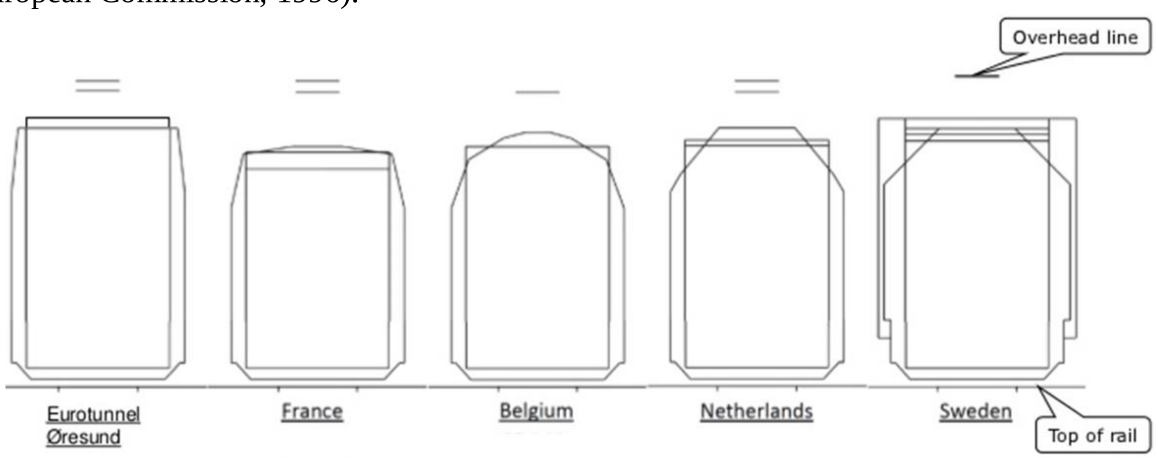

Figure 7. Different National Trainset Gauges (Maximum Trainset Size, Boysen, 2012)

Harmonization of technical and operational specifications for the trans-European rail system was vital for free movement of trains and related equipment in the European internal market, and the wider success of railways as a competitive, cost-effective, reliable and safe transport alternative. In 1996 the European Union therefore issued the council directive 96/48/EC and published the **technical specifications for interoperability (TSI)** with the objective of creating a regulatory framework of mandatory TSIs, and of voluntary or (where necessary) mandatory harmonized standards with the purpose of ensuring interoperability on the European high-speed network.

For the purposes of the directive, the high-speed rail system was divided into the following structural and operational HSR subsystems:

- **Structural subsystems**: (1) Infrastructure, (2) Energy, (3) Control- command and signaling, and (4) Rolling stock (trainsets);
- **Operational subsystems**: (1) Maintenance, (2) Environment, (3) Operations and (4) Users.

Each TSI subsystem followed the same document structure/outline and described the respective HSR subsystem, including the functional and technical specification of the interfaces. Figure 8 provides an example of an interface between the infrastructure (INF) and the rolling stock (RST) subsystems. The specific interface ensures that HSR trainsets can safely pass through tunnels, under bridges, and stay clear of any wayside structures. The interface is viewed from the infrastructure subsystem perspective (shown in red). Each subsystem provides the relevant interface requirements and implementation details (shown in blue). References are then made to an interoperable interface standard (shown in green). The same interoperability approach was applied to all types of interfaces, including data interfaces such functional train interface specifications between the command, control and signaling (CCS) TSI and Rolling Stock (RST) TSI.

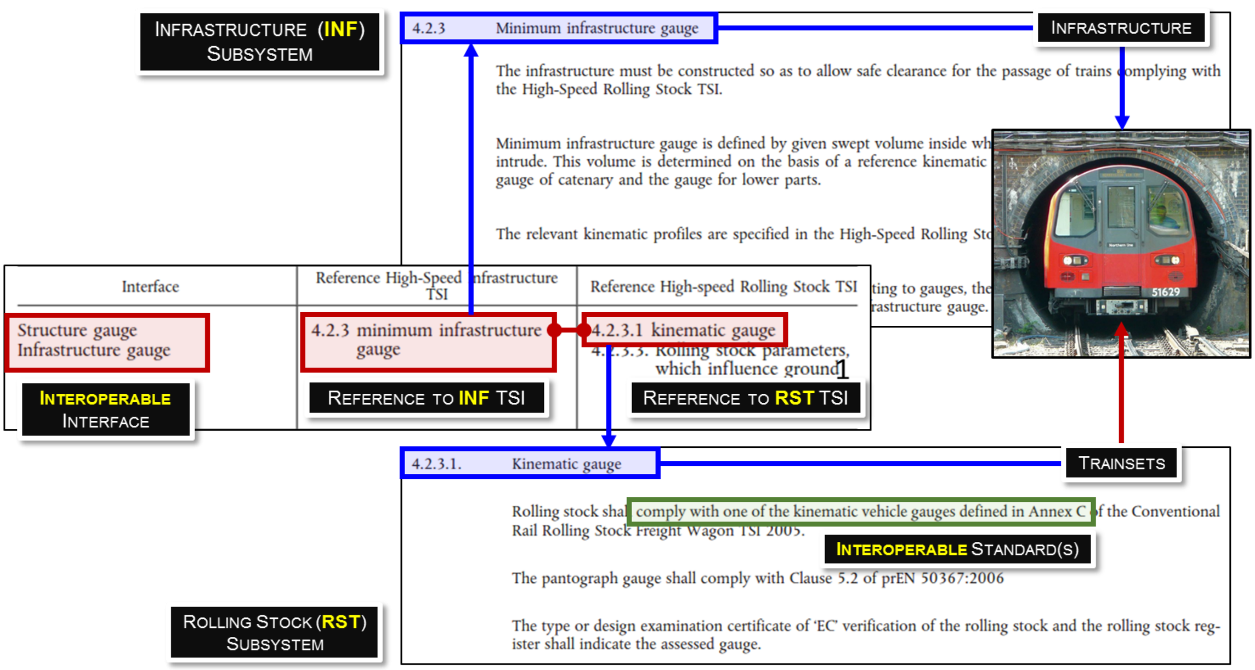

Figure 8. Technical Specifications for Interoperability (TSI) – Example Interface

