

Railway cyber-security in the era of interconnected systems: a survey

Simone Soderi¹, *Senior Member, IEEE*, Daniele Masti¹, Yuriy Zacchia Lun², *Member, IEEE*,

Abstract—Technological advances in the telecommunications industry have brought significant advantages in the management and performance of communication networks. The railway industry, where signaling systems are now fully computerized, is among the ones that have benefited the most. These interconnected systems, however, have a wide area exposed to cyberattacks. This survey examines the cybersecurity aspects of railway signaling systems by considering the standards, guidelines, and frameworks most widely used in the industry. We dedicate specific attention to communication networks since data communication systems are essential to signaling architectures. To this end, we explore using dedicated cyber ranges as an enabling technology to model attacks to computer networks, emulate attack-defense scenarios, study vulnerabilities impact in general, and finally devise countermeasures to them.

I. INTRODUCTION

Railways have been one of the main commodities to move passengers and freight since at least the late 19th century. Nevertheless, operators have faced mounting pressure in recent years to meet ever-increasing performance and safety demands from the public [1]. On top of such targets, the awareness of cybersecurity themes has also changed. Securing railway systems from cyber attacks has become a central issue for practitioners and the public, especially after recent news stories such as [2].

The cause for this abrupt need for answers is simple: while, in the past, railway systems often depended on specifically purposed electromechanical devices that operated in an air-gapped environment, newer infrastructures are often based on commercial-off-the-shelf (COTS) systems that operate in a fully networked setting. This means that such new installations offer both a much larger attack surface and that attacks can be carried out with shallower knowledge than before. This problem is amplified by the reliance on shared infrastructures for the operations of multiple subsystems (e.g., both VOIP and signaling might use the same network infrastructure to carry information), making the possibility of *lateral movements* extremely relevant. This possibility is problematic because railway companies may operate (through the same shared infrastructure) information and communication technology (ICT) services, which have also been hit by various attacks [3].

Simone Soderi and Daniele Masti are with Scuola IMT Alti Studi Lucca, Piazza San Francesco 19, 55100 Lucca, Italy. email: {simone.soderi,daniele.masti}@imtlucca.it. Yuriy Zacchia Lun is with Università degli Studi dell’Aquila, Via Vetoio, Coppito, 67100, L’Aquila, Italy. email:yuriy.zacchialun@univaq.it

This scenario is not unique to the railway sector: many public infrastructures have become victims of cyber attacks in recent years. Nevertheless, it is a highly problematic situation, as a successful attack on railway systems can result in the loss of safety guarantee of the network [4]. For these reasons, the rail transportation sector can no longer consider cybersecurity, physical protection, and safety as separate issues, developing effective methods for verifying and hardening rail systems is of great practical and theoretical importance.

To address this issue, in 2008, the “European Programme for Critical Infrastructure Protection” (EP-CIP) [5] was established to improve security of *critical infrastructures*, which are defined as all those systems considered essential to maintaining the vital functions of society. Recently [6], debates restarted to update this Directive to deal with the present threat landscape, championing an approach focused on the resilience of the overall integrated infrastructures rather than on protecting the individual assets and for the inclusion of a much broader landscape of systems, including the transportation industry and the railway sector.

In this survey, we investigate how the industry has responded to such a challenge by:

- collecting the standards governing the many safety-critical subsystems that make up a complete railway network;
- performing a comprehensive analysis of the cyberattacks carried out in recent years on railways systems;
- investigating the cybersecurity projects involving railway signaling systems
- proposing an approach based on the use of *cyber ranges* to emulate and verify the security of networking systems similar those used in the railway industry.

The paper is organized as follows: in Section II, we recall the main components of a railway system; in Section III, we introduce the facet of security in the railway sector; in Section IV we discuss in depth the security of signaling systems. How cyber ranges can be valuable for security assessments is reported in Section V. In Section VI we finally draw some final remarks and discuss further developments.

II. RAILWAYS AS AN INTEGRATED SYSTEM

In a broad sense, railways can be defined as a collection of different systems whose purpose is to transfer passengers and goods on wheeled vehicles running on

rails located on tracks. Such sub-systems can be broadly collected into three families:

- **Railway infrastructure**, comprises all the tracks (sometimes referred to as the *permanent way*), all the civil works, and the systems and premises that ensure the regular traffic flow. In literature, this latter component is often further divided to distinguish between the *wayside systems* (namely: level crossing, electrification facilities, and signaling machines) that operate along the lines and the so-called “facilities and premises,” which encompass stations, depots, and other similar facilities.
- **Rolling stocks** comprise powered vehicles (locomotives, single rail cars, shunters, etc.), engineering vehicles, and trailer vehicles.
- **Railway operations** encompass the technical duties performed to ensure trains circulate and the commercial operations that railway companies perform to ensure revenue [1].

Please note that most tasks carried out in a railway company involve all those three subsystems simultaneously. This suggests that “holistic” approaches that favor securing the system as a whole (see, for instance, [7]) should be preferred to approaches that focus on securing a single component of the system without caring for its overall capability to accomplish its many tasks.

A. The dualism between safety and security

Railways and other transportation systems are classified as safety-critical since their failure may result in loss of human life or disaster of another sort. The design of this kind of system has traditionally followed a “safety above all” paradigm, meaning that, to be considered safe to be used, each component of such system (and the system as a whole) must achieve a minimum Safety Integrity Level (SIL) [8], [9]. To achieve a given SIL, specific design rules and test procedures must be implemented, guaranteeing that the system continues to fulfill its safety requirements in case of random failure. It is worth underlining that any system responsible for critical functions needs to be safety certified, and if it controls vital applications, a fail-safe behavior must be implemented. However, the safety standards used as references for railway infrastructure design do not consider cybersecurity but only mention that the implementer should design a cybersecurity mechanism for use with the standard [10], [11], [12].

For example, the IEC 61508 [9], which can be considered the general standard for achieving the safety of electronic and electrical devices, does not cover security issues [12]. Another railway-related example is the standard used to design communication between safety-related equipment, namely the CENELEC EN 50159 [13]. While such a standard addresses the topics such as message authenticity, integrity, etc., it does not cover general cybersecurity issues such as preventing

overloading transmission systems or ensuring the confidentiality of safety-related information. Both standards only mention that intentional malicious human actions must be considered, proposing the ISA/IEC 62443 [14] standard, which considers four degrees of a safety hazard and four levels of security.

A similar landscape can be found concerning the technical norms governing control platforms doors and wayside control systems. For the former, the primary reference is the GB 50157-2003 [15], which again does not tackle security issues [12]. For the latter, relying on IEC 62264 [16] is common. Although such a standard has several enterprise-control system facets, security issues are again not in scope.

B. Security landscape in the railway industry

This lack of cybersecurity awareness in such often legally-binding standards is a severe issue for the railway sector. Many solutions have been envisioned to address it but, before listing them, it is meaningful to analyze the unique requirements of railway systems compared to ICT systems and classical industrial control systems (ICS).

As already mentioned, technological evolution has led to increasingly important computerization of control systems, including those used in railways. Nowadays, railway projects heavily rely on ICS to control electromechanical systems and automate industrial processes and operations in various applications. The main components of such ICSs include programmable logic controllers (PLCs), data communication systems (DCSs), and supervisory control and data acquisition (SCADA).

The communication between such components is achieved through a transportation network managed via a central operation control center (OCC), where many operational tasks are merged. At the present time, there is no consensus about how to design such control centers [12], and many different OCC configurations have been designed following possibly incompatible standards. Among them, the APTA RT-OP-S-005-03 [17] is among the most used ones, yet it considers only physical security and provides no guidelines for cybersecurity.

Securing ICS systems poses different challenges than securing pure ICT systems. Consider, for instance, the Confidentiality, Integrity, and Availability (CIA) triad, a well-known model that defines the security requirements to support organizations in specifying the core security objectives of their systems [18]. As shown in Figure 1, while ICT security focuses on confidentiality to prevent stealing private information, ICSs are more concerned with data integrity and avoiding unplanned system outages that can disrupt production availability and profitability. Moreover, compared to classical ICSs, the transportation sector poses even more importance to the concept of resilience [19] since the availability of each subsystem has a paramount priority.

In light of recent news events (we report a few confirmed events in Appendix II), such a situation in recent

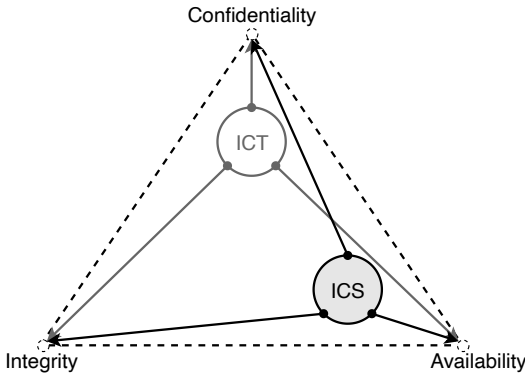


Fig. 1. The different meanings of the CIA triad in ICT and ICSs.

years, there has been a substantial call for technical norms that deal with the issue of cybersecurity in the railway industry.

