CASE STUDY

Succeed with migrations of old signaling and traffic management systems

Based on a controlled step-by-step process using digital twins.

Table of contents

Introduction 3

The need for migrating old traffic management and signaling systems to modern open solutions based on COTS hardware 4

Why migrate to modern signaling solutions? 4

What's preventing migration? 5

Old interlocking systems are still widely used across Europe 6

The different parts of a migration project 7

How Cactus and Prover complement each other 8

Introduction to the Stockholm Metro 9

The old architecture of the Stockholm Metro 10

The new architecture of the Stockholm Metro 10

The migration project in steps 11

Introduction to digital twins and railway signaling migration project 11

Step 1: Digital model of the existing system 12

Step 2: Generation of PLC application software 13

Step 3: Digital model of the future system 14

Step 4: Introduce an actual PLC 15

Step 5: Connect the model to the interlocking relays 16

The system architecture 17

Working with digital twins 18

The value of a successful migration project 19

Your first step toward a migration project 20

Introduction

Railway operations worldwide continue to rely heavily on relay-based signaling systems, some of which have been in service for over half a century. While these systems have provided reliable performance, the growing shortage of expertise, spare parts, and documentation poses a significant risk to railway operations. Railway operators face increasing maintenance costs, operational inefficiencies, and security vulnerabilities without proactive modernization.

This case study explores the necessity of migrating from aging relay-based traffic management and signaling systems to modern, open solutions using Commercial Off-The-Shelf (COTS) hardware. It delves into the challenges of migration, from knowledge gaps and budget constraints to the complexities of transitioning vital railway components without disrupting daily operations.

By highlighting real-world examples, including the ongoing Stockholm Metro modernization, we demonstrate how a structured migration approach leveraging digital twins and formal verification can ensure a seamless transition.

This case study outlines a scalable, cost-effective strategy for securing the future of railway operations, using the combined expertise of Cactus Rail in traffic management and Prover in railway signaling.

Whether you are in the early stages of planning or ready to initiate a migration project, this document provides essential insights into executing a successful transition while maintaining safety, efficiency, and operational continuity.

What you will learn

This case study provides practical insights into the challenges and solutions for modernizing aging railway signaling and traffic management systems. You will learn:

- Why relay-based signaling systems need to be upgraded.
- The biggest obstacles to migration and how to overcome them.
- How digital twins and formal verification improve migration success.
- A step-by-step framework for executing a smooth transition.
- Key takeaways from the Stockholm Metro modernization project.

The need for migrating old traffic management and signaling systems to modern open solutions based on COTS hardware

Relay-based signaling systems have long been the backbone of railway operations. While experts predict these systems will remain in use for a long time, a growing challenge is emerging: relay expertise and spare parts are rapidly disappearing. Many organizations face a critical knowledge gap, with limited documentation and training resources.

This is one of the main drivers for the need to start planning a migration project that should also include the Traffic Management System if it has not already been modernized. Without action, the risk of losing essential know-how increases over time.

Why migrate to modern signaling solutions?

Aging relay-based systems come with growing challenges that make migration essential:

- **Loss of expertise & know-how** - Skilled professionals are retiring, and training resources are scarce.
- **Rising maintenance costs** - Aging hardware requires frequent servicing, which increases operational expenses due to a lack of relay spare parts.
- **Operational & security risks** - Older systems are more vulnerable to failures and security threats.
- **Compliance concerns** - Meeting modern industry standards is becoming increasingly difficult.

What's preventing migration?

Both Cactus and Prover have decades of experience in railway infrastructure, and one of the biggest challenges we see today is the urgent need to modernize aging traffic management and signaling systems. Many of these systems have been in operation for 50 to 60 years—or even longer. While there are numerous initiatives to upgrade these legacy systems, migration projects must be executed quickly, without unnecessary disruptions, and within a reasonable budget. Subway systems are essential for cities, and even brief shutdowns can cause chaos, disrupting commutes and daily life.

Several key challenges often arise during migration:

Lack of documentation and system knowledge
Many legacy systems have little to no updated documentation, making it difficult to fully understand their functionality and capture all requirements for a successful migration.