Description of the CHSRS SoS Engineering Performed

Addressing the SoS Challenges: Following the international best practice review, the CHSRS systems integration function determined that the **interoperability** approach applied in the European Union would work quite well addressing the SoS integration challenges in the context of the CHSRS program for the following reasons:

- **SoS Authority**: Identifying and managing technical interfaces was well within the power and authority of the CHSRS systems integration team (see Figure 4),
- **SoS Architecture & Leadership**: The decomposition of the CHSRS program into CHSRS system elements (projects) was well understood and documented as the CHSRS procurement strategy in the CHSRS business plan (CHSRS, 2018),
- **SoS Collaboration & Integration**: Individual contracts (constituent systems) would become independent of (other) interfacing contracts as they could rely on interoperable interface standards,
- **SoS Autonomy & Emergence**: Individual contracts would be allowed to provide innovative solutions as long as they adhere to the interoperable interface standards, and
- **SoS Constituent Systems**: Defining interoperable interface standards would clearly communicate the interface requirements during procurement, avoiding incompatible project solutions.

SoS Architecture: Similar to the European HSR system, the CHSRS program was subdivided into subsystems (or contracts / procurement packages / projects / modules). Four different subsystems were identified: (1) Civil works, (2) Track & systems, (3) HSR trainsets, and (4) the Train operator, as presented in Figure 9. This enabled the CHSRS systems integration team to identify the key interfaces between the constituent systems of the CHSRS SoS.

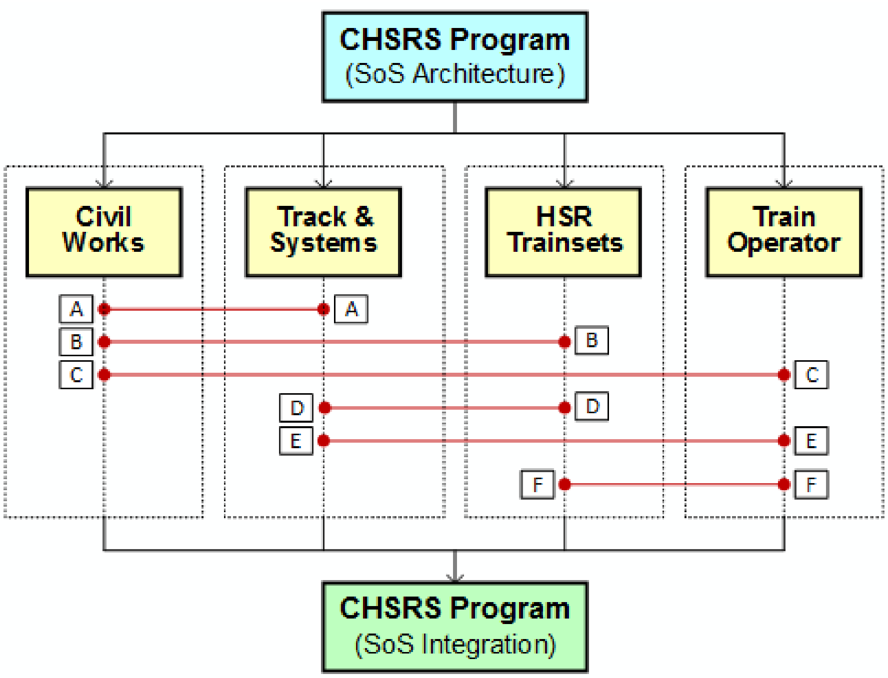

Figure 9. CHSRS (SoS) Subdivided into CHSRS Subsystems (CS)

Interoperable Constituent Systems: Figure 10 provides a high-level process overview for the development of interoperable constituent systems using the trainset gauge as an example. The process is described in further detail on the following pages:

- **Step 1:** SoS architect (systems integration team) identifies key interfaces,
- **Step 2:** HSR trainset subject matter expert (SME) identifies candidate HSR trainsets,
- **Step 3:** HSR trainset SME determines interoperable interface requirements,
- **Step 4:** Civil works SME develops corresponding interoperable interface design,
- **Step 5:** Civil works contractor implements interoperable civil works contract,
- **Step 6:** HSR trainset contractor implements interoperable HSR trainset contract,
- **Step 7:** SoS system integrator (track & systems contractor) integrates, tests, and commissions (taking into service) the interoperable contracts

