On Train Automatic Stop Control Using Balises: Attacks and a Software-Only Countermeasure

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***Abstract*—The components and systems involved in railway operation are subject to stringent reliability and safety requirements, but up until now the cyber security of those same systems has been largely under-explored. In this work, we examine a widely-used railway technology, track beacons or balises, which provide a train with its position on the track and often assist with accurate stopping at stations. Balises have been identified as one potential weak link in train signalling systems. We evaluate an automatic train stop controller that is used in real deployment and show that attackers who can compromise the availability or integrity of the balises' data can cause the trains to stop dozens of meters away from the right position, disrupting train service. To address this risk, we have developed a novel countermeasure that ensures the correct stopping of the trains in the presence of attacks, with only a small extra stopping delay.**

***Index Terms*—train automatic stop control, cyber physical system security, railway system, balise, simulation**

I. Introduction

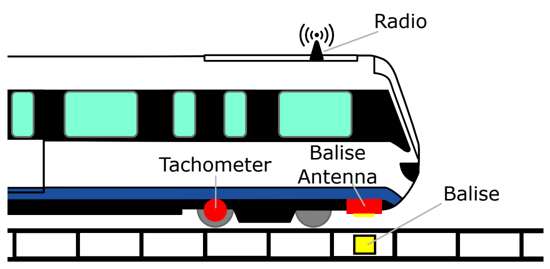
Modern railway systems increasingly rely on real-time communication, embedded computing, and control to support or replace human drivers/operators. As an example, many of today's state-of-the-art metro (mass rapid transit) systems are driverless. The rail industry has always placed a strong emphasis on reliability, availability, maintainability and safety, and this has continued to be an area of focus when it comes to cyber systems and assets. However, until recently, the cybersecurity of those same systems and assets had not been seriously considered. Over the last 5–10 years, the emergence of cyber attacks targeting industrial control systems and physical infrastructure has contributed to a greater focus on evaluating and improving the cybersecurity of railway infrastructure around the world.

A driverless rail system, such as an airport people mover or an underground metro is an example of a cyber-physical system (CPS): there is a *plant* (e.g., a train) governed by *physical laws* (e.g., equations of motion), which is influenced by one or more *controllers* (e.g., speed controller, service and emergency brake logic), and those control actions are coordinated and implemented using communication networks and computing devices. As is the case with other CPS (e.g., electric power grid), a cyber incident can have serious and far-reaching physical consequences. Therefore it is critical to analyze both the cyber attack surface and vulnerabilities of railway communication and control systems as well as the physical impact of a successful attack.

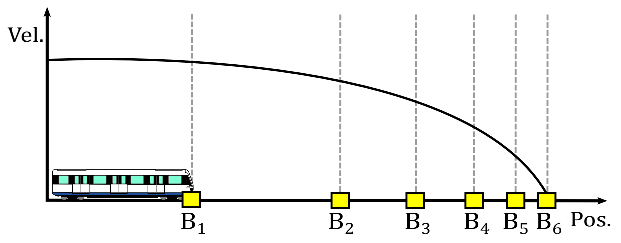
In many railway systems, transponders called absolute position reference beacons or balises are mounted on the track to assist with positioning [1]. When a train passes over a balise, the device will transmit an *absolute position reference* which is used to re-calibrate the train's local position. This input source is combined with other sources (e.g., local measurements from a tachometer), however the balise position data is assumed to represent ground truth. Unfortunately, balises were not designed with security in mind, and to the best of our knowledge they contain no authentication or integrity checking mechanisms: the specifications in Eurobalise [1] only consider failures such as air-gap noise, cross-talk, and bit errors. In fact, the potential vulnerability of balises has been highlighted by the safety and security engineering communities [2], [3], [4]. In this paper, we examine the trustworthiness of balise position data and evaluate the impact of a loss of their availability and/or integrity on train operations. Our aim is to characterize the physical impact of bad position data and use this understanding to enhance the reliability and security of train operations. To achieve this, we consider the specific case of train automatic stop control (TASC), as described in [5]. In this scenario, a train approaching a station uses data from a series of balises placed in a specific manner to control its braking action, in order to stop at a specific target point (e.g., to match train doors with platform screen doors). Our study is based on the TASC setting and the braking controller design from [5], which has been successfully deployed in a real-world metro system and operated for years.

Our contributions in this paper are threefold:

- Based on the real-world setup and controller in [5], we quantify the significant impact of untrustworthy balise position data on TASC. Our evaluation is conducted using a high-fidelity train braking simulation model we implemented in Simulink.
- We propose a software-only countermeasure that requires no physical changes to the railway system. Our countermeasure provides assurances on the train stopping accuracy against all possible attacks under our threat model, and incurs small overhead in term of the overall time needed for train stopping control.
- We evaluate the operational assurance of our counter-



(a) Train sensors and communication.