Conflicting stakeholder priorities
Within organizations, there is often a tension between maintaining the system "as is" versus introducing improvements. This debate can slow decision-making and impact project timelines.

Risk of delays and their consequences
Large-scale migration projects are inherently complex, and any delay can have cascading effects on budgets, operations, and overall project success.

Late discovery of issues
Bugs and system inconsistencies are often found late in the process, leading to extended verification and validation cycles, which can further delay deployment.

Unforeseen complexity and cost overruns
As migration progresses, unexpected technical and operational complexities can emerge, leading to increased costs beyond initial projections.

User adaptation to new systems
A new system requires operational changes, training, and acceptance from users who are accustomed to the old way of working, which can create additional hurdles.

Successfully overcoming these challenges requires careful planning, a structured approach, and the right technological tools.

Old interlocking systems are still widely used across Europe

A review of railway interlocking systems across 15 countries in Europe shows that old mechanical and relay-based interlockings remain widely used despite advancements in electronic systems.

Mechanical interlockings are still prominent in some regions, with Poland having the highest share (55%).

Relay-based interlockings continue to dominate in 9 out of 15 countries, with Romania leading at 85%. Even in countries with a stronger shift toward modern systems, such as Finland, relay interlockings still make up at least 24% of the network.

Notably, seven countries, including Romania, Bulgaria, Switzerland, and Sweden, still rely primarily on relay-based interlockings. Despite their age, these legacy systems remain the backbone of many national railway networks, underscoring the challenges and opportunities for modernization efforts across Europe.

The hesitation to replace these aging interlocking systems largely comes from the challenges mentioned earlier associated with modernization. Relay-based systems, despite being outdated, can function reliably for up to 100 years. Computer-based systems, on the other hand, typically require replacement after just 20 years. This creates concerns about future upgrades and their extent.

The different parts of a migration project

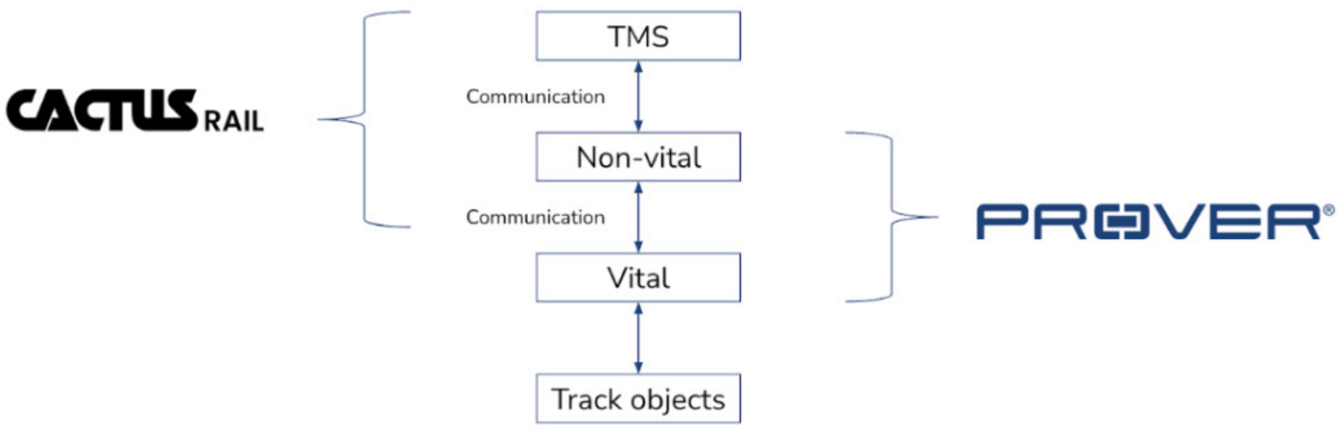
A migration project consists of four key components that must be carefully addressed to ensure a successful transition from legacy systems to modern, open solutions:

Traffic management system (TMS)
The high-level system responsible for overseeing train movements, scheduling, and overall traffic flow.