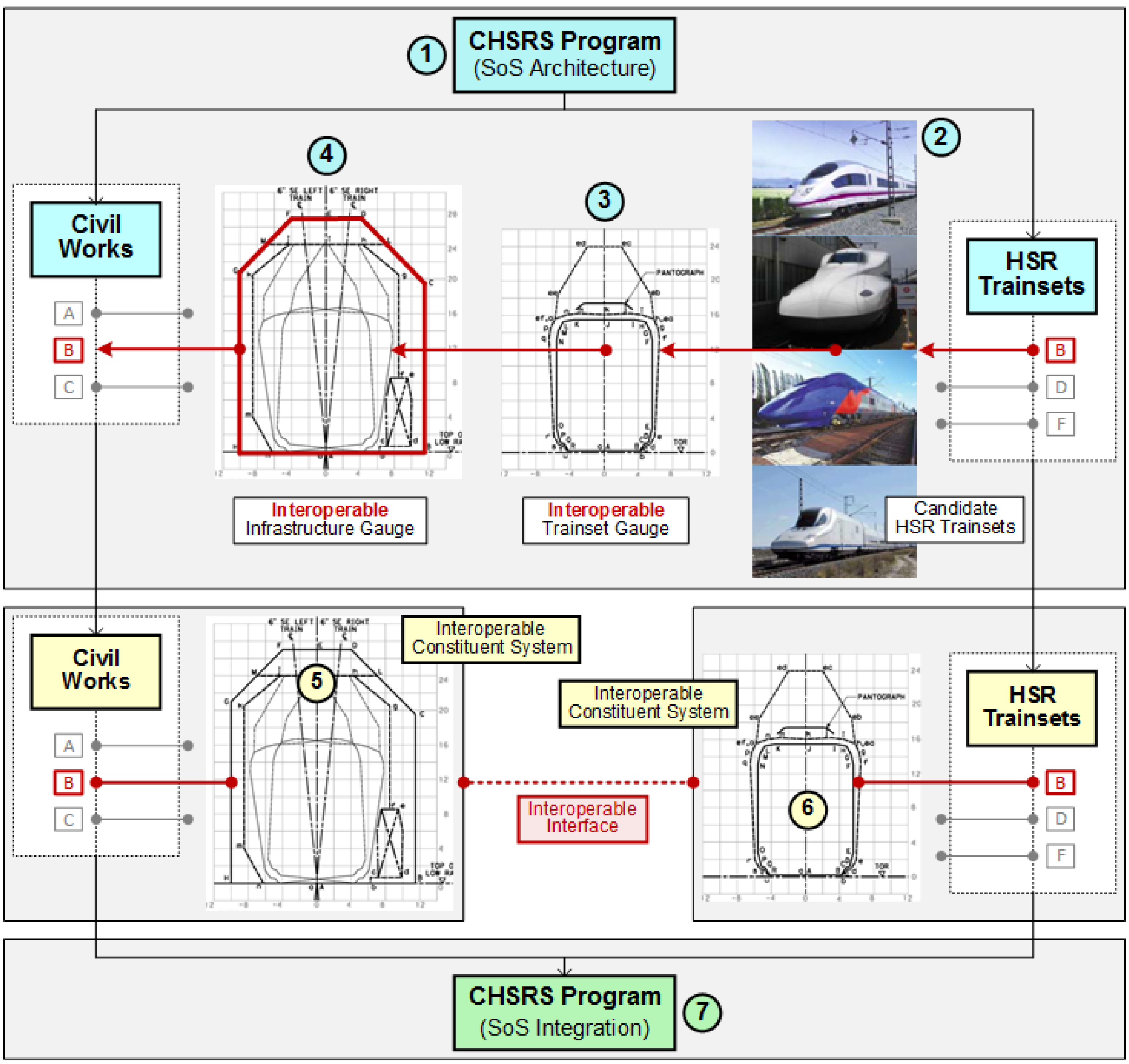

Figure 10. Creating Interoperable Constituent Systems

Step 1 - Identification of Key Interfaces: The CHSRS systems integration team analyzed the eight European HSR subsystem TSIs using an N^2 chart approach, and captured the identified interfaces in a **TSI interface register** (IF-REG) using a requirements management tool, as presented in Figure 11. For example, the **minimum infrastructure gauge** of the infrastructure TSI interfacing with the **kinematic gauge** of the rolling stock TSI (Figure 8) resulted in the **Interface between INF minimum infrastructure gauge and RST kinematic gauge** (Figure 11).