C. A deeper look on signaling systems

Signaling comprises all the machinery necessary to ensure safe movements of rolling stocks on railway infrastructure [20] and is part of the so-called wayside systems. In such a family, we can also include many other critical components of railway systems, such as the electrification systems (which hardening is deeply interlaced with the security of the electrical grid as a whole [21], [22]) and level crossings.

As a whole, signaling systems are comprised of a few main components tasked to:

- check the clearance of track sections using either track circuits or axle counters;
- lock movable track elements such as switches and crossings in a proper position;
- prevent conflicting train movements through the action of an interlocking (IXL) system. Railway IXL systems are those systems that are responsible for granting a train exclusive access to a *route* which is a sequence of track elements exclusively assigned for train movement through a station or a junction [23];
- controlling railway vehicles to keep them safely apart and within speed limits through Automatic Train Control (ATC) systems.

ATC systems can be further divided into three subsystems: Automatic Train Protection (ATP), Automatic Train Supervision (ATS), and Automatic Train Operation (ATO) [24]. ATP is a vital subsystem continuously ensuring compliance with the maximum safe speed and minimum safe distance limits. ATS often acts upon the signals generated by the IXL system to monitor and adjust the performance of individual trains to ensure smooth railway service. The ATO subsystem performs those functions otherwise assigned to the train operator and meets all operating conditions and limits set by the ATC, following the requirements of the railway system to ensure passenger comfort by establishing policies for safe operations [23]. All modern railway signaling systems,

such as the “European train control system” (ETCS) and “Communications-based train control” (CBTC), include ATP functions [24].

Speaking about ETCS, such a system is used as the signaling and control component of the European rail traffic management system (ERTMS), which is the *de facto* global standard [25] in the high speed and main-line railway market segment (please refer to Appendix I for an overview of railway market). ERTMS has been designed with the hope of being an almost universal solution to traffic management. In order to achieve so, the European Union Agency for Railways (ERA) specified several ERTMS/ETCS levels for the wayside equipment to address different operating needs [20].

Speaking about the CBTC, this system [26] was designed mainly for the metro market [27], and it is employed for signaling and controlling platforms. Nevertheless, it has found applications also in non-urban railway systems. CBTC provides a *continuous* ATP and offers flexible grades of automation (GoA) that goes from merely helping human engineers (at the GoA1 level) up to a fully unattended train operation (at GoA4), in which automatic pilot and automatic on-board monitoring systems are employed [1]. Two international standards provide the general requirements for CBTC systems, IEEE 1474.1-2004 [24] and IEC 62290 [28]. Unfortunately, they fundamentally differ in terminology and structure, meaning that it is not automatic for a product to meet both standards [27].

D. Communication systems for wayside system

The functioning of modern signaling systems is primarily based on (possibly discontinuous) wireless communication between wayside equipment and railway vehicles. Many solutions exist to achieve such a communication channel. Among them, the leading standards [29] are the “Global System for Mobile communications – Railway” (GSM-R) [30], [31] and “Terrestrial Trunked Radio” (TETRA) [32], [33]. We also cite the novel “Future Railway Mobile Communication System” (FRMCS) [34]. TETRA, for instance, is used for data and voice communication, allowing group calls and the walkie-talkie mode [32], possibly involving multiple users at each time thanks to dedicated IP-based dispatchers [35]. At Level 1, ERTMS/ETCS relies on *intermittent* ATP architecture that relies on controlled transponders (balises¹ or loops) in the track, which gets their information from a traditional signaling system via a line-side electronic unit (LEU). At ERTMS/ETCS Level 2 and 3, the ETCS works as a *continuous* ATP system with bidirectional vehicle-to-infrastructure (V2I) communication (either through the GSM-R or FRMCS radio). Interestingly, thanks to the strong push on commonality, all ETCS levels use the same onboard equipment. In

¹Eurobalise Transmission System is a safe spot transmission based system conveying safety related information between the wayside infrastructure and the train and vice-versa [36]



Fig. 2. Main railway signaling and communication systems in railway market segments of interest (in gray)

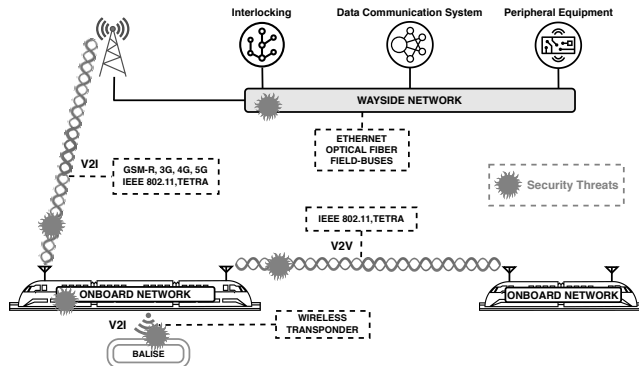


Fig. 3. Security threats in a railway signaling system. They affect the DCS directly through the wired wayside network (in gray) and indirectly via vehicles’ on-board network and wireless V2I and V2V communications. Dashed boxes next to each means of communication list possible technological solutions. Cybercriminals can attack these systems through the same interfaces the IXL uses to monitor and manipulate objects.

ERTMS, a railway cab can receive the train control information from transponders (so-called balises), short loop antennas (a.k.a. loops), or digital radio (mainly GSM-R). We also cite the “Next generation of train control” (NGTC) [37] study²: in this project, ETCS and CBTC have been analyzed to establish possible commonalities between the two systems.

Interconnected computers control all these systems, expanding the attack surface towards the railway systems. Later in this paper, we introduce the most significant projects that investigated the security of the railway systems. Figure 3 shows the schematic representation of a railway system. In there each component and each V2I, V2V and spot communication channel can be subject to security threats. Indeed, wireless communication offers new possibilities for support and new services, it also increases complexity during development as it exposes a broader attack surface. This picture is useful to see how securing a single subsystem without regard for its placement in an general scheme may not achieve desirable overall security characteristics.

Figure 4 shows a common railway wayside scenario where the IXL drives other systems through a computer communication network. Figure 2 summarizes the most common application scenarios of CBTC systems and ETCS.

III. TOWARD SECURITY REQUIREMENTS FOR RAILWAY SYSTEMS

The first step in mitigating risks is to identify risk scenarios. The result of this analysis, in turn, is used to compute the *unmitigated* risk and mitigate it. In other words, the first step of this pipeline is to perform a *security assessment* of the existing systems to identify weaknesses in the system [38].

There are different types of security assessment. A way to classify them is to distinguish by whom they are performed [39]. When an organization’s internal teams perform the evaluation, we speak about Cybersecurity Assessment (CSA). Its main goal is to understand the sources of threats, threat events, and possible vulnerabilities on different levels. It ranges from the security policies to infrastructure security spanning, e.g., network, hardware, cyber-physical systems (CPSs), and physical layer security. To do so, the cybersecurity assessors rely on standards and their experience to gauge the strength and effectiveness of the company’s security posture. When external experts conduct the analysis, the focus is to assess and measure the compliance of an organization’s systems and processes against specific policies, standards, and criteria in the cybersecurity field. In such a case, we call this analysis a *security audit* (SA).

In both cases, cybersecurity risk assessments (CRA) are integral to any security assessment. CRAs categorize cyber risks by their likelihood and impact, and detail findings and potential controls to communicate to management. The security assessment process, as a whole, will produce a report directed to the company’s management that will include the evaluation results and final recommendations to improve the security of the test environment [39].

It is important to note that such kinds of audits are often very intrusive. Consider, for instance, performing a vulnerability assessment: this task aims to identify, categorize, and evaluate asset vulnerabilities. Since vulnerability scans may involve intrusive automated scans or penetration tests, they may heavily impact their target by creating considerable traffic load, abnormal interactions, and alerts in system and security management tools. For this reason, the security assessors must carefully plan and communicate scanning activities to all parties affected by a possible service outage. This reasoning is even more actual for penetration tests: this technical methodology extends vulnerability assessment with sanctioned attempts to exploit the discovered vulnerabilities to show their potential real-world impact.