(b) Train stop with position input from 6 balises.

Fig. 1. Illustration of train systems and automatic stop control scenario.

measure and demonstrate its superior performance. To understand the end-to-end impact on the passengers, we developed a train simulator based on the open-source Open Rails software [6] and incorporated real passenger data from the Shenzhen Metro [7] into our simulator.

The outline of the paper is as follows: Section II presents the background on train systems and train automatic stop control, focusing on the role that balises play in helping a train stop accurately. Section III presents the threat model for attacks that impact the system via balises, while Section IV evaluates the impact of those attacks. Section V then proposes countermeasures to balise attacks, and Section VI evaluates their effectiveness. Section VII discusses related work, the limitations of current study, and future work. Section VIII concludes the paper.

II. Train Automatic Stop Control

Like many other critical infrastructures, trains increasingly rely on intelligent devices and wireless communication rather than mechanical systems and human operators. The critical subsystems in a train control system are: automatic train supervision (ATS), automatic train operation (ATO), and automatic train protection (ATP). ATS works at the upper-most level, handling train scheduling and time tables. ATP works at the lowest level, providing redundancies and emergency braking capabilities to prevent train collisions. ATO systems control train speed, and can include anything from driver assistance mechanisms to fully autonomous train operation. Railway balises, which we discuss in the next section, are a critical component of both ATO and ATP systems.

A. The Role of Balises

Railway *balises*, also known as absolute position reference (APR) beacons or transponders, are found in railway systems around the world. Most commonly found in Europe and Asia, thanks to their inclusion in the European Train Control System (ETCS) [1] and Chinese Train Control System (CTCS) specifications [8], balises are also found in Japanese railway systems. There are two types of balises: *active* (controlled) and *passive* (fixed). We focus on passive balises in this work. A passive balise is a standalone device on the track that receives a radio frequency signal from a passing train and responds by transmitting its location. The train then uses this information, along with input from other sources (e.g., tachometer), to re-calibrate its location and/or current speed (see Figure 1(a)). In ETCS terminology, this corresponds to Level 2 and Level 3 functionality. In contrast, active balises are connected to wayside equipment and can transmit local speed limits or even control commands.

Traditionally, the position data from balises is regarded as ground truth in train control operations. For example, in the ETCS the train's onboard sensors produce an position estimate that depends on distance travelled [9], [10], and that estimate is re-calibrated every time the train encounters a balise. The purpose of our work is to critically examine this trust assumption by applying realistic train control models (Section II-B) and a clearly defined threat model (Section III).

B. Train Automatic Stop Control Model

To analyze the impact of untrustworthy balise position data on train operations, we apply a model from [5] and introduce additional logic to implement our threat model. We model a scenario where a train approaching a station controls its braking action using balise data to stop at a desired position. The model is based on real systems in use today [5]. It is common in many modern train systems to have a set of platform screen doors (PSDs) between the station platform and the train cars to improve commuter safety. In such systems, the coordination between the train doors and PSD system necessitates a precise stop.

We consider a system with m balises, $B = \{B_1, B_2, \ldots, B_m\}$ where balise B_m is the desired stop point. This is depicted in Figure 1(b) for a system with six balises. A stop is considered successful if it is within $\pm\gamma$ from the last balise. Each balise B_i is represented as a tuple $B_i =< b_i, s_i >$ where b_i is the physical location of the balise and s_i is its reported location. Obviously in the absence of failures or malicious tampering $s_i = b_i$ for all balises. Positions are defined relative to the stopping point, i.e. $b_m = 0$, and $b_1 < b_2 < \ldots < b_m$. As the train passes over balise B_i it will adjust its deceleration rate α to compensate for disturbances as it tries to achieve a full stop at B_m. While there can be many types of disturbances affecting a controller's performance (e.g., actuator delay, friction, wheel slip), we focus on variations in the characteristic parameters of the train braking system—time delay (T_d) and time constant (T_p). For the control model, we make use of the heuristic online learning algorithm (HOA) in [5] which has been successfully applied in an operational subway system over several years. Compared to a traditional