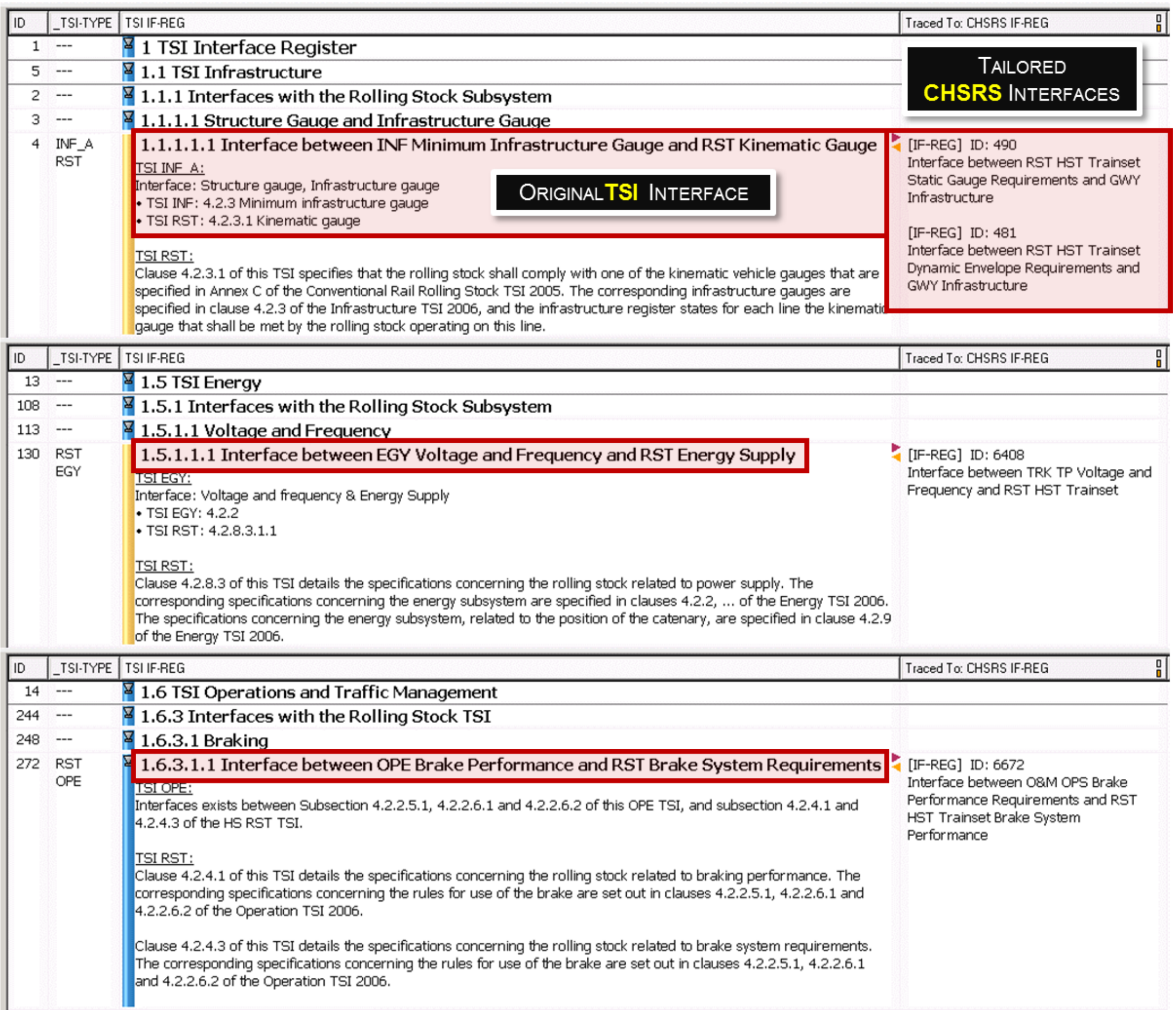

Figure 11. Identification of Key Interfaces

In total, 175 TSI interfaces were identified and evaluated for applicability in the CHSRS program. Figure 11 identifies two more interface examples between the energy (EGY) & rolling stock (RST), and operations (OPE) & RST subsystems. The interfaces were tailored to the specific needs of the CHSRS program, by applying the CHSRS terminology and partition interfaces as necessary (see first interface in Figure 11). For example, 49 TSI infrastructure interfaces resulted in over 100 CHSRS guideway (GWY) infrastructure interfaces. The CHSRS interfaces were then captured in their own CHSRS interface register, traced from the originating TSI IF-REG (Figure 11).

The CHSRS guideway can be presented in four main typical sections, including at-grade (embankments), aerial structures (bridges), trenches, and tunnels. Each typical section requires the integration of the four CHSRS subsystems identified in Figure 9 above. The CHSRS systems integration team developed integrated cross sections for each typical section as shown in Figure 12, applying the key CHSRS interfaces to improve visibility and recognition of these interfaces.

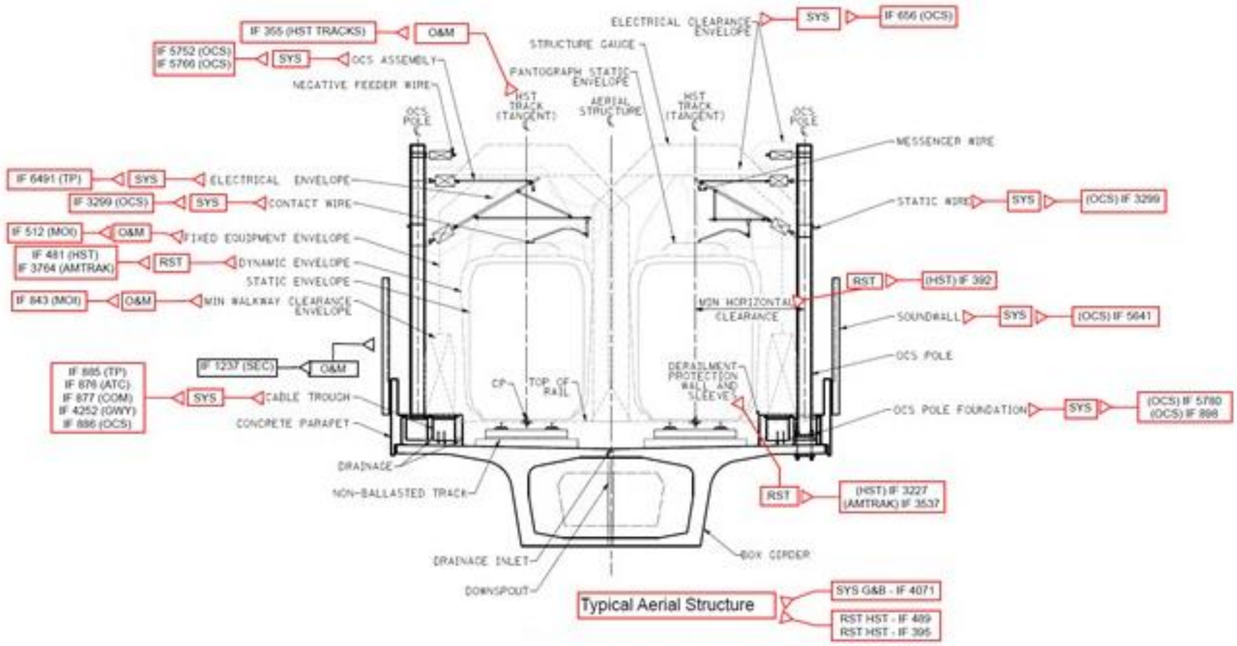

Figure 12. Key Interfaces applied to CHSRS Aerial Structures

Step 2 – Identify Candidate HSR Solutions: The HSR trainset subject matter experts performed a review of over 30 commercially available HSR trainsets that were operated in China, France, Germany, Italy, Korea, Japan, Russia, Spain, Taiwan, and the U.S. Four candidate trainsets were identified that met all the CHSRS requirements, three of which are presented in Figure 13.