It is then easy to see that security assessments of any

²Sometimes referred also as “EU Project 605402”

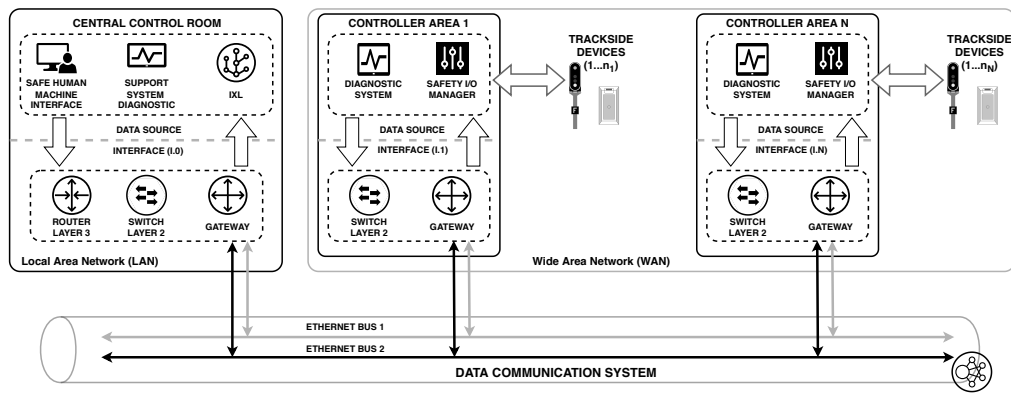


Fig. 4. Wayside network scenario. The central control room connects the safe HMI with support system diagnostic and interlocking in LAN and controller areas via WAN. Each LAN comprises networking devices such as gateways, routers, and switches. The control areas link trackside devices to their safety input/output manager and diagnostic system.

kind must be seen as a project themselves: clear goals and scope must be established in the planning of the assessment itself, and constraints must be taken into account.

To facilitate this process, Section V will show that it is often convenient to perform the tests required within a virtual perimeter (named *cyber range* in the rest of the article) that provides isolation from production devices. The *cyber ranges* allow the execution of the tests foreseen by the security analysis by quickly replicating the scenarios of interest.

A. Standards for Cybersecurity assessments

Currently, procedures for security assessment of railway systems are mostly framed within the ISA/IEC 62443 standard [14], which is the global standard for network security of industrial control systems (ICSs). Such a document guides ICS operators through a pipeline that establishes all the requirements, controls, and best practices necessary for securing industrial networks.

Other generally applicable norms and frameworks regarding cybersecurity are:

- the “Common Criteria for Information Technology Security Evaluation” (CC), also known as ISO/IEC 15408 [40]. This standard introduces security specifications, implementation, and evaluation procedures tailored for the designated use environment;
- the ISO/IEC 27001 [41] standard, which specifies requirements for establishing, implementing, and maintaining information security management systems;
- the Cybersecurity Framework (CSF) [42]. CSF consists of standards, guidelines, and best practices related to cybersecurity risk management. It also provides a common language for communicating cybersecurity expectations and awareness within and across organizations.

All those standards and frameworks, however, are rather generic and not tailored to the needs of railway systems. To address this issue, the European Networks

and Information Systems Agency (ENISA) has established a series of specific security requirements and measures for the operators of essential services (OES) that can be recast in the frameworks mentioned above [43].

Besides, the issue of safety certification still stands: since no standard guidelines to certify the safety of security modules exist, certifying products, including such modules, is far from trivial. Unfortunately, as we have already mentioned, safety certifications are a must for the railway industry. To address this issue, some Authors [12] suggested that manufacturers should physically separate the security modules from the safety modules. This approach, however, would hardly be optimal as it would leave security as a side objective for the overall system.

The novel CENELEC TS 50701 “Railway Applications – Cybersecurity” [38] is possibly the first attempt to solve such an integration issue. This technical specification is based on ISA/IEC 62443 and provides a tailored solution for the railway industry, including rolling stock, signaling, and infrastructure. CENELEC will assess this document in three years and possibly transform it into a standard [44].

B. Guidelines and other comprehensive studies

Players like the UK Department for Transport, the International Union of Railways (UIC), etc., have produced various guidelines to enhance the security of railway systems [45], [46], [47]. Bloomfield *et al.* [48] also provided a high-level cyber security risk assessment procedure for generic ERTMS-based railway infrastructures and ETCS onboard systems. Several projects have also tried to address the rail sector cybersecurity challenges under the Shift2Rail [49] initiative, a European public-private joint undertaking for rail research. In particular, the two most significant ones have been:

- 4SECURail [50], a project that addresses the call for formal methods in the railway environment and supports implementing a “Computer Security Incident Response Team” (CSIRT) for railways;
- CYRail, which has produced various guidelines to enhance the security of railway systems [51].

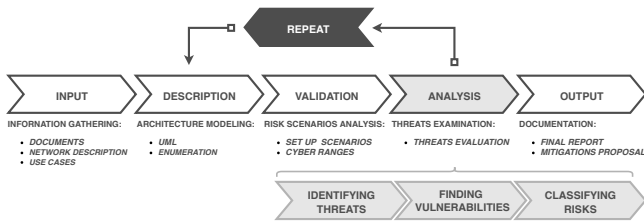


Fig. 5. General cybersecurity assessment process. The core stage and its main steps have a gray background.

Within the Shift2Rail umbrella, projects that consider cybersecurity topics within a broader context have also been proposed. Examples are X2Rail-1 [52], Roll2Rail [53], and Safe4RAIL [54]. Roll2Rail, for instance, studied the impact, likelihood, and risk evaluation for specific train control and monitoring component, i.e., the external door control system [55]

For a comprehensive review of other projects regarding these issues, we refer the interested reader to [49].

In addition to that, we must mention:

- the NIST Special Publications Series 800, and in particular the NIST SP 800-53 [56], includes the NIST CSF security controls, while the NIST SP 800-82 [57] deals with ICSs security controls often used for security in railway;
- the Open Source Security Testing Methodology Manual (OSSTMM) [58], which is the de facto standard for vulnerability assessment thanks to an auditing methodology aimed to satisfy regulatory and industry requirements.

IV. RAILWAY SIGNALING NETWORKS CYBERSECURITY ASSESSMENT

In this subsection we show how a security analysis can possibly be carried out. In particular, we take as a test case the network security analysis of a wayside system,³ like the one shown in Figure 4. This procedure can be seen as a summarization of the rules in the standards/guidelines mentioned in Section III-A. An overall scheme of the procedure is shown in Figure 5.

The first step in the procedure is the so-called *information gathering* phase. At this stage, one collects information regarding the system under concern, such as requirements, assumptions on technologies, network characteristics, etc. These data will be used to extract a list of all network components and all interfaces that allow communication between them. Such analysis is the main object of the *architecture modeling* phase.

With such a scheme at hand, one proceeds with *risk scenarios analysis*. Depending on the use case, this will involve auditing network device configurations; inspecting the policies already in place and real traffic, and identifying protocol weaknesses, etc. The analysis of security requirements also takes place at this stage.

³The scheme we present can also extend to onboard networks.

Using the risk scenario analysis output, one can further proceed with the *threat examination* phase. At this stage, the auditor tries to identify the *threats* that might affect the network under test, namely all those circumstances that might disclose, manipulate, or destroy information together with all those events that might result in a loss of the network availability. This stage, in turn, comprises performing three steps (highlighted in gray at the bottom of Figure 5), namely:

- *identifying threats* in software, protocols, and architecture is preliminary for determining the associated risks in the last step;
- *finding vulnerabilities* in software, protocols, and architecture;
- *identifying the associated risk* that derives from the threat event's likelihood and the impact it might have on the network.

Such states are highlighted in gray at the bottom of Figure 5. It is helpful to note that referring to the Common Vulnerabilities and Exposures (CVE) [59] list, such as the one overseen by MITRE Corporation.

The cybersecurity assessment ends with a *report* with the primary objective of providing the proper network security awareness.

It is important to remark that, despite being based on the current literature, the procedure we presented in this section is *novel* as no specific standard nor scientific consensus has been established to perform this task.

It is also worth mentioning that the threat examination stage resembles the hazard analysis involving hazard identification and related risk analysis and evaluation in the safety assessment process (see [60] and the references therein). However, as described in Section II-A, the safety and security analyses differ in their focus.

V. CYBER RANGES AS ASSESSMENT TOOLS

Studying many security threats related to the network domain is challenging to reproduce in the laboratory and highly disruptive to analyze on live systems. Virtualization technologies and digital twins provide a valuable alternative in this case as they enable the creation of virtual scenarios that can be scaled and maintained remotely. With the term *Cyber ranges*, we indicate all those interactive platforms that allow one to create possibly fully virtual representations (called *scenarios*) of the existing network infrastructure and emulate its operations. Scenarios can represent a particular system setup, specifying active elements, applicable rules, and selected interconnections so that the operators can carry out the testing in an isolated environment [61]. In addition, the cyber ranges are invaluable tools for training purposes [62], [63]: events such as the Cyber-Challenge.IT [64] become possible thanks to such tools.

Cyber ranges can also be used as tools to replicate the communication network used for railway signaling. To do so, one of the critical challenges to overcome is obtaining highly detailed knowledge from the system owners about

their systems. Almost ironically, the first benefit one gets when building such virtual scenarios is thus not technological since it forces both owner/operator and security assessors to detail the internal functioning of the original system [65].

A. The landscape of cyber ranges

Many solutions have been proposed to create cyber ranges, depending on the complexity, typology, and purpose of use. To better assess the technological landscape, an idea is to distinguish between cyber ranges based on *simulation-based* architectures from those based on *emulation-based* architectures. The difference is that a simulation environment mimics the essential characteristics of the physical system but neglects low-level implementation details⁴. Instead, an emulation environment reproduces most physical system peculiarities on a virtual platform. Cyber ranges based on actual physical systems also exist.