Non-vital layer
A functional block that interfaces between the TMS and the interlocking system. It can consist of relays, PLCs (Programmable Logic Controllers), or other intermediary components.

Vital layer
The safety-critical part of the project, often composed of relays or computer-based interlocking, ensures that train operations comply with strict safety regulations.

Trackside objects
The physical components on the railway network, such as switches, signals, and sensors, that interact with the system.



How Cactus and Prover complement each other

Prover specializes in system logic	Cactus specializes in traffic management and system integration
Prover's expertise lies primarily in the vital and non-vital logic that governs how these subsystems operate. This includes the generation, formal verification and validation of interlocking software.	Cactus focuses on traffic management systems, communication, and non-vital system implementation, ensuring a smooth connection between the operational level and the field-level equipment.

The good fit between Prover and Cactus comes from our different expertises, but also our slight overlap in the non-vital layer.. This ensures efficient collaboration, with Cactus handling traffic management and system integration, while Prover ensures the safety and correctness of the signaling logic.

Introduction to the Stockholm Metro

Over the years, Cactus Rail and Prover have collaborated on multiple migration projects in Stockholm, modernizing traffic management systems across the city's railway network.

So far, we have been involved with:

- Several signaling systems managing five commuter lines
- 61 million passengers per year
- 106 stations
- 118 km of track

And there's more to come!

In 2024, Cactus Rail secured a turnkey order to deliver a new Traffic Management System (TMS) for the Stockholm Metro, covering 64 stations along the Red and Blue lines. For this major project, Cactus chose to collaborate with Prover to ensure a safe and efficient migration process.

This project marks a significant breakthrough, reinforcing Cactus and Prover's partnership in delivering cutting-edge railway solutions. The new TMS will manage 250 million passengers per year, ensuring improved efficiency and reliability for Stockholm's growing metro network.

A key aspect of the project is the safe migration of non-vital relay logic to PLC, a critical step in ensuring seamless integration with existing infrastructure. Prover plays a central role in this process, ensuring that the transition is both safe and efficient while preserving the reliability of relay interlockings, which will be retained and expanded.

By combining Cactus Rail's expertise in traffic management with Prover's specialization in railway logic, the Stockholm Metro is set to benefit from an open, modern, future-proof system that enhances both performance and safety.

The old architecture of the Stockholm Metro

Before diving into the migration process, it is important to understand the current architecture of the Stockholm Metro and the legacy system it relies on today.

The existing system is based on an electromechanical operator board (maneuver panel), where operators manually control train movements by pushing or pulling buttons and switches. Train status and system feedback are provided through indicator lamps on the panel.

This control setup is wired to non-vital relays, which handle operational commands and route priorities before transmitting signals via copper wiring to vital interlocking relays. These vital relays ensure the safe operation of switches and signals, preventing conflicting movements and enforcing safety rules.

This architecture is not unique to Stockholm; it was originally developed in the United States about 100 years ago and has been widely implemented in railway systems across the world. While the Stockholm system itself is newer, it is based on century-old design principles. Despite its age, it has remained remarkably reliable. However, the working environment for operators is outdated, and the system lacks the flexibility and efficiency required for modern rail operations.

The new architecture of the Stockholm Metro

The goal of this project is to create a modern and efficient work environment for operators by replacing the outdated electromechanical system with a computerized Traffic Management System (TMS). This modern TMS will integrate seamlessly with timetable systems and other digital tools, improving efficiency and automation.

A programmable logic controller (PLC) is introduced to bridge the gap between the new computerized system and the existing relay-based interlocking. The PLC serves as the intermediary, converting digital signals into relay outputs while also handling all non-vital logic. Moving non-vital logic to the PLC makes the system more flexible, scalable, and easier to maintain.

Summary of the new architecture:

- **Computerized traffic management system (Cactus)** – A modern, digital system for managing train operations, optimizing schedules, and enhancing operator control.
- **Programmable logic controller, PLC (Prover)** – Converts digital signals to relay outputs and manages non-vital logic, ensuring smooth communication between the TMS and relay-based interlocking.
- **Vital interlocking relays** – Maintain safety-critical signaling logic, ensuring the safe operation of routes, points, and signals.