Model		Builder	Year Built	AW0 [UST]	Produced	Consist	Seats	Country	Length (m)	Width [m]	Train Length [m]	Height [m]	Maximum Operating Speed [kph]	Weight [tonnes]
Velaro E (ICE 3)		Siemens	2004	467	26 Trainsets	MCC-TC-MC-2TC-MC-TC-MCC	404	Spain	25.67 CC 24.77 C	2.95	200	3.89	350	425/T
700N		Hitachi/Kawasaki/ Nippon Sharyo	2005~	769	97 Trainsets by 2011	TCC-14MC-TCC	1323	Japan	25 C 27.35 CC	3.36	430.6	3.6 or 3.5	300	40/C
AGV		Alstom	2008	270 to 510	1 Prototype	7C~14C	250~650	France	17.1 CC 17.3 C	2.9	130~250	/	360	270~510

Figure 13. Identify Candidate HSR Solutions (CHSRS, 2008)

Step 3&4 – Develop Interoperable Interface Standards: For the trainset and infrastructure gauge interface example, the candidate HSR trainsets were analyzed in detail, and consequently developed into interoperable HSR trainset and infrastructure gauges, as depicted in Figure 14. The resulting interoperable interface standards were then documented as design criteria (requirements) in both the civil works and HSR trainset procurement documents.

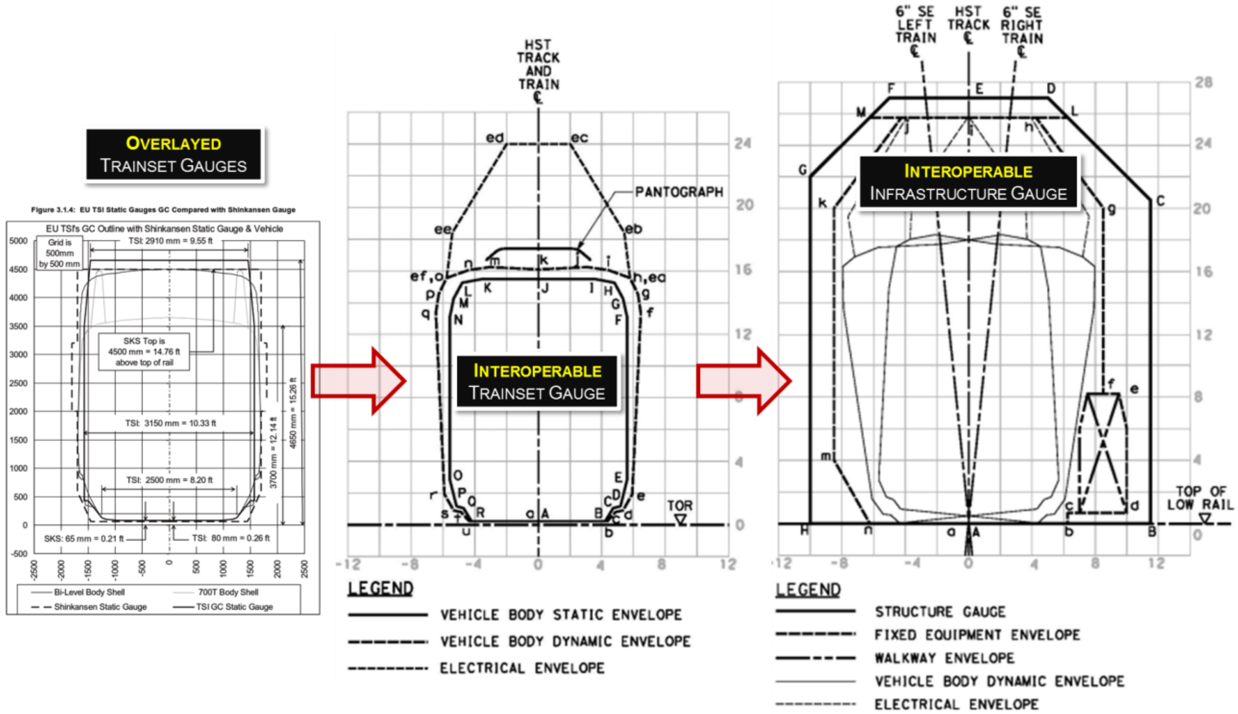

Figure 14. Develop Interoperable Interface Standards (CHSRS, 2010)

The list of applicable interoperable infrastructure (INF) interfaces (Figure 11) was then provided to the first three civil works contractors – together with the references to the associated interface requirements – as part of the procurement documents. Figure 15 presents the excerpted list of RST to INF interfaces, the equivalent of the interfaces labelled "B" in Figure 9 above.

Figure 15. List of Interoperable Interfaces – Excerpt (CHSRS, 2013)

Step 5 – Civil Works Contractors Implement Interoperable Interface Standards: The three active civil works contracts cover approximately 119 miles from north of Fresno, CA to north of Bakersfield, CA, and include the design and construction of over 100 structures, delivered in hundreds of design submittals. As the CHSRS program chose the design-build delivery method, contractors are performing the final design. Figure 16 shows an excerpt of the Fresno Trench "ready for construction" (RFC) submittal, and the Fresno Trench currently under construction.