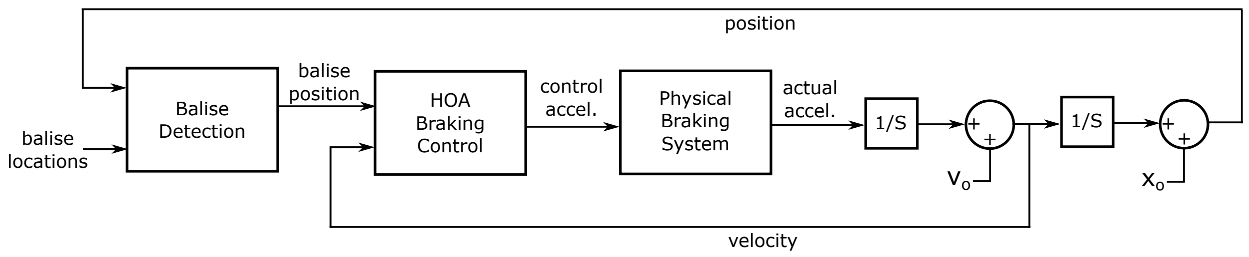


Fig. 2. Block diagram of the stop control model with no countermeasures against balise attacks.

proportional/integral/derivative (PID) controller, which is not continuously tuned, the learning-based HOA control can better handle disturbances.

In this model there is a distinction between the expected deceleration without disturbances (α_i^e), the controller deceleration (α_i^c), and the estimation of the actual deceleration (α_i^r) realized by the train. The expected deceleration as a train passes a balise is obtained by applying classical mechanics. Based on an initial velocity v_i and a final velocity of 0, the constant deceleration (without disturbances) is given by: $\alpha_i^e = \frac{v_i^2}{2s_i}$. Note that this takes a negative value since s_i is negative with respect to the zero point. The controller deceleration is obtained by adjusting α_i^e in response to the observed train deceleration. Specifically,

$$\alpha_{i+1}^c = \alpha_{i+1}^e - \eta_i(\alpha_i^r - \alpha_i^c), \tag{1}$$

where

$$\eta_{i+1} = \begin{cases} 0.95 \times \eta_i & \text{if } |\alpha_i^r - \alpha_i^c| > 0.05 \\ 1.05 \times \eta_i & \text{if } |\alpha_i^r - \alpha_i^c| \leq 0.05 \end{cases} \tag{2}$$

α_i^r is calculated using v_i, v_{i+1}, and the distance between successive balises $D_i = |s_i| - |s_{i+1}|$. The acceleration is given by: $\alpha_i^r = (v_{i+1}^2 - v_i^2)/2D_i$. The actual train deceleration, α_i^{train}, is influenced by various disturbances and system implementation features. We follow [5] and use a train braking model that was empirically determined based on data from an operating subway system. In the Laplace domain, the actual deceleration of the train is given by the transfer function:

$$\alpha^{train} = \frac{\alpha_0}{T_p s + 1} e^{-T_d s} \tag{3}$$

where T_d is the system's time delay and T_p is the time constant. The overall control model, which is implemented in Matlab/Simulink, is illustrated in Figure 2. The intuition behind the control process is that the HOA controller adjusts the braking force each time the train passes over a balise, in a manner similar to that of a driver. The adjustments allow the train to smoothly decelerate and stop at the target point in spite of characteristic lag and random disturbances. In our threat model, discussed in the next section, the balises' data can be altered. Therefore, the model has been adapted to decouple the train's true position and its perceived position on the tracks.

C. System-level Simulation

The train automatic stop control model introduced above captures the behavior of a single train at a single station. While much of our impact analysis (Section IV) focuses on that micro scale and quantifies a train's performance in terms of stopping error (distance) and stopping time under different attack scenarios, a broader system perspective is necessary to fully understand how potential cyber attacks and coutermeasures affect rail infrastructure. To this end, we have developed a railway system simulator based on an open-source tool that simulates train movement over user-defined maps and time tables.

There are a number of commercial and open-source railway simulation tools available online (see [11]). Ultimately, we selected Open Rails [6] because it (i) simulates train movement along user-constructed tracks and stations; (ii) is built on an engine with time-based simulation and object-oriented programming; and (iii) offers a 3D view of trains as well as a supervisory-level view of all train movement. We have added additional features to support the integration of passenger flow data: e.g., passengers' station and time for tap-in and tap-out, the number of doors on each train, the train capacity, and adding a user-specified dwell time to be added to a train's waiting time at each station.

We refer readers to [11] for further information about our customized train simulator. In short, we have built an enhanced version of Open Rails and modeled a line in the Shenzhen metro system to allow system-level modeling of the impact of attacks to balises. We will discuss selected system-level results in Section VI.

III. Attacks Targeting Balises

In a railway system, the key properties to uphold are passenger safety and operational reliability. In this work we focus on attacks with an operational impact, targeting the track infrastructure (i.e., balises). Previous research in railway system security has indicated that the presence of redundant systems and fail-safe mechanisms makes safety challenging for an attacker to compromise, yet those same systems can make service disruption easier to achieve [3], [12]. Within the context of operational reliability, we focus on attacks targeting track infrastructure rather than the rolling stock (trains) themselves for two reasons.