By introducing this new architecture, the Stockholm Metro will benefit from a modern, future-proof system that enhances operational efficiency, safety, and maintainability—while ensuring a seamless transition from legacy relay interlockings to digital control.

The migration project in steps

Introduction to digital twins and railway signaling migration project

With such a large and complex migration project, a critical question arises:
How can we be certain that the new system will work seamlessly with the existing infrastructure?

Since some relays will be replaced while others remain, and the legacy system is decades old, there is an inherent risk of missing important details during migration. Starting the project without a clear method for verifying system behavior could lead to costly mistakes, delays, or safety concerns.

To mitigate these risks, we adopted a model-based approach using digital twins. This approach significantly increases confidence in the migration process by allowing us to simulate, test, and validate the new system before deployment.

The five-step digital twin methodology used in this project is applicable to all railway signaling migration projects, providing a structured way to ensure accuracy, safety, and efficiency throughout the transition.

Step 1: Digital model of the existing system

The first step in the migration process is to build a digital model of the existing system. More precisely, we create a digital twin aggregate, a system composed of multiple smaller digital twins, each representing a specific part of the railway infrastructure.

A digital twin, in this context, is a simulation-ready digital model that allows for thorough testing and investigation of system behavior. To ensure accuracy, we develop three separate subsystem models:

- **Maneuver panel** – Models the operator interface, including push/pull buttons and indicator lamps.
- **Non-vital relays** – Models the route selection logic, automation rules, and communication with the maneuver panel.
- **Vital interlocking relays** – Models the safety-critical relay logic, responsible for route locking, switch control, and signal aspects.

Simulating the existing system

These three independent models communicate with each other. Through simulation, we check that the models behave exactly like the actual system.

For example, when an operator presses a button to request a route, the digital model:

- Sends the request to the non-vital logic, which processes it and checks if conditions are met.
- If the route is available, the non-vital logic requests the route from the interlocking relays.
- The vital interlocking relays then lock the route and clear the corresponding signal.

Key outcome of step 1

The primary goal of this step is to validate the accuracy of our digital models and ensure that they correctly represent the architecture and behavior of the existing system. This gives us the confidence that we can simulate and analyze the migration process effectively, reducing risks before making changes in the actual system.

Step 2: Generation of PLC application software

In the second step, we replace the non-vital relays with a PLC application. To achieve this, we generate a PLC program based on the digital model of the non-vital relays.

Additionally, we introduce new functionalities that are not originally part of the non-vital relay logic. Some tasks that operators previously performed manually now need to be digitally integrated into the traffic management system. These adjustments ensure that all necessary functions are accounted for in the new system.

By developing the PLC application in this structured way, we also gain the ability to formally verify that the generated software meets all reasonable requirements for non-vital logic. This step ensures that the new system maintains the intended functionality and reliability while modernizing operations.

Key outcome of step 2

- The non-vital relay logic is successfully replaced with a PLC application.
- New digital functions are introduced to replace manual operator routines.
- The PLC software is formally verified to ensure it meets functional and safety requirements.
- The system maintains consistency with the original behavior while improving automation and reliability.

Step 3: Digital model of the future system

In the third step, we create a digital model of the future system. The primary purpose of this step is to validate that the newly generated PLC program works seamlessly with the upgraded system, including the new functions that replace manual procedures.

One key advantage of this approach is the loose coupling between the PLC and the Traffic Management System (TMS). This means that while we first test the PLC with a model of the TMS, we can later replace the model with the real TMS and validate that everything still works as expected. This allows for a smooth transition from simulation to real-world deployment, reducing the risk of errors during implementation.

Key outcome of step 3

- A digital model of the future system is created to validate PLC functionality.
- The PLC program is tested with both the existing and future system architecture.
- New functions, previously performed manually, are integrated and verified.

The traffic management system model can be replaced with the real system in later stages to ensure seamless integration.