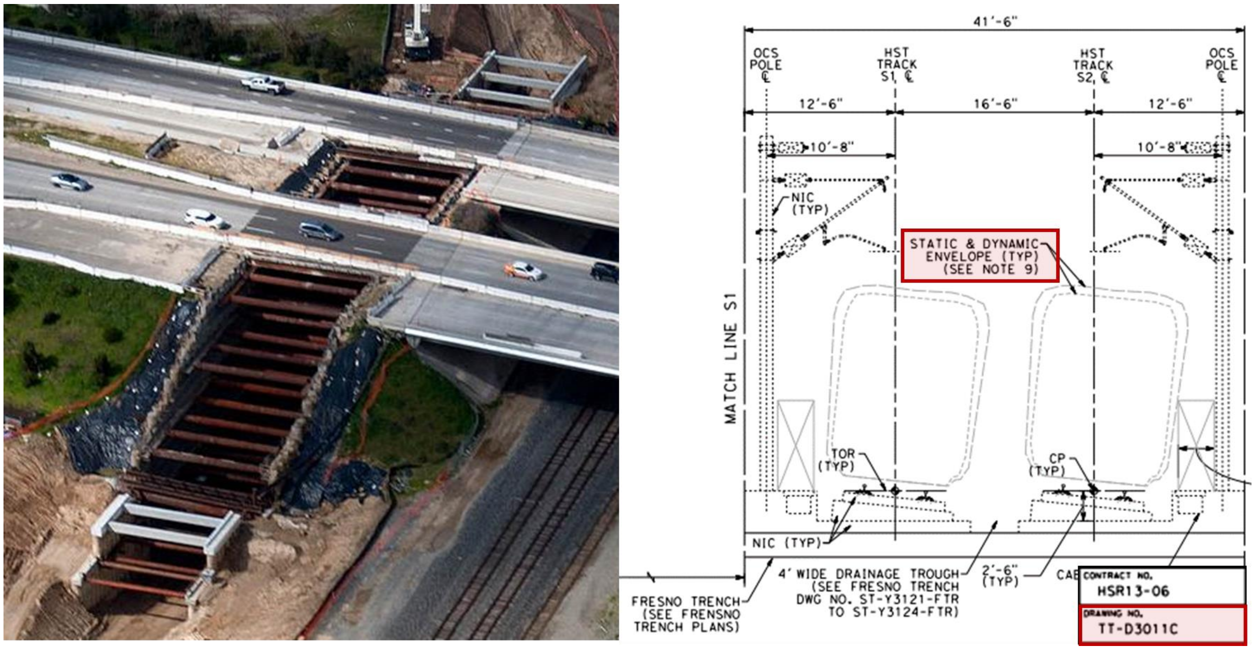

Figure 16. Implementing Interoperable Interface Standards – Fresno Trench

During final design, the contractor changed the preliminary design from a U-shaped trench to a separate bottom plate and independent trench walls, including the way the future overhead contact system (electric wires providing power to trains) would be attached to the infrastructure. However, the interoperability interface standards ensured that the infrastructure gauge was maintained, ensuring interoperability with future HSR trainsets. Contractors are required to demonstrate conformance to the imposed interoperability standard using requirements traceability, as presented in Figure 17 (interface # 481, see Figure 11, and reference to drawing number in Figure 16).

ID	DOC ID	CIL-Safety	Document Section	Requirements Text	Reference
71	Interoperability	CHSRIR329 (IF 481)	4 Rolling Stock 4.1 HST Trainset 4.1.1 Interfaces with Guideway (excl. trackwork) 4.1.1.2 Vehicle Static Gauge & Dynamic Envelope 4.1.1.2.2 Interface between RST HST Trainset Dynamic Envelope Requirements and GWY Infrastructure	Purpose/Scope: Ensures that the RST HST trainset dynamic envelope requirements have been addressed by the INF team. INTEROPERABLE INTERFACE	TT-D3001C DEMONSTRATION OF COMPLIANCE

Figure 17. Demonstrating Conformance to Interoperable Interface Standards – Fresno Trench

Step 6 – Track & Systems, HSR Trainset and Train Operator Implementation: The CHSRS program has not issued the track and systems, HSR trainset, or train operator contracts yet. However, the civil works – once completed – will conform to the interoperable interface standards imposed by future HSR contracts.

Civil Works contractors are required to prepare standalone certification packages in form of interface control documents (ICD) for each interface, including: (1) Contractor signed cover pages, (2) Traceability matrices for all applicable submittals [see Figure 17], and (3) Excerpts of the referenced material as attachments. The ICDs are then made available to future HSR contractors, demonstrating how the interoperable interface standards were implemented by prior contractors. Figure 18 presents the workflow for the example interface, starting with the candidate trainsets (Figure 10 & 13), the development of interoperable trainset and infrastructure gauges (Figure 14), the interoperable civil works implementation (Figure 16), the design and manufacturing of interoperable HSR trainsets, and finally the successful integration of the individual CHSRS projects into the CHSRS program.