First, as a large, physically distributed infrastructure, railway track and wayside systems presents a large physical attack surface, whereas the rolling stock is typically housed at a central depot with strict access control. Second, while there are train onboard systems involved in localization (see Figure 1(a)), targeting the balises maximizes an attacker's impact since multiple trains passing through a single compromised track section will be affected. Furthermore, this impact may be different for different trains and/or at different times, making detection more difficult.

We assume the attacker's goal is to create a service disruption. This is achieved by manipulating balises (e.g., using a manufacturer's balise reader/programmer device) to cause trains to have inaccurate stops at the station. By maximizing the stopping error, the attacker introduces additional dwell time at stations as the trains correct their alignment with the platform screen doors (either automatically or with human intervention). This process, called jogging, can have an adverse system level effect on train timetables. Within this context, we make the following assumptions:

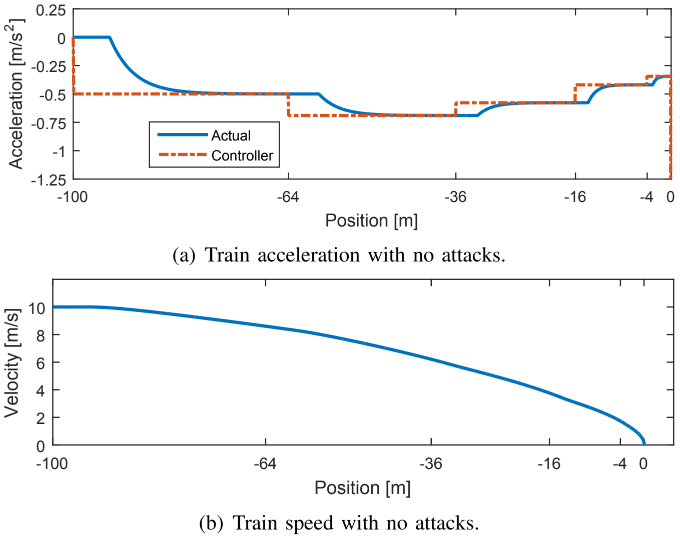
- **Fixed Balises:** The attacker cannot physically move the balises, nor introduce additional balises. Only balise data availability and integrity may be altered.
- **Trusted Zero Balise:** The last balise, B_m, is assumed to be trusted. This balise, at position 0, is often active rather than passive, and it is not used for control in the HOA algorithm. This last balise interacts with other components (e.g., the platform screen door controllers) which would make tampering easier to detect. We assume the attacker is unable to make any other passive balises impersonate the zero balise.
- **Attacker's Knowledge and Capability:** The attacker is familiar with the technology and operations of the rail system, including countermeasures deployed. Specifically, the attacks can be launched by insiders (e.g., disgruntled employees, malicious contractors) intentionally, or unintentionally (either by mistake, or through a malware-infected balise programming device). In addition, the vast physical attack surface of railway tracks makes it feasible for an external attacker who understand the working principal of balises to launch the attack.

Since the balises are passive, once the attacker alters the availability or integrity of one or more balises, those balises stay in the compromised state. This helps the attacker to create a prolonged impact on the system rather than a one-off incident. Additional assumptions related to our proposed countermeasures are discussed in Section V. In short, we assume that the trains are provided with prior knowledge about where balises are located (e.g., expect 6 balises prior to a station, reporting a fixed set of distance values), and we assume a certain accuracy level for the train's onboard odometry.

In this work, we focus on the attack on a single station. The attacker can have access to one or more balises at one train station. For future work the study can be extended to consider attacks over multiple stations.

IV. Impact of Attacks

Before introducing and assessing countermeasures for balise availability and integrity attacks, we use the model in Section II-B to establish the impact of those attacks on the system as it is. For the results presented in the rest of this paper we consider a train approaching a station with balises located at positions [-100, -64, -36, -16, -4, 0]. The first five balises are passive, while the final one is active. There are several fixed and adjustable parameters that characterize the train stop scenario. We assume an initial position of $x = -100m$ (relaxed in Section VI), initial velocity $v = 10m/s$, maximum deceleration of $\alpha_{max} = -1m/s^2$, and an allowable stopping error of $\gamma = 0.3m$. In our analysis we vary the train brake parameters—the time delay (T_d) and time constant (T_p)—to capture the impact of control disturbances and variations between different trains. We consider a range of $\pm 20\%$ around default values $T_d = 0.6$ and $T_p = 0.4$ as used in [5].



(a) Train acceleration with no attacks.
(b) Train speed with no attacks.

Fig. 3. Train acceleration/speed with HOA controller and default parameters.

To provide intuition into how the train uses balise data during a stop, Figure 3(a) shows the train's acceleration curve with no attacks under the default simulation setting described above. Observe that at each balise location the train's brake controller acceleration changes and the actual acceleration follows the change based on parameters T_d and T_p. Figure 3(b) shows the resulting train speed curve, which achieves a smooth and accurate stop in the absence of disturbances or attacks.