When all the scenario components in a theater adopt virtualization solutions to emulate physical devices, some authors classify them as *virtual*. *Physical* theaters provide a replica of the target infrastructure in an isolated and secure environment. *Hybrid* cyber ranges adopt solutions relying on a combination of hardware, virtualized, and simulated elements. An example of a hybrid cyber range is PAIDEUSIS [63], a theater offering integration between a virtual environment and physical machinery such as ICS, IoT, and network hardware devices.

B. The machinery behind cyber ranges

The development and execution of experiments in cyber ranges are labor-intensive and error-prone operations, thus making automation a highly desirable feature [66], [67]. General-purpose configuration management automation tools [68], such as Ansible [69], and Chef [70], Puppet [71], provide the means for systematically configuring certain types of components individually or in bulk, so it is no surprise that they have found also use in *theater automation frameworks* [72]. Specifically:

- Alpaca [73] and EZSetup [74] rely on Ansible;
- KYPO [75] uses Ansible and Puppet;
- Security Scenario Generator (SecGen) [76] employs only Puppet, and EDURange [77] adopts Terraform [67];
- Alfons [78], ADLES [79], CRATE [66], and CyRIS [80] propose customized special-purpose automation engines.

Finally, frameworks based on domain-specific languages such as virtual scenario description language (VSDL) [81], [67] have also been developed and allow for the complete definition, verification, and deployment of cyber range scenarios in an automated fashion under

⁴such details, however, are often crucial for a thorough network security analysis.



Fig. 6. Data flow in cyber range configuration.

the cloud computing paradigm. The theater automation frameworks above mentioned, however, are often limited to unique existing cyber range facilities (like StarBED [82] in the case of Alfons) or do not provide a complete set of network-related functionalities (traditionally offered by dedicated network emulation tools [83]). This fact makes them unsuitable for running virtualized networking scenarios.

Luckily, network-centered cyber ranges also exist. Table I presents a comparison between well-known network emulators, including Cisco Modeling Labs (CML) [84], Common Open Research Emulator (CORE) [85], Emulated Virtual Environment - Next Generation (EVE-NG) [86], Graphical Network Simulator 3 (GNS3) [87], and Mininet [88]. All these emulators provide means for connecting external nodes, but only CML, EVE-NG, and GNS3 support device operating system virtualization. They, however, differ in performance and implementation methods. In particular, GNS3 can be considerably slower than EVE-NG, CORE and Mininet, although relatively easy to use, do not support the emulation of the operating system of the nodes in the network. This functionality is, however, essential for a thorough network security assessment. CML is geared toward Cisco products, and although it has been given the possibility to emulate devices from manufacturers, it is quite an expensive product.

1) *Integration with the cloud*: In the case cloud networking assessment is also required, it is possible to integrate a network emulator with a cloud platform such as OpenStack and software-defined networking (SDN) controller like OpenDaylight, as illustrated with the case of the OpenStackEmu testbed [89]. We remark that SDN has become the main concept for defining network infrastructure in recent years. The paradigm behind SDNs separates that network control logic (i.e., control plane) from the actual data flow (i.e., data plane) [90]. With the SDN, one can abstract much of the hardware details. However, in an industrial scenario, or when the network must interface with ICS and SCADA systems, using virtualization in such an extreme way is unsuitable for interfacing with CPSs [63].

C. The role of cyber ranges for network security

As already introduced, one of the cyber range key applications is to enable security testing of complex systems of which computer networks are part. Cyber ranges allow one to investigate, for instance, the behavior of malware on various networked computers or an attack at L2 of a computer network. This section considers the role of cyber ranges in network security assessment.

TABLE I
NETWORK EMULATORS.

	CORE [85]	Mininet [88]	EVE-NG [86]	GNS3 [87]	CML [84]
Network configuration	Python, Labs	Python, CLI	API, Labs	API, Labs	API, Labs
Network emulation level	L3, (L1/L2 EMANE)	L2	L2	L2	L2
Connection to external nodes	Yes	Yes	Yes	Yes	Yes
Nodes operating system emulation	No	No	Yes	Yes	Yes
Licensing	BSD	BSD	GPL, Commercial	GPL	Commercial

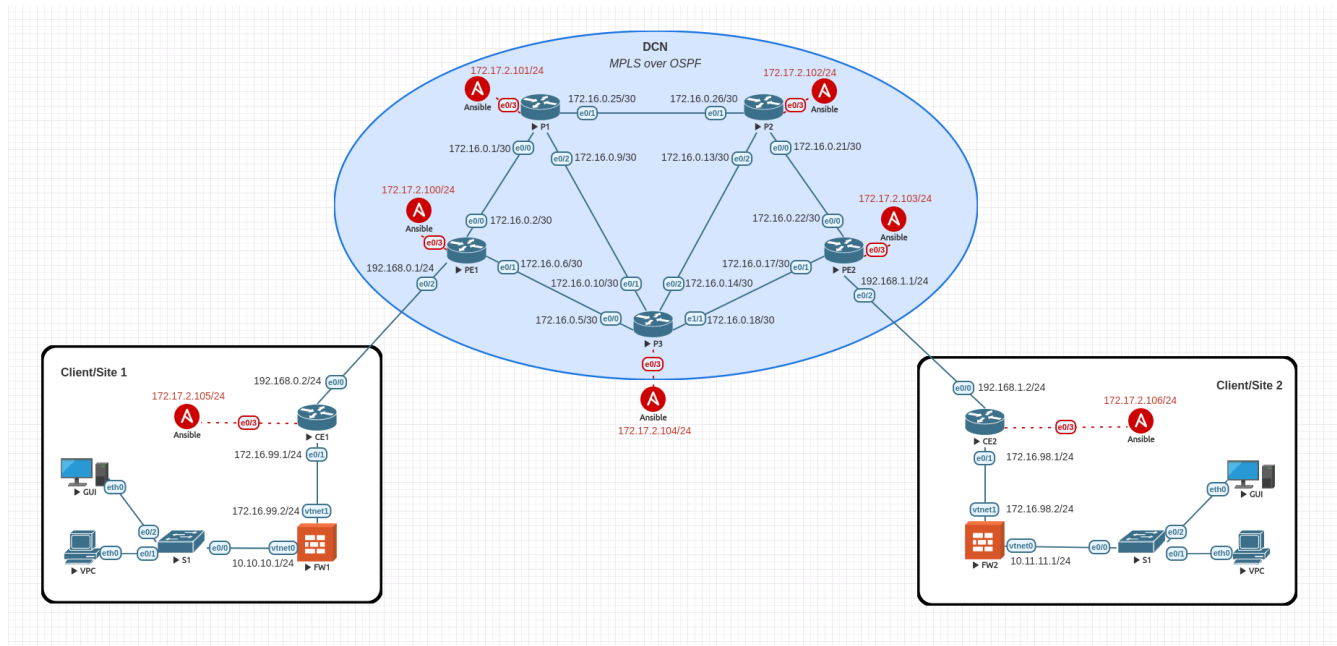


Fig. 7. Example of using cyber-range to emulate an MPLS IP network.

Indeed, with these tools, we can automatically define test scenarios to evaluate network security issues.

Cyber ranges naturally fit in the workflow presented in Figure 5. Following the procedure we proposed, one can proceed by enumerating the system components and modeling them in a “cyber range-friendly way,” i.e., in a way configuration management and orchestration tool language, e.g., YAML in the case of Ansible, can immediately process. If done right, this allows one to automatically create a cyber range scenario and analyze the system vulnerabilities in such a controlled scenario in a non-disruptive way. For example, security threats may reside in the network architecture, device configurations, operating systems, and communication protocols. So, we can study and test different combinations of cyber threats affecting the system with various cyber range scenarios.

Conforming to a reconnaissance strategy (please refer to Appendix III for details), the workflow for using a cyber range to evaluate network security is shown in Figure 6 and considers the following steps:

- 1) emulate the network (or a part of it) using the actual configurations and operating systems of the

involved devices;

- 2) research the vulnerabilities through automatic tools and scripts created for the specific case;
- 3) enumerate the vulnerabilities and measure their impact on the system under test.

Once one has found a vulnerability with the cyber range, the security analyst can proceed in developing a countermeasure and give evidence of it. This process will result in new scenarios that do not contain the vulnerability anymore. We document this threat analysis step in the mitigation proposal. The procedure can be repeated until the analysis has covered all the network segments.

Cyber ranges can also be used to model attacks on computer networks [91] to emulate attack-defense scenarios [92]. This capability allows organizations to understand potential network weaknesses and train cyber security response teams to respond to attacks [93] by different kind of attackers. Indeed, using cyber ranges, one can make several assumptions about the attacker (internal or external to the network?), its capabilities (is it a one-person job or state-sponsored action?), etc.