Step 4: Introduce an actual PLC

In the fourth step, we replace the digital model of the PLC with a real, physical PLC. Instead of using a simulated PLC, we introduce an actual industrial PLC into the loop and verify that it functions correctly within the system.

To achieve this, we connect the real PLC using industrial communication protocols on both ends, ensuring it can communicate seamlessly with:

- The digital model of the Traffic Management System (TMS).
- The digital model of the vital interlocking relays.

At this stage, the PLC must behave exactly like the original non-vital relay circuits it replaces, ensuring that the migration process remains smooth and risk-free.

Key outcome of step 4

- The real PLC successfully communicates with the TMS and interlocking models.
- The system continues to function as if the original non-vital relay circuit were still in place.
- The use of industrial communication protocols ensures compatibility with real-world railway infrastructure.

Step 5: Connect the model to the interlocking relays

In the final step, we connect the real PLC to the actual vital interlocking relays while still using a model of the Traffic Management System (TMS). This allows us to validate the PLC's functionality in a real-world environment before the actual TMS is developed and deployed.

This setup enables us to test the end-to-end integration:

- In one direction, the PLC communicates with the TMS model, ensuring it correctly processes traffic management commands.
- In the other direction, the PLC is physically connected to the real interlocking relays, allowing us to verify that it can control switches, signals, and other safety-critical elements in the relay room.

By performing these tests on-site, we confirm that the PLC, as developed, works as expected with both the future TMS and the existing interlocking relays before any major changes to the traffic management system are implemented.

Key outcome of step 5

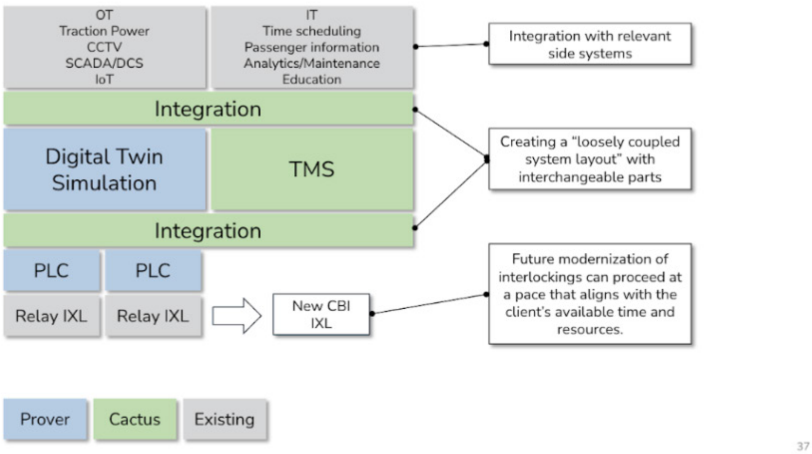
- The real PLC is successfully connected to the actual interlocking relays.
- The TMS model is used to validate communication and ensure proper operation.
- The PLC is tested on-site, proving its ability to control switches, signals, and other railway elements.
- The migration process is validated before the traffic management system is fully developed, minimizing risks.

The system architecture

The system architecture of this 5 step migration process based on open standards, is designed to be modular, flexible, and future-proof. This allows seamless upgrades and long-term operational stability.

At a high level, the final architecture consists of three main component groups:

- **Prover components** (Blue) – Responsible for safe transfer methodology, digital twin technology, and PLC integration, ensuring continuous operations and maintaining system quality as the installation evolves.
- **Cactus components** (Green) – Delivering the Traffic Management System (TMS) and handling data integration from multiple sources, including the digital twin.
- **Existing signaling systems** (Gray) – Retaining the relay interlockings and integrating them into the new setup while allowing for gradual modernization.



A key feature of this architecture is the integration platform, which acts as a layered structure separating different components. This modular approach ensures that individual elements such as the digital twin, TMS, or PLCs can be upgraded or replaced independently without affecting the entire system.