A. Availability Attacks

Within the context of our threat model (Section III), a potential attacker has access to a single train station and the balises located therein. A natural attack to consider is an availability attack affecting one or more balises. This could be perpetrated by an insider or intruder, or it could simply represent a non-malicious failure from a reliability perspective. To assess the impact of availability attacks on train automatic stop control, we exhaustively evaluate all combinations of available and unavailable balises (31 in total, excluding the scenario where all balises are available). We simulate those 31 scenarios, each with combinations for 10 values of T_d and 10 values of T_p that are uniformly chosen to cover the $\pm 20\%$ range of their default values. This leads to a total of 3100 different settings.

The key metrics for evaluating the impact of balise data attacks (and later countermeasures) are the *stopping error*, measured in meters with respect to the 0 point, and the *stopping time*. A typical value for the allowable stopping error is ±0.3m. For reference, a typical metro train's door width is around 1.4m. During normal operations, a train will wait at a station for a dwell time of 30s to 1-2min (based on Singapore's train system). If the train stops outside of its allowable stopping error it needs to correct either manually or automatically. This process can easily add a few minutes to the dwell time, potentially creating a cascading effect as subsequent trains are also delayed. Based on measurements taken in an automated train system, the additional time associated with automatic jog is substantial. Due to safety considerations, each automatic jog covers a small distance ($0.2 - 0.3$m on average) and takes about 8.6s. Therefore, correcting a large stopping error (e.g., 5m) can easily take over a dozen jogs, adding more than 100 seconds to a train's dwell time at the station.

Out of the 3100 availability attack scenarios evaluated, only 138 (4.5%) resulted in a successful stop within the allowable ±0.3m range. The results are presented in Section VI together with the countermeasure analysis. Specifically, Figure 7 (a) shows scatter plots of the train stopping error (m) and total time to stop (s) for all 3100 scenarios, grouped by the number of unavailable balises. Intuitively, the operational consequences of an attack become more severe as the number of affected balises increases. For example, when two or more balises are unavailable the stopping error can be above 6m: a threshold where automatic jog will not be executed and a train that overshoots must skip the current station and proceed to the next one. In Figure 7 (b), which shows the stopping times for the 3100 scenarios, the cases where a station is skipped are marked as N.A.

To provide a concrete example of these availability attacks, Figure 4 shows acceleration and speed curves for two cases. The first attack makes balise B_1 unavailable. Contrasting Figure 4(a) with the no-attack baseline profile in Figure 3(a), we observe late braking action followed by sharper than normal deceleration as the train attempts to compensate. The resulting overshoot and stopping error of $1.3m$, while out of the allowable region, is not terribly disruptive: it takes around 62 seconds to correct the error. However, making a second balise unavailable (Figure 4(c)) causes the braking controller to saturate at $-1m/s^2$ and the train is unable to stop until $22.1m$ past the target point. As explained previously, this train would likely continue to the next station rather than jogging.

B. Advanced Attacks

While availability attacks on balises can seriously disrupt train automatic stop control, under our threat model the adversary is not limited to these actions. We will discuss in Section V how the design of a countermeasure should deal with all combinations of such attacks. Before that, here we will briefly describe more sophisticated attacks involving data integrity attacks, and combinations of availability and integrity attacks. As we show, an attacker capable of changing the position reported by one or more balises can create disruptive train stopping errors by affecting fewer balises than an availability-only attacker.

Integrity attack on a single balise: An attack affecting balise data integrity is able to cause a significant stopping error. For example, an attacker could tamper with balise B_1 so that it reports -4m rather than -100m. As shown in Figures 5(a) and 5(b), the result is a hard stop and an undershoot of -43.7m, which would certainly be alarming for passengers. Based on the train jog parameters described previously it would take around 1646 seconds (over 27 minutes) to correct this position error without human intervention.

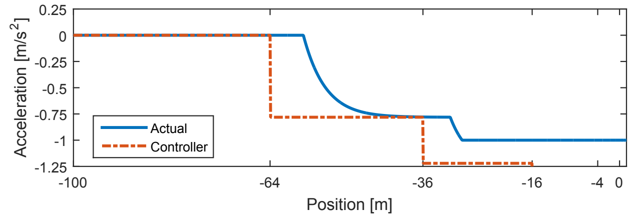
Integrity attack on consecutive balises: Similar to the above attack on the first balise, an attack overwriting the values of B_1 and B_2 to -64 and -36, respectively, will cause the train to think it is closer to the stop point than it actually is. The result, shown in the acceleration profile in Figure 5(c), is sharper-than-expected braking and a stop at -29m. While the impact in terms of stopping error is less severe due to the lower speed, this attack causes the train to pass consecutive balises reporting -36, which could cause an error with the HOA algorithm if exceptions are not handled correctly. This was the case in our original Matlab/Simulink implementation based on [5], and it is unclear whether the operational instances of the HOA controller contain the same error.