D. Building cyber ranges: an applicative example

As a practical example of the proposed procedure, in this Section, we show how EVE-NG can be used to investigate an imaginary IP/MPLS backbone like the one shown in Figure 7. This kind of network is a realistic representation of what a railway operator may use to interconnect equipment in different stations. This scenario has been inspired by [94], [95].

There, we can recognize a core network⁵ (the central part composed of provider devices) whose task is to interconnect various Local Area Networks (LAN) into private networks. In each LAN, we can recognize a customer edge router connected both to the core and to a firewall. This latter device guards the traffic flowing into each local area.

The configuration of each device is managed via Ansible, meaning that different configurations for each device can be very easily modified and applied to stress different aspects of the network and to discover vulnerabilities better and assess their impact. We can quickly run security tests in a cyber range by creating and executing different scenarios. For example, we can verify using Ansible that the configurations applied to each device is defined in the initial design of the communication network or we can test whether an attacker can implement attacks such as BGP/OSPF poisoning or OSPF link flapping. It is clear that through a cyber range we can automate a good part of the security analysis process.

We remark that in this shown scenario, the devices are not emulated but virtualized. Although this may cause more difficulties for the first setup, it also means that each component indeed behaves like the real one and is not a mere reproduction whose functioning may differ from the one of the original equipment.

VI. FUTURE CHALLENGES AND CONCLUSION

In this survey, we reviewed the current landscape for security issues of railway signaling. To do so, we first analyzed how trackside and onboard systems communicate in various application scenarios, discussing the overall architecture of such systems, and noting how they strongly rely on complex communication networks. The continuous evolution of attacks on such systems has spawned interest in new tools and methodologies for cybersecurity rapid risk assessment for safety-critical infrastructure. To this end, we reviewed the existing rail and cybersecurity standards and guidelines that can be applied to rail signaling scenarios and proposed a cybersecurity assessment procedure for communication networks used for railway systems. We also analyzed how cyber ranges can be used as an enabling technology to create virtual scenarios in which each vulnerability can be tested and its impact/risk assessed. As a result, our assessment procedure can help improve the cybersecurity

⁵A proper tractation of MPLS networks is outside the scope of this document. We refer the interested reader to [96] for further readings on the topic.

posture of railway systems by understanding and mitigating cyber threats and vulnerabilities. Our solution is, however, not final. At the present time, the most pressing open challenge is how to integrate such tools with digital twins (i.e., a digital replica that implements the same behavior as the physical system). This would allow for an unprecedented level of fidelity and allow studying safety and security aspects of the systems under concern simultaneously. An open question here is how to address the computational requirements of high-fidelity simulation environments. Indeed, as the final goal would be to emulate a railway signaling system in its entirety, it is easy to see how the required computational resources might be beyond the current state-of-the-art capability.

Another challenge is definitely on the cultural level: how can we train tomorrow's technicians? Gamification has been used in cybersecurity for many years as an analysis tool in virtual environments such as cyber ranges. It will undoubtedly be interesting to see and study what solutions can be adopted to train railroad companies' personnel in a cyber range with capture-the-flag type exercises.

APPENDIX I

AN OVERVIEW OF RAILWAY MARKET

In order to better understand the scenarios that a company may have to face when assessing the security profile of a railway system, it is helpful to introduce the way railway systems are often classified based on the intended task they are meant to achieve. The first distinction to be made is between passenger and freight rail services. Among the former, we can further distinguish based on the distance traveled and the kind of territory served (e.g., urban, inter-regional, etc.) Railway networks are often organized around mainline rails that serve as a route between major urban centers and to which branches, yards, sidings, and spurs are connected. Mainline is used to provide both High-Speed Rail⁶ (HSR) services and conventional speed rail services. *Regional traffic* may or may not share the infrastructure with mainline traffic [99] and provides conventional medium/short-based services. Finally, there is an urban/sub-urban segment that may share the tracks with ordinary road traffic and is often separated from the mainline rail traffic. Examples of such traffic are metros, tramways, and light rails.

APPENDIX II

INCIDENTS AND THEIR MODELING

In this appendix, we provide in Table II a non-exhaustive list of significant confirmed cybersecurity incidents that have affected transportation operations or have endangered or had the potential to compromise transportation safety. Please note that we do not list the cyber events that resulted exclusively in data theft and leakage. We can note that while the earliest incidents

⁶An HSR service is defined as a service that achieves a speed [97] of at least 200 km/h, regardless of the distance covered [98].

TABLE II

TIMELINE OF CYBERSECURITY INCIDENTS IN THE RAILWAY SECTOR WITH THEIR DESCRIPTION.

Date	Description
August 2003	A computer virus disabled the CSX Transportation headquarters in Florida, affecting signaling in thousands of km of railway line. [100].
January 2008	A teenager derailed four tram vehicles causing injuries to twelve people after hacking a train network of Lodz, Poland [2].
December 2012	A cyberattack on a Northwestern US rail company's computers disrupted railway signals for two days [101].
March 2015	The HoneyTrain Project recorded 2.745.267 logins attempts with four successful illegal accesses to the human-machine interface (HMI) of a virtual train control system in the space of six weeks [102], [103].
February 2016	BlackEnergy and KillDisk malware infected the systems of a prominent Ukrainian rail company. In December 2015 the Ukraine power grid cyberattack was also attacked using the same malwares [104].
July 2016	A study reported that the UK Network Rail had been hit by at least four significant cyberattacks over 12 months, including intrusion in rail infrastructure itself. According to such a study, these attacks seemed to be exploratory [105].
November 2016	A ransomware attack took ticket machines of the San Francisco light rail transit system (SF Muni) offline for a day, There was no impact on transit service, the safety systems, or customers' personal information [106], [107].
May 2017	Deutsche Bahn, suffered a ransomware attack on its data systems [108]. The same computer virus also hit the national railway systems in Russia [109] and China [110].
October 2017	Sweden's transportation Administration was targeted by a DDoS attack on the IT systems that monitor railway traffic. Two DDoS attacks hit the public transportation operator Västtrafik the next day [111].
May 2018	The Danish operator DSB came under a DDoS attack, making it impossible to purchase tickets. Internal mail and telephone systems used by the DSB staff were also affected [112].
March 2019	An Israeli cyber threat intelligence company identified an actor operating on a top-tier dark web forum selling access to an administrative panel of a Chinese rail control system [113].
October 2020	A ransomware attack hit the Société de transport de Montréal (STM) compromising 624 operationally sensitive servers. The outage also affected STM for over a week [114], [115].
December 2020	A ransomware attack hit OmniTRAX. It was the first publicly disclosed case of a so-called double-exhortation ransomware attack against a US freight rail operator [116].
December 2020	The Egregor ransomware attack hit TransLink, forcing the company to shut down several IT services including part of payment systems [117]. No transit safety systems were affected, but the IT problems impacted GPS functions on buses [118] and information regarding personal banking social insurance information may have been compromised [119].
July 2021	A cyberattack on Iran's railroad system caused chaos across the whole country [120].
October 2021	The Toronto Transit Commission (TTC) became a victim of a ransomware attack, losing access to systems used to communicate with vehicle operators, online booking, etc. [121]. Subsequently, the TTC announced that personal information of (former) employees, may have been stolen [122].

could have directly afflicted transportation operations and safety, the most recent attacks involving ransomware have not impacted railway safety systems but significantly disturbed the transportation services.

Many authors have proposed approaches to analyze such cyber attacks formally. We cite here attack graphs [123], trees [124], [125], vectors [126], surfaces [127], over and above diamond model [128], OWASP threat model [129], [130], and the so-called "kill chain" approach. See, e.g., [131] for an overview of some of these models and [132], [133] for applications of attack-fault trees to analyze some cybersecurity-related incidents in the rail industry.

APPENDIX III

THE KILL CHAIN APPROACH

According to the kill chain approach to modeling threats [134], cyber *reconnaissance* is the first step an attacker performs when trying to breach a system. There are two types of reconnaissance: passive and active. Passive reconnaissance is when the attacker gathers information about a target without direct interaction. Active reconnaissance is when an attacker directly interfaces with a target system to gather specific details later helpful in delivering a malicious payload. We refer the reader

to [133], [134], [135] for a more detailed presentation of this topic and how kill chains can be used to analyze cybersecurity-related incidents in the rail industry.

ACKNOWLEDGMENTS

The authors would like to thank Maurice H. ter Beek and Rocco De Nicola for their insightful comments.

REFERENCES

- [1] C. N. Pyrgidis, *Railway transportation systems: design, construction and operation*. CRC press, 2016.
- [2] J. Leyden, "Polish teen derails tram after hacking train network," *The Register*, Jan. 11 2008. https://www.theregister.com/2008/01/11/tram_hack/.
- [3] H. Jo, G. Kim, J. Baek, K. Lee, D. Shin, Y. Shin, and J. Lee, "A study on the on-board centered train control system through ICT convergence," in *International Conference on Control, Automation and Systems (ICCAS)*, pp. 1206–1210, Oct. 2012.
- [4] D. Milligan, "Securing a railway control system," in *International Conference on System Safety and Cyber Security*, pp. 1–6, IET, Oct. 2014.
- [5] Council of the EU, "Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection," *Official Journal of the European Union (OJ) - Legislation series (L)*, vol. 51, no. 345, pp. 75–82, 2008.