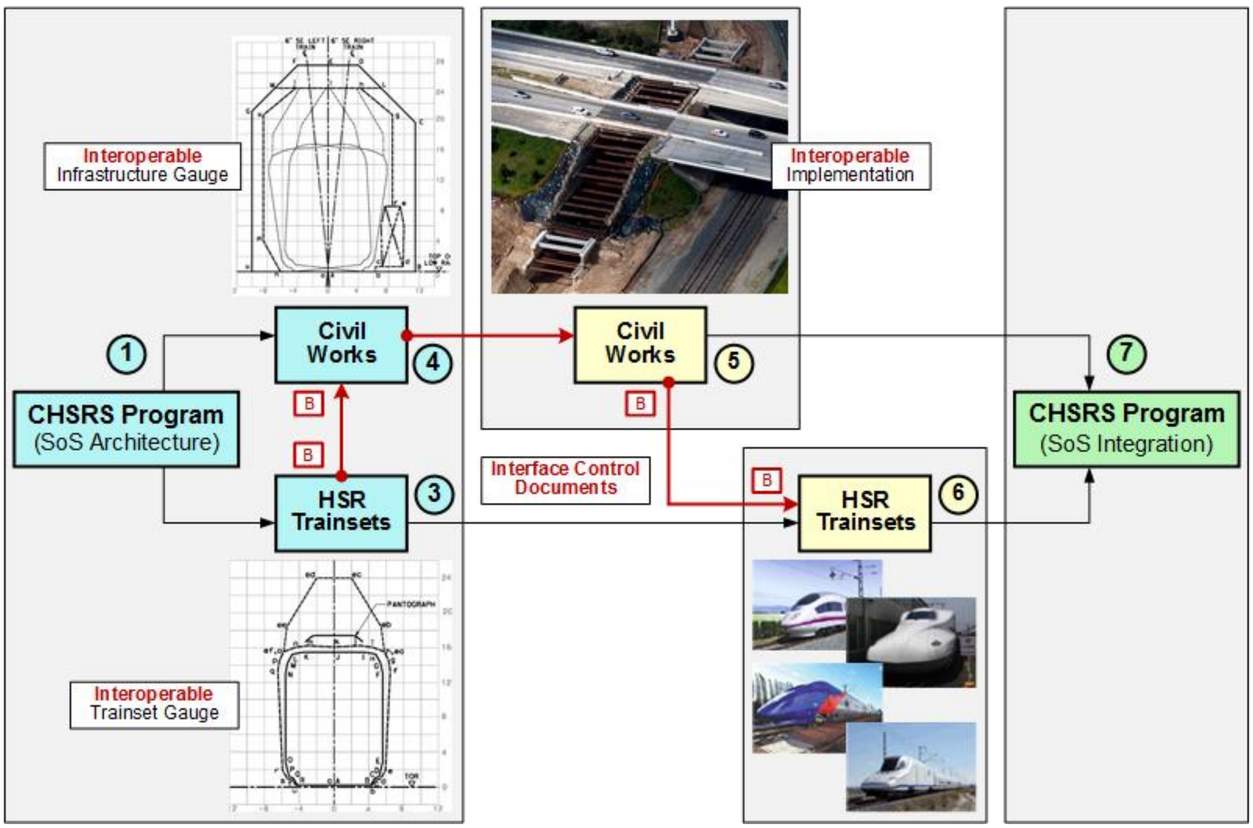

Figure 18. Handover of Interoperable Civil Works Implementation

Step 7 – SoS Integration: In large infrastructure programs, it is common that the last contractor is also assigned the role of the systems integrator. The same decision was made by the CHSRS program – the track and systems contractor will be responsible for integrating the four CHSRS subsystems, and for testing, commissioning, and certification of the CHSRS program. However, the CHSRS systems integration effort will be substantially easier due to the modular and interoperable nature of the four CHSRS subsystems.

Summary

This paper presented a case study demonstrating how systems integration can successfully be achieved in a large SoS – the California High-Speed Rail System – through the concept of interoperable interfaces and the development of modular and interoperable constituent systems – the CHSRS projects. The paper provided a brief introduction into system of systems, gave an overview of the California High-Speed Rail System, and presented the case why CHSRS as a program of projects can be considered a system of systems.

The paper described the traditional approach to systems integration in the U.S infrastructure and transportation industries, the prevailing design-build project delivery methods, and the preferred hands-off approach to systems integration using coordination. The description of the challenges faced discussed why the traditional systems integration approach does not work well in an SoS/program environment, especially if one or more of the interfacing projects/contracts are not available for interface coordination. The challenges were then discussed in the context of SoSE, specifically with regards to SoS authority, SoS architecture & leadership, SoS collaboration & integration, SoS emergence, and SoS constituent systems.

The paper presented an overview of the international best practices in HSR systems integration applied to the Trans-European HSR Rail System, an introduction into the concept and development of the technical specifications for interoperability (TSI), with the objective of creating a regulatory framework of mandatory TSIs, and of voluntary or (where necessary) mandatory harmonized standards with the purpose of ensuring interoperability on the European high-speed network.

Finally, the paper provided the description of the CHSRS SoS engineering performed, combining the SoSE principles, the traditional U.S industry systems integration approach, the prevailing project delivery methods, and the European interoperability concept into a tailored CHSRS systems integration process. The CHSRS system integration process was described as a seven (7) step process, using the specific trainset & infrastructure gauges as an interface example. The seven steps included SoS architecting, the review and analysis of candidate HSR solutions, the development of interoperable interface standards, the conforming implementation of interoperable projects, and eventually the successful integration of interoperable constituent systems into a SoS.

Outcomes

The CHSRS program has issued three civil works contracts since 2013. The contracts have largely completed the design phase and have advanced to the construction phase. The tailored CHSRS systems integration process has achieved results that would otherwise not have been obtained using the traditional systems integration process, including:

- **SoS Architecting:** Defined the CHSRS program as a SoS with four modular and interoperable constituent systems (Figure 9), with a clear understanding of the system integration scope based on the identified key interfaces (Figure 11 & 12).
- **SoS Collaboration:** Developed interoperable interface standards based on candidate HSR solutions (Figure 13) prior to issuing of HSR contracts. Incorporated interoperable

interface standards (Figure 14) into early civil works contracts, thereby creating interoperable constituent systems / contracts.