Combination of availability and integrity attacks: An interesting observation from our evaluation with HOA is that launching a pure integrity or availability attack is more impactful than more sophisticated attacks that combine both integrity and availability compromises. As shown in Figure 5(d), an attack making B_1 report -64, making B_2 unavailable, and making B_3 report -4 will result in a stop at -27.6m. This is certainly impactful, but not as severe as the cases we described earlier. Intuitively, due to the physics of train operation, the first few balises are the most critical: the train is far from the target stop point and moving fast, so for maximum impact an attacker would seek to keep it moving fast, or to brake quickly. Either of those actions can be achieved without mixing availability and integrity attacks.

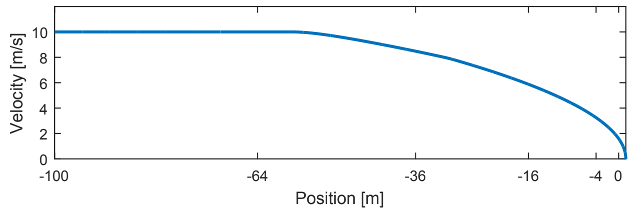
However, if one considers more advanced controllers rather than HOA, this observation may no longer hold. Let us revisit Figure 5(a) and 5(c). For both cases, before the train fully stops, it actually passes through one balise that is not manipulated by the attacker (the -64m balise for Figure 5(a) and the -36m balise for 5(c)). While HOA's heuristic control logic is not able to react fast enough to leverage such genuine balise inputs, a more resilient controller could potentially do so. However, if the attacker can combine availability/integrity attacks and manipulate balises as in Figure 5(d), the train does not have a chance to receive any genuine balise inputs before it enters a full stop, which can make the design of a resilient controller even more challenging.

V. COUNTERMEASURES

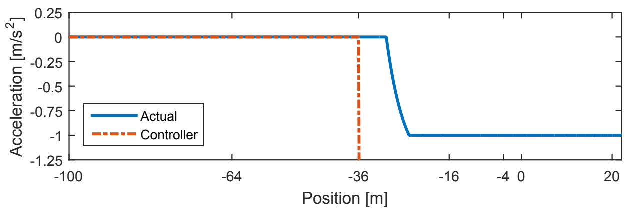
In the previous section, our model-based analysis showed that an attacker could cause train stopping errors up to dozens of meters by compromising the availability or data integrity



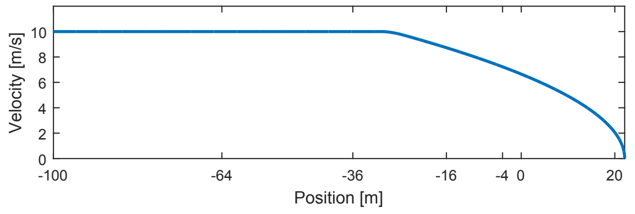
(a) Acceleration with B_1 unavailable.



(b) Speed with with B_1 unavailable.

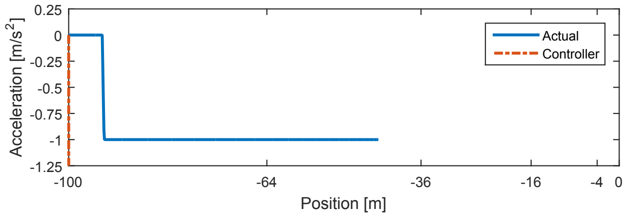


(c) Acceleration with B_1 & B_2 unavailable.

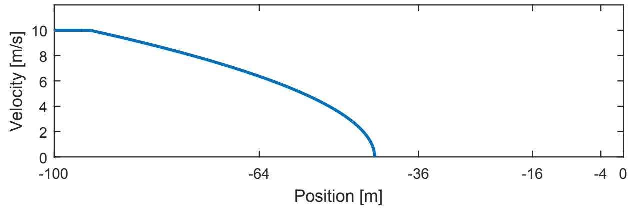


(d) Speed with with B_1 & B_2 unavailable.

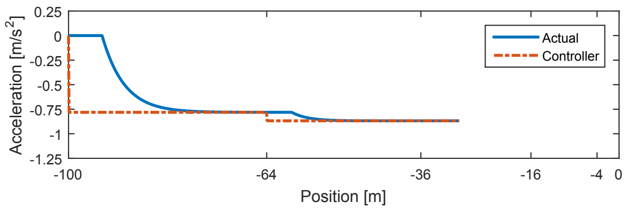
Fig. 4. Train acceleration and speed profiles during braking with an availability attacks.