Beyond core railway operations, the architecture also supports Operational Technology (OT) and IT system integration, enabling communication with:

- Time scheduling systems
- Passenger information displays
- Traction power monitoring (e.g., SCADA, DCS, and alarm systems)

By establishing this open and adaptable structure, the solution avoids vendor lock-in, giving the infrastructure owner full control over modernization efforts. Upgrades can be implemented incrementally, whether replacing relay interlockings, TMS components, or other subsystems, ensuring a scalable and future-ready railway system.

Working with digital twins

Using digital twins in railway migration projects, such as the Stockholm metro, provides significant advantages throughout the entire process, from preparation and validation to training and continuous adaptation.

Digital twins help already in the preparation phase

- By modeling behaviors and interactions, provides a clear understanding of the existing system.
- Define requirements and expectations for the future system, ensuring a structured migration plan.

By gaining early insights, infrastructure owners and operators become well-prepared for the transition, reducing uncertainty and risks.

Digital twins help in testing and validation

- Allow for thorough verification of system modularity and interface definitions.
- Ensure a safe replacement of legacy components, such as non-vital relays with PLCs.
- Enable controlled testing of new components before full deployment.

By testing the migration strategy before implementation, digital twins help to secure the transition and enable future system adaptations with minimal risk.

Digital twins help in training sessions

- The Traffic Management System (TMS) can be connected to a simulator for hands-on training.
- New traffic managers can use the simulation to familiarize themselves with the system in a safe and controlled environment.
- Experienced operators can train to handle rare or complex scenarios in their spare time.

By integrating digital twins into training programs, operators can improve decision-making skills and ensure a smooth transition to the new system.

The value of a successful migration project

A well-executed migration of railway signaling and traffic management systems delivers long-term operational, financial, and safety advantages. By following a structured approach, railway operators, such as the Stockholm metro, can transition from legacy systems to modern solutions smoothly and efficiently.

1. Increased System Reliability and Safety

- Ensures compliance with safety standards through formal verification and simulation before deployment.
- Reduces the risk of errors, failures, and unforeseen issues by thoroughly testing the system in a digital environment before implementation.
- Validates that new components, such as PLCs, integrate seamlessly with existing interlocking systems.

2. Reduced Operational Disruptions and Down-time

- Enables a phased migration approach, allowing incremental upgrades rather than requiring a full system overhaul.
- Ensures continuity of operations by testing and validating new systems before deployment in the field.
- Field testing and on-site validation help confirm the reliability of new components with minimal disruption to railway services.

3. Cost-effective and Future-Proof Solution

- Avoids costly rework and unexpected expenses by identifying and addressing potential issues early in the process.
- Creates a modular, open system architecture, allowing for future upgrades without vendor lock-in.
- Reduces lifecycle costs by ensuring the new system is flexible and scalable, adapting to future needs.

4. Improved Training and Operational Efficiency

- Digital twins serve as training tools, allowing new traffic managers to familiarize themselves with the system in a risk-free simulation environment.
- Experienced operators can practice handling rare or complex scenarios, improving overall response capabilities.
- The Traffic Management System (TMS) can be connected to simulators, enhancing hands-on learning opportunities.

5. Long-Term Adaptability and Scalability

- A modular migration approach ensures flexibility, allowing components such as relay interlockings, TMS, or PLCs to be replaced at the operator's pace.
- The digital twin remains a valuable asset for future adaptations, supporting training, continuous improvement, and system expansion.
- Provides infrastructure owners full control over future upgrades, avoiding dependence on a single vendor.

GET IN TOUCH TO SCHEDULE A MEETING

Your first step toward a migration project

Are you interested in starting the planning, or have you decided to start a migration project for your railway signaling and traffic management system? Book a meeting with us (Prover and Cactus) to discuss how best to prepare and ensure a smooth, efficient transition.

During the meeting, we will go through:

- Your specific needs – What challenges and requirements are unique to your system?
- Current infrastructure assessment – What can be kept, and what needs to be upgraded?
- Step-by-step execution – How to minimize risks and disruptions during migration.
- A long-term strategy – Ensuring your system remains scalable, adaptable, and future-proof.

CONTACT US

https://www.prover.com/about-us/contact-us/

PROVER®