- [6] E. Commission, “Proposal for a directive of the European parliament and of the council on the resilience of critical entities,” (*COM (2020) 829 final*), 2020.
- [7] A. Thaduri, M. Aljumaili, R. Kour, and R. Karim, “Cybersecurity for eMaintenance in railway infrastructure: risks and consequences,” *International Journal of System Assurance Engineering and Management*, vol. 10, no. 2, pp. 149–159, 2019.
- [8] CENELEC EN 50126, “Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS),” standard, European Committee for Electrotechnical Standardization, 2018.
- [9] IEC 61508, “Functional safety of electrical/electronic/programmable electronic safety-related systems,” standard, International Electrotechnical Commission, Apr. 2010.
- [10] K. Hansen, “Security attack analysis of safety systems,” in *Emerging Technologies & Factory Automation (ETFA)*, pp. 1–4, IEEE, 2009.
- [11] J. Grønbaek, T. K. Madsen, and H. P. Schwefel, “Safe wireless communication solution for driver machine interface for train control systems,” in *International Conference on Systems (ICONS)*, pp. 208–213, IEEE, Apr. 2008.
- [12] L. J. Valdivia, I. Adin, S. Arrizabalaga, J. Añorga, and J. Mendizabal, “Cybersecurity – the forgotten issue in railways: security can be woven into safety designs,” *IEEE Vehicular Technology Magazine*, vol. 13, no. 1, pp. 48–55, 2018.
- [13] CENELEC EN 50129, “EN 50129 -Railway applications - Communication, signalling and processing systems - Safety related electronic systems for signalling,” standard, European Committee for Electrotechnical Standardization, Nov. 2018.
- [14] ISA/IEC 62443, “Security for Industrial Automation and Control Systems,” series of standards, International Society of Automation & International Electrotechnical Commission, Jul. 2009.
- [15] GB 50157-2003, “Code for Design of Subway,” national standard, Ministry of Construction, People’s Republic of China, May 2003.
- [16] IEC 62264, “Enterprise-control system integration,” standard, International Electrotechnical Commission, May 2013.
- [17] APTA RT-OP-S-005-03, “Operations Control Centers,” standard, American Public Transportation Association, Jul. 2018. 3rd revision.
- [18] R. J. Anderson, *Security engineering: a guide to building dependable distributed systems*. John Wiley & Sons, 2nd ed., 2008.
- [19] C. Lévy-Bencheon and E. Darra, “Cyber security and resilience of intelligent public transport: good practices and recommendations,” tech. rep., European Union Agency for Cybersecurity (ENISA), Attiki, Greece, Dec. 2015.
- [20] J. Pachel, *Railway Signalling Principles*. Braunschweig, 2.0 ed., October 2021.
- [21] Y. Zacchia Lun, A. D’Innocenzo, F. Smarra, I. Malavolta, and M. D. Di Benedetto, “State of the art of cyber-physical systems security: An automatic control perspective,” *Journal of Systems and Software*, vol. 149, pp. 174–216, 2019.
- [22] S. M. M. Gazafurdi, A. T. Langerudy, E. F. Fuchs, and K. Al-Haddad, “Power quality issues in railway electrification: A comprehensive perspective,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 5, pp. 3081–3090, 2014.
- [23] A. Fantechi, “Connected or autonomous trains?,” in *3rd International Conference on Reliability, Safety, and Security of Railway Systems: Modelling, Analysis, Verification, and Certification (RSSRail)*, (Cham), pp. 3–19, Springer, 2019.
- [24] IEEE 1474.1, “IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements,” standard, The Institute of Electrical and Electronics Engineers, Feb. 2005.
- [25] M. Ghazel, “A control scheme for automatic level crossings under the ERTMS/ETCS level 2/3 operation,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 10, pp. 2667–2680, 2017.
- [26] R. D. Pascoe and T. N. Eichorn, “What is communication-based train control?,” *IEEE Vehicular Technology Magazine*, vol. 4, no. 4, pp. 16–21, 2009.
- [27] A. Ferrari, G. O. Spagnolo, G. Martelli, and S. Menabeni, “Product line engineering applied to CBTC systems development,” in *Leveraging Applications of Formal Methods, Verification and Validation (ISoLA)*, pp. 216–230, Springer, 2012.
- [28] IEC 62290, “Railway applications - Urban guided transport management and command/control systems,” standard in 3 parts, International Electrotechnical Commission, Jul. 2014.
- [29] P. Fraga-Lamas, T. M. Fernández-Caramés, and L. Castedo, “Towards the Internet of smart trains: A review on industrial IoT-connected railways,” *Sensors*, vol. 17, no. 6, p. 1457, 2017.
- [30] R. He, B. Ai, G. Wang, K. Guan, Z. Zhong, A. F. Molisch, C. Briso-Rodriguez, and C. P. Oestges, “High-speed railway communications: From GSM-R to LTE-R,” *IEEE Vehicular Technology Magazine*, vol. 11, no. 3, pp. 49–58, 2016.
- [31] S. Banerjee, M. Hempel, and H. Sharif, “A survey of wireless communication technologies & their performance for high speed railways,” *Journal of Transportation Technologies*, vol. 6, no. 1, pp. 15–29, 2016.
- [32] ETSI, “TERrestrial Trunked Radio (TETRA),” 2011.
- [33] J. Moreno, J. M. Riera, L. De Haro, and C. Rodriguez, “A survey on future railway radio communications services: challenges and opportunities,” *IEEE Communications Magazine*, vol. 53, no. 10, pp. 62–68, 2015.
- [34] UIC - Rail System Department, *FRMCS and 5G for rail: challenges, achievements and opportunities*. International Union of Railways (UIC), Paris, France, Dec. 2020.
- [35] W. Qi, Y. Xin, and X. Dechun, “Design of tetra-based dedicated radio dispatching system of urban rail transit,” in *2013 Third International Conference on Intelligent System Design and Engineering Applications (ISDEA)*, pp. 574–578, Jan. 2013.
- [36] UNISIG, “FFFIS for Eurobalise - SUBSET-036,” Standard, 2012.
- [37] P. Gurník, “Next generation train control (NGTC): More effective railways through the convergence of main-line and urban train control systems,” *Transportation Research Procedia*, vol. 14, pp. 1855–1864, 2016.
- [38] CENELEC CLC/TS 50701:2021, “Railway applications – Cybersecurity,” technical specification, European Committee for Electrotechnical Standardization, Jul. 2021.
- [39] J. Warsinske, M. Graff, K. Henry, C. Hoover, B. Malisow, S. Murphy, C. P. Oakes, G. Pajari, J. T. Parker, D. Seidl, and M. Vasquez, *The Official (ISC)² Guide to the CISSP CBK Reference*. John Wiley & Sons, fifth ed., May 2019.
- [40] ISO/IEC 15408-1:2009, “Information technology – Security techniques – Evaluation criteria for IT security – Part 1: Introduction and general model,” standard, International Organization for Standardization (ISO) & International Electrotechnical Commission, Dec. 2009.
- [41] ISO/IEC 27001, “Information technology – Security techniques – Information security management systems – Requirements,” standard, International Organization for Standardization, Oct. 2013.
- [42] M. Barrett, “Framework for improving critical infrastructure cybersecurity,” NIST Cybersecurity Framework, National Institute of Standards and Technology, Apr. 2018. ver. 1.1.
- [43] ENISA, “Mapping of OES security requirements to specific sectors,” European Union Agency for Cybersecurity, Dec. 2017.
- [44] C. Schlehüser and S. Benoliel, “CENELEC prTS 50701 (Railway applications – CyberSecurity),” in *Cybersecurity in Railways*, pp. 1–18, ENISA-ERA, 2021. presentation only.
- [45] UK DfT, *Rail cyber security: guidance to industry*. UK Department for Transport (DfT), London, UK, 2016.
- [46] UIC - Rail System Department, *Guidelines for cyber-security in railway*. International Union of Railways (UIC), Paris, France, 2018.
- [47] M. Antoni and N. Ammad, “Argus project-harnessing asset management to do cyber security to an uic guideline for railways,” in *Congrès Lambda Mu 21 «Maîtrise des risques et transformation numérique: opportunités et menaces»*, 2018.
- [48] R. Bloomfield, M. Bendele, P. Bishop, R. Stroud, and S. Tonks, “The risk assessment of ERTMS-based railway systems from a cyber security perspective: Methodology and lessons learned,” in *International Conference on Reliability,*