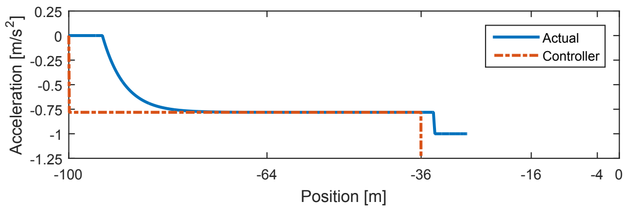
(a) Acceleration under integrity attack on B_1.



(b) Speed under integrity attack on B_1.



(c) $\{B_1, B_2\}$ changed to $\{-64, -36\}$.



(d) $\{B_1, B_2, B_3\}$ to $\{-64, N.A., -4\}$.

Fig. 5. Train acceleration and speed profiles for advanced attacks.

of the balises at a station. We now propose software-only countermeasures that make a train's automatic control robust to potential attacks to balises.

A. Design Intuition

The design of our countermeasure is based on four key observations, which we discuss in the paragraphs below.

Observation 1*: Trains can reduce stopping errors by sacrificing some performance.* Consider the scenario where all the balises used for the control algorithm are compromised (only the final stopping position can be learned). A train can still stop close to the right position by travelling at a low speed and applying the brake when it passes position 0. If the speed is low enough, the train should be able to stop within a short distance from the correct position. The drawback of this conservative strategy is that the train's stopping performance (in terms of time) may be sacrificed. In particular, if the train slows down to $0.3m/s$ at $30m$ away from the position 0 (e.g., due to local position estimation error), the train then needs $100s$ to cover this short distance.

Observation 2*: Trains can leverage the trustworthy physical-world setup information.* In a railway environment, the distance between stations and the position of balises are fixed once the system is built and put into operation. It is a common practice to load such physical-world information into a train's on-board controller and the controller can use that trustworthy information to make decisions. Note that our threat model assumes the attacker cannot change the physical setup, e.g., moving a balise to a different position. Such physical attacks would be time-consuming and easier to detect than cyber attacks.

Observation 3*: Trains can leverage less accurate but more trustworthy sensing data.* A train can infer its location using multiple sensors, including its onboard tachometer and Doppler radar. The estimation of location from onboard sensors is not as accurate as the value obtained directly from balises: the estimation error accumulates with the distance that a train travels. For example, estimates based on wheel rotation can be inaccurate when the wheels slip on the rails. Fortunately, with modern information fusion techniques and model-based controls, the onboard system is already able to provide well-bounded accuracy based on these imperfect sensors. For ETCS, the minimum accuracy requirement for on-board train position measurement is $\pm(5m+5\%d)$ where d is the distance travelled since the last reference point [9]. In practice, the accuracy for a system can be better: for example an error less than $\pm 20m$ for every $1000m$ travelled ($\pm 2\%d$ [10]). Since we believe it is harder for an attacker to compromise on-board equipment, we consider these sensors more trustworthy than balises, though they may be less accurate.

Observation 4*: Trains can use trusted information to verify information from untrusted sources.* As mentioned above, both the physical setup information and the position estimations based on-board sensors are deemed trustworthy information. They can be used to cross check the report from the less trustworthy sources (i.e., the balises). Once the information from balises is deemed trustworthy, it can be used to improve performance. In particular, consider a train that adopts the conservative strategy after it misses the first balise. If it can trust the information it gathers from a later balise, it will be able to use that reading, e.g., to avoid slowing down too early.

B. Detailed Design

Based on our observations, we have developed a software-only countermeasure for dealing with attacks on balise data. To describe our countermeasure in detail we introduce some additional notation: let p denote the train's position as it approaches a station; let p_{est} denote the train's onboard position estimate, which has an associated position error δ; let v_{con} denote a reduced speed setting. At a high level, our robust controller uses two parallel control modules—the original HOA controller, and a new conservative controller—which are activated based on an anomaly detection and correction (ADC) module. This control architecture is shown in Figure 6.

By default a train will operate using the HOA controller [5], as it normally would. If the ADC module detects that there is a balise missing, by using its knowledge about the physical world setup, its onboard estimated position p_{est} in conjunction with whether or not data is received, it will fall back to a conservative controller (Observation 1). This detection is possible thanks to the static physical-world setup information (Observation 2) and the less accurate but more trustworthy local sensing data (Observation 3). The conservative controller uses 2 PID controllers to slow the train to v_{con}, where it remains until it reaches the stop marker. At that point the train will brake at α_{max} until it stops. There is a need to select between multiple PIDs at different velocity stages due to conflicting requirements in terms timing and stability. The key parameter is v_{con}, which is selected based on the train system's allowable stopping error γ (in our analysis, $\pm$0.3m). Note that this design avoids the need for further adjustment through jogs after the train first stops. One can further trade off between the (initial) stopping error and the overall stopping time by allowing a small number of jogs to be carried out.