- **SoS Autonomy, Emergence & Constituent Systems:** Considered the prevailing design-build project delivery methods that encourages innovation within constituent systems (contracts), but may result in unanticipated and/or undesirable SoS emergent behavior. The clear communication of the interoperable interfaces (Figure 15) led to the compliant implementation of interoperable interface standards (Figure 16 & 17), despite numerous changes by contractors during design and construction.
- **SoS Integration:** CHSRS systems integration is anticipated to benefit significantly from interoperable interfaces and contracts (Figure 18), avoiding the late discovery of new interfaces and the non-compatibility of existing interfaces many programs suffer from when relying on the traditional systems integration approach.

Conclusion

As mentioned in the SoS introduction, identifying and addressing unanticipated and/or undesirable emergent behavior is a frequent challenge in the engineering of SoS.

In summary, the prevailing design-build project delivery methods encourages innovation (aka changes or emergent behavior) within a constituent system. As contracts are issued independently, there are no incentives to consider their roles in the SoS. Additionally, the traditional systems integration approach relies on coordinating active contracts once they have been issued, without the provision of specific interface definitions, leading potentially to late integration challenges.

In conclusion, it can be confidently stated that the tailored CHSRS systems integration process addresses the challenges described above. Key interfaces are proactively identified and specified using industry accepted interoperable standards. Contractors can take full advantage of delivering innovative solutions as long as they can demonstrate conformance to the identified interoperable interface standards. The tailored CHSRS systems integration approach creates modular and interoperable constituent systems that can be efficiently integrated into a SoS, successfully achieving system integration through interoperability.

Considerations for Future Work

Based on valuable peer review feedback, the following topics are being considered for future INCOSE papers and publications:

- **Lessons Learned:** As of today, only CHSRS Civil Works contracts have been issued. Lessons learned could be described once the follow-on CHSRS track and systems, HSR trainset, and train operating contracts have been released and are sufficiently advanced. The discussion could include a review of the effectiveness of the presented systems integration approach.
- **System Integration Framework**: Use this case study to define a System Integration Framework that other projects could follow. The use of agile processes as well as an

incremental integration and delivery approach may be included, potentially reducing risk and providing quicker delivery of benefits.

- **Suitability of new ISO SoS Engineering Standards**: Review the suitability of the new ISO standards for SoS Engineering, including ISO/IEC/IEEE 21839:2019 *Systems and Software Engineering – System of Systems (SoS) Considerations in Life Cycle Stages of a System*, and ISO/IEC/IEEE 21841:2019 *Systems and Software Engineering – Taxonomy of Systems of Systems*.
- **Integration between PMI and INCOSE**: Program of projects (PMI) and system of systems (INCOSE) offer similar if not equivalent views and methods. Insights and techniques for applying a new systems engineering and integrated management approach, including the overall impact on program management as applied in rail projects, and discussions on obtaining executive management support, could be explored.

References

Boysen, Hans E., 2012, 'Fran-Scan, Hi Cube Intermodal Corridor, Britain – France – Scandinavia', Department of Transport Science, Royal Institute of Technology, viewed 17 November 2019, < https://www.slideshare.net/hansboysen/session-34-hans-boysen>.

California High-Speed Rail Authority, 2013, 'Verification, Validation and Self-Certification', Agreement No.: HSR 13-06, Book 3, Part B, Subpart 1, Execution Version, Sacramento, CA (US).

California High-Speed Rail Authority, 2018, 'Program Management Plan', Revision 0, Chief Executive Office, Sacramento, CA (US).

California High-Speed Rail Authority, 2018, 'Business Plan', 2018 Revision, Sacramento, CA (US).

Dahmann, J., 2015, 'The State of Systems of Systems Engineering Knowledge Sources', SoS Working Group Webinar, October 2015, INCOSE, San Diego, CA (US).

Design Build Institute of America (DBIA), 2015, 'Choosing a Project Delivery Method: A Design-Build Done Right Primer.', April 2015, Design Build Institute of America

European Commission, 1996, The Trans-European High-Speed Rail System, Guide for the application of the high-speed TSIs of Council Directive 96/48/EC, 2003 Edition, European Union, Brussels, Belgium.

Harris, G., 2010, 'Technical Memorandum, High-Speed Equipment Structure Gauges, TM 1.1.10', Version 0, California High-Speed Rail Authority, Sacramento, CA (US).

Haskins, C., ed. 2015, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, Version 4.0, Revised by R. Douglas Hamlin, M. Krueger and D. Walden, San Diego, US-CA: INCOSE.

Hoehne, O., Russell, J., 2018. 'San Diego, We Do NOT Have a Problem! – SE Leadership in the Construction Industry', INCOSE International Symposium, 2018, Washington, DC (US)

ISO/IEC/IEEE 15288-2015, 2015, 'Systems and software engineering – System life cycle processes', ISO/IEC/IEEE International Standard.

Silien, J., 2008, "Technical Memorandum, Selected Train Technologies, TM 6.1", Version 0, California High-Speed Rail Authority, Sacramento, CA (US).

WSP, 2019, 'California High-Speed Rail', What We Do – Projects, viewed 17 November 2019, <https://www.wsp.com/en-GL/projects/california-high-speed-rail>.

Biography

Oliver Hoehne is a Technical Fellow, Systems Engineering, a Project Manager, and the U.S. Global Technical Excellence Sector and Practice Lead on Systems Engineering, Communications and Control Systems for WSP, a company with 30,000+ employees, in 500 offices across 39 countries. Mr. Hoehne is a Project Management (PMP) and Systems Engineering Professional (CSEP) with over 20 years of extensive international and domestic experience in Software and Systems Engineering across industries, and has worked in leading Systems Engineering, Integration & Testing (SEIT) roles on several multi-billion-dollar programs.