- Safety, and Security of Railway Systems (RSSRail)*, pp. 3–19, Springer, 2016.
- [49] E. Masson and C. Gransart, “Cyber security for railways – a huge challenge – Shift2Rail perspective,” in *International workshop on communication technologies for vehicles (Nets4Cars / Nets4Trains / Nets4Aircraft)*, pp. 97–104, Springer, 2017.
- [50] “4SECU Rail.” <https://www.4securail.eu/>.
- [51] L. Alexe, H. Pereira, P. Ribeiro, M.-H. Bonneau, and F. Marqués, “Safety and security requirements of rail transport system in multi-stakeholder environments,” deliverable d2.1, CYbersecurity in the RAILway sector (CY Rai) EU Project 730843, 2017.
- [52] “X2Rail.” <https://cordis.europa.eu/project/id/730640>.
- [53] “Roll2Rail.” <http://www.roll2rail.eu/>.
- [54] “Safe4RAIL.” <https://safe4rail-1.safe4rail.eu/>.
- [55] M. Rezik, C. Gransart, and M. Berbineau, “Cyber-physical security risk assessment for train control and monitoring systems,” in *Conference on Communications and Network Security (CNS)*, pp. 1–9, IEEE, 2018.
- [56] NIST Joint Task Force, “Security and privacy controls for information systems and organizations,” NIST Special Publication 800-53, National Institute of Standards and Technology, Sep. 2020. Rev. 5.
- [57] K. Stouffer, V. Pillitteri, S. Lightman, M. Abrams, and A. Hahn, “Guide to industrial control systems (ICS) security,” NIST Special Publication 800-82, National Institute of Standards and Technology, May 2015. Rev. 2.
- [58] P. Herzog, “The open-source security testing methodology manual,” tech. rep., Institute for Security and Open Methodologies (ISECOM), Dec. 2010.
- [59] “Common Vulnerabilities and Exposures (CVE).” <https://cve.mitre.org/>.
- [60] D. Basile, M. H. ter Beek, and V. Ciancia, “Statistical model checking of a moving block railway signalling scenario with Uppaal SMC,” in *Leveraging Applications of Formal Methods, Verification and Validation (ISoLA)* (T. Margaria and B. Steffen, eds.), vol. 11245 of *Lecture Notes in Computer Science*, (Cham), pp. 372–391, Springer, 2018.
- [61] E. Russo, G. Costa, and A. Armando, “Scenario design and validation for next generation cyber ranges,” in *International Symposium on Network Computing and Applications (NCA)*, pp. 1–4, IEEE, 2018.
- [62] M. M. Yamin, B. Katt, and V. Gkioulos, “Cyber ranges and security testbeds: Scenarios, functions, tools and architecture,” *Computers & Security*, vol. 88, p. 101636, 2020.
- [63] G. Berra, G. Ferraro, M. Fornero, N. Maunero, P. Prinetto, and G. Roascio, “PAIDEUSIS: A remote hybrid cyber range for hardware, network, and IoT security training,” in *Italian Conference on Cybersecurity (ITASEC)*, pp. 284–297, 2021.
- [64] “CyberChallenge.IT.” <https://cyberchallenge.it/>.
- [65] H. Winter, “System security assessment using a cyber range,” in *International Conference on System Safety, incorporating the Cyber Security Conference*, pp. 1–5, IET, 2012.
- [66] T. Gustafsson and J. Almroth, “Cyber range automation overview with a case study of CRATE,” in *Nordic Conference on Secure IT Systems*, pp. 192–209, Springer, 2020.
- [67] E. Russo, G. Costa, and A. Armando, “Building next generation Cyber Ranges with CRACK,” *Computers & Security*, vol. 95, p. 101837, 2020.
- [68] S. R. Goniwada, *Cloud Native Architecture and Design. A Handbook for Modern Day Architecture and Design with Enterprise-Grade Examples*. Apress, 1st ed., 2022.
- [69] “Ansible.” <https://www.ansible.com/>.
- [70] “Chef.” <https://www.chef.io/products/chef-infra>.
- [71] “Puppet.” <https://puppet.com/>.
- [72] N. Chouliaras, G. Kittes, I. Kantzavelou, L. Maglaras, G. Pantziou, and M. A. Ferrag, “Cyber ranges and testbeds for education, training, and research,” *Applied Sciences*, vol. 11, no. 4, p. 1809, 2021.
- [73] J. Eckroth, K. Chen, H. Gatewood, and B. Belna, “Alpaca: Building dynamic cyber ranges with procedurally-generated vulnerability lattices,” in *Southeast Conference (ACMSE)*, pp. 78–85, ACM, 2019.
- [74] Y. Li, D. Nguyen, and M. Xie, “Ezsetup: A novel tool for cybersecurity practices utilizing cloud resources,” in *Annual Conference on Information Technology Education (SIGITE)*, pp. 53–58, ACM, 2017.
- [75] J. Vykopal, R. Ošlejšek, P. Čeleda, M. Vizvary, and D. Tovarňák, “KYPO cyber range: Design and use cases,” in *International Conference on Software Technologies (ICSOFT)*, pp. 310–321, SciTePress, 2017.
- [76] Z. C. Schreuders, T. Shaw, M. Shan-A-Khuda, G. Ravichandran, J. Keighley, and M. Ordean, “Security scenario generator (SecGen): A framework for generating randomly vulnerable rich-scenario VMs for learning computer security and hosting CTF events,” in *Workshop on Advances in Security Education (ASE)*, pp. 1–10, USENIX, 2017.
- [77] R. S. Weiss, S. Boesen, J. F. Sullivan, M. E. Locasto, J. Mache, and E. Nilsen, “Teaching cybersecurity analysis skills in the cloud,” in *Technical Symposium on Computer Science Education (SIGCSE)*, pp. 332–337, ACM, 2015.
- [78] S. Yasuda, R. Miura, S. Ohta, Y. Takano, and T. Miyachi, “Alfons: A mimetic network environment construction system,” in *International Conference on Testbeds and Research Infrastructures*, pp. 59–69, Springer, 2016.
- [79] D. Conte de Leon, C. E. Goes, M. A. Haney, and A. W. Krings, “Adles: Specifying, deploying, and sharing hands-on cyber-exercises,” *Computers & Security*, vol. 74, pp. 12–40, 2018.
- [80] R. Beuran, C. Pham, D. Tang, K.-i. Chinen, Y. Tan, and Y. Shinoda, “Cybersecurity education and training support system: CyRIS,” *IEICE Transactions on Information and Systems*, vol. 101, no. 3, pp. 740–749, 2018.
- [81] G. Costa, E. Russo, and A. Armando, “Automating the generation of cyber range virtual scenarios with VSDL,” *arXiv preprint arXiv:2001.06681*, 2020.
- [82] T. Miyachi, K.-i. Chinen, and Y. Shinoda, “StarBED and SpringOS: Large-scale general purpose network testbed and supporting software,” in *International Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS)*, pp. 30–es, ACM, 2006.
- [83] P. Segeč, M. Moravčík, M. Kontšek, J. Papán, J. Uramová, and O. Yerenenko, “Network virtualization tools – analysis and application in higher education,” in *International Conference on Emerging eLearning Technologies and Applications (ICETA)*, pp. 699–708, IEEE, 2019.
- [84] “Cisco Modeling Labs (CML).” <https://developer.cisco.com/modeling-labs/>.
- [85] “Common Open Research Emulator (CORE).” <https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Information-Technology/NCS/CORE/>.
- [86] “Emulated Virtual Environment - Next Generation (EVE-NG).” <https://www.eve-ng.net/>.
- [87] “Graphical Network Simulator 3 (GNS3).” <https://www.gns3.com/>.
- [88] “Mininet.” <http://mininet.org/>.
- [89] C. H. Benet, R. Nasim, K. A. Noghani, and A. Kassler, “OpenStackEmu – a cloud testbed combining network emulation with OpenStack and SDN,” in *Consumer Communications & Networking Conference (CCNC)*, pp. 566–568, IEEE, 2017.
- [90] D. Kreutz, F. M. V. Ramos, P. E. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, “Software-defined networking: A comprehensive survey,” *Proceedings of the IEEE*, vol. 103, no. 1, pp. 14–76, 2015.
- [91] M. E. Kuhl, M. Sudit, J. Kistner, and K. Costantini, “Cyber attack modeling and simulation for network security analysis,” in *Winter Simulation Conference*, pp. 1180–1188, 2007.
- [92] M. H. ter Beek, A. Legay, A. Lluch Lafuente, and A. Vandin, “Quantitative security risk modeling and analysis with RisQFLan,” *Computers & Security*, vol. 109, p. 102381, 2021.
- [93] K. B. Vekaria, P. Calyam, S. Wang, R. Payyavula, M. Rockey, and N. Ahmed, “Cyber range for research-inspired learning of “attack defense by pretense” principle and practice,” *IEEE Transactions on Learning Technologies*, vol. 14, no. 3, pp. 322–337, 2021.
- [94] C. Systems, “Mpls in the dcn,” 2007. https://www.cisco.com/c/en/us/td/docs/ios/solutions_docs/telco_dcn/Book/telco5.html.
- [95] C. Systems, “Configuring a basic mpls vpn,” 2020. https://www.cisco.com/c/en/us/td/docs/ios/solutions_docs/telco_dcn/Book/telco5.html.

- [//www.cisco.com/c/en/us/support/docs/multiprotocol-label-switching-mpls/mpls/13733-mpls-vpn-basic.html](http://www.cisco.com/c/en/us/support/docs/multiprotocol-label-switching-mpls/mpls/13733-mpls-vpn-basic.html).
- [96] L. D. Ghein, *MPLS Fundamentals*. Cisco Press, 2016.
- [97] UIC - Passenger Department, *High Speed Rail – Fast Track to Sustainable Mobility*. International Union of Railways (UIC), Paris, France, May 2018.
- [98] M. Garmendia, C. Ribalaygua, and J. M. Ureña, “High speed rail: implication for cities,” *Cities*, vol. 29, pp. S26–S31, 2012.
- [99] UIC - Communication Department, *A global vision for railway development*. International Union of Railways (UIC), Paris, France, Nov. 2015.
- [100] M. Niland, “Virus disrupts train signals,” *CBS News*, Aug. 21 2003. <https://www.cbsnews.com/news/virus-disrupts-train-signals/>.
- [101] K. Zetter, “Hackers breached railway network, disrupted service,” *WIRED*, Jan. 24 2012. <https://www.wired.com/2012/01/railway-hack/>.
- [102] Koramis GmbH, “Projekt HoneyTrain: Aufbau, Durchführung und Ergebnisse [in German],” whitepaper, Koramis GmbH, 2015.
- [103] F. A. Scherschel, “Simuliertes Zug-Steuersystem HoneyTrain: 2,7 Millionen Angriffe in sechs Wochen,” *heise online*, Sep. 11 2015. <https://www.heise.de/security/meldung/Simuliertes-Zug-Steuersystem-HoneyTrain-2-7-Millionen-Angriffe-in-sechs-Wochen-2810967.html>.
- [104] K. Wilhoit, “KillDisk and BlackEnergy go beyond energy sector,” *Trend Micro*, Feb. 11 2016. https://www.trendmicro.com/en_us/research/16/b/killdisk-and-blackenergy-are-not-just-energy-sector-threats.html.
- [105] T. Cheshir, “Four cyber attacks on UK railways in a year,” *Sky News*, Jul. 12 2016. <https://news.sky.com/story/four-cyber-attacks-on-uk-railways-in-a-year-10498558>.
- [106] A. Thomas, “Germany’s Deutsche Bahn rail operator targeted in global cyberattack,” *The Wall Street Journal*, May 13 2007. <https://www.wsj.com/articles/germanys-deutsche-bahn-rail-operator-targeted-in-global-cyberattack-1494658493>.
- [107] S. Gibbs, “Ransomware attack on San Francisco public transit gives everyone a free ride,” *The Guardian*, Nov. 28 2016. <https://www.theguardian.com/technology/2016/nov/28/passengers-free-ride-san-francisco-muni-ransomware>.
- [108] AFP and The Local, “International cyber attacks put ransoms on German rail station screens,” *The Local*, May 13 2017. <https://www.thelocal.de/20170513/international-cyber-attacks-put-ransoms-on-german-train-departure-boards>.
- [109] TASS, “Virus attack targeting Russian Railways localized,” *TASS*, May 13 2017. <https://tass.com/world/945717>.
- [110] AP, “The Latest: 29,000 Chinese institutions hit by cyberattack,” *The Associated Press*, May 15 2017. <https://apnews.com/article/f3bc9c0749624febb3770aa362555317>.
- [111] The Local, “Swedish transport agencies targeted in cyber attack,” *The Local*, Oct. 12 2017. <https://www.thelocal.se/20171012/swedish-transport-agencies-targeted-in-cyber-attack>.
- [112] Ritzau and The Local, “Cyber attack hits Danish rail network,” *The Local*, May 14 2018. <https://www.thelocal.dk/20180514/cyber-attack-hits-danish-rail-network/amp>.
- [113] Sixgill Report, “Hacked Chinese rail control system,” *Sixgill*, Mar. 3 2019. <https://www.hackread.com/wp-content/uploads/2019/03/Hacked-Chinese-Rail-Control-System.pdf>.
- [114] CBC, “STM says it refused hackers’ \$2.8M demand in ransomware attack,” *Canadian Broadcasting Corporation News*, Oct. 29 2020. <https://www.cbc.ca/news/canada/montreal/stm-refused-to-pay-2-8-million-ransomware-attack-1.5782838>.
- [115] L. Abrams, “Montreal’s STM public transport system hit by ransomware attack,” *Bleeping Computer*, Oct. 21 2020. <https://www.bleepingcomputer.com/news/security/montreals-stm-public-transport-system-hit-by-ransomware-attack/>.
- [116] N. Tabak, “Ransomware attack hits short line rail operator OmniTRAX,” *FreightWaves*, Jan. 9 2021. <https://www.freightwaves.com/news/ransomware-attack-hits-short-line-rail-operator-omnitrax>.
- [117] C. Cimpanu, “Ransomware attack cripples Vancouver public transportation agency,” *ZDNet*, Dec. 4 2020. <https://www.zdnet.com/article/ransomware-attack-cripples-vancouver-public-transportation-agency/>.
- [118] M. Macmahon, P. James, and K. Tindale, “TransLink CEO confirms ransomware hack, says payment info not compromised,” *News 1130*, Dec. 3 2020. <https://www.citynews1130.com/2020/12/03/translink-suspicious-activity-response/>.
- [119] S. Boynton and J. Armstrong, “TransLink warns staff hackers accessed personal banking information in cyberattack,” *Global News*, Dec. 30 2020. <https://globalnews.ca/news/7548761/translink-cyberattack-personal-info/>.
- [120] Reuters, “Hackers breach Iran rail network, disrupt service,” *Reuters*, Jul. 9 2021. <https://www.reuters.com/world/middle-east/hackers-breach-iran-rail-network-disrupt-service-2021-07-09/>.
- [121] R. Rocca, “TTC says investigation underway amid ransomware attack,” *Global News*, Oct. 29 2021. <https://globalnews.ca/news/8337090/ttc-ransomware-attack/>.
- [122] J. Patton, “TTC cyberattack may have stolen information from up to 25K employees, former employees,” *Global News*, Nov. 8 2021. <https://globalnews.ca/news/8358094/ttc-cyber-attack-investigation-employee-information/>.
- [123] C. Phillips and L. P. Swiler, “A graph-based system for network-vulnerability analysis,” in *New Security Paradigms Workshop (NSPW)*, pp. 71–79, 1998.
- [124] B. Schneier, “Attack trees,” *Dr. Dobbs’s journal*, vol. 24, no. 12, pp. 21–29, 1999.
- [125] S. Mauw and M. Oostdijk, “Foundations of attack trees,” in *International Conference on Information Security and Cryptology (ICISC)*, pp. 186–198, Springer, 2005.
- [126] M. Mulazzani, S. Schrittwieser, M. Leithner, M. Huber, and E. Weippl, “Dark clouds on the horizon: using cloud storage as attack vector and online slack space,” in *USENIX Security Symposium*, pp. 1–11, 2011.
- [127] P. K. Manadhata and J. M. Wing, “An attack surface metric,” *IEEE Transactions on Software Engineering*, vol. 37, no. 3, pp. 371–386, 2010.
- [128] S. Caltagirone, A. Pendergast, and C. Betz, “The diamond model of intrusion analysis,” *Tech. Rep. ADA586960*, DTIC, 2013.
- [129] “OWASP Threat Modeling Project.” <https://owasp.org/www-project-threat-model/>.
- [130] V. Drake, “Threat Modeling.” https://owasp.org/www-community/Threat_Modeling.
- [131] H. Al-Mohannadi, Q. Mirza, A. Namanya, I. Awan, A. Cullen, and J. Disso, “Cyber-attack modeling analysis techniques: An overview,” in *International Conference on Future Internet of Things and Cloud Workshops (FiCloudW)*, pp. 69–76, IEEE, 2016.
- [132] G. Pizzi, “Cybersecurity and its integration with safety for transport systems: not a formal fulfillment but an actual commitment,” *Transportation research procedia*, vol. 45, pp. 250–257, 2020.
- [133] R. Kour, A. Thaduri, and R. Karim, “Railway defender kill chain to predict and detect cyber-attacks,” *Journal of Cyber Security and Mobility*, pp. 47–90, 2020.
- [134] M. J. Assante and R. M. Lee, “The industrial control system cyber kill chain,” white paper, SANS Institute, October 2015.
- [135] E. M. Hutchins, M. J. Cloppert, and R. M. Amin, “Intelligence-driven computer network defense informed by analysis of adversary campaigns and intrusion kill chains,” in *Leading Issues in Information Warfare and Security Research* (J. Ryan, ed.), vol. 1, pp. 80–106, Academic Publishing International Limited, 2011.