When the ADC switches to the conservative controller, it will still check and correct the position information it receives. The corrected information, denoted as *corrected balise value* in Figure 6, is then supplied to the conservative controller. This corrected information is determined based on Algorithm 1, which returns an updated position estimate and error, if there is new balise input that is deemed trustworthy. This implementation is inspired by our Observation 4. In particular, if even a partial set of balise information can be obtained and their trustworthiness can be attested, the position estimation can be made more accurate. As a result the conservative controller's performance can be improved. For example, if the conservative controller knows that it is still some distance away from the final stopping point, it can wait for a while before slowing down to the pessimistic speed of v_{con}. Opportunistically using trustworthy information reduces the delay.

Algorithm 1 Derive-Trustworthy-Info(), with (p_{est}, δ) being the estimate so far.

```
 1: if there is a unique known balise position $b_i$ such that $|p_{est} - b_i| < \delta$ then
 2:     return $(b_i, 0)$ as new $(p_{est}, \delta)$;
 3: else        //there are multiple known balise positions $b_i \in B$ such that $|p_{est} - b_i| < \delta$
 4:     set $r \leftarrow \{local = p_{est}, candidates = B\}$;
 5:     append $r$ into $R$, an unverified record list;
 6:     if there are multiple records $r_1, \ldots r_k$ in $R$ then
 7:         for $i$ in $1, \ldots, k-1$ do
 8:             $d \leftarrow r_k.local - r_i.local$;
 9:             compute distance between all combinations of $r_i.candidates$ and $r_k.candidates$;
10:             if there is only one pair of candidates $(b_l, b_m)$ that has distance of $d$ then
11:                 return $(b_m, 0)$ as new $(p_{est}, \delta)$;
12:             end if
13:         end for
14:     end if
15: end if
```

To derive trustworthy information (in spite of potential availability and integrity attacks), Algorithm 1 runs two different checks based on trustworthy information:

Check 1*:* (line 1 in Algorithm 1): if the train encounters a balise, and it can uniquely associate the balise with a valid balise position, according to both its current trustworthy estimate of p_{est} and δ, as well as the static information about the physical setup, this encounter will be used to update p_{est} and δ. Note that, p_{est} is updated to the balise position b according to the static physical model, instead of the information reported by the encountered balise. This is because an attacker may manipulate a balise at an actual position of b to report a different position of b'. For example, if the train's local estimate is $p_{est} = -90m$ from the stopping point, with a $\delta = 20m$, when it encounters a balise, the train can potentially be at any point between $-70m$ to $-110m$ from the target. Based on the static physical information, there is only one valid balise that can fall in this region (at -100m). Hence, even if the balise reports its value as some other value (e.g., -16m), the train's estimated position will be updated as -100m.

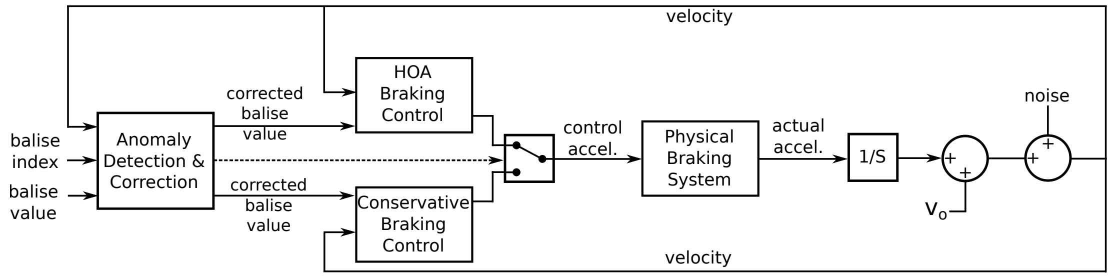


Fig. 6. Simplified block diagram of the train stop control model with countermeasure logic.

Check 2*:* (lines 7-14 in Algorithm 1): Check 1 may fail to derive trustworthy information if the train encounters a balise but cannot map it uniquely to a valid one. For example, if the train's local estimate is $p_{est} = -81m$ from the stopping point, with a $\delta = 20m$, there are two valid balises that can be potential candidates (the one at -100m and the one at -64m). In this case, Check 2 uses the additional information about the possible valid values of distances between balises to further distinguish. Continuing the example, if the train encounters another balise at an estimated position of $p_{est} = -45$m, since the difference between the two local estimates is $(-45) - (-81) = 36$m, and among all pairs of balises (excluding the final stopping balise), only the pair of -100m and -64m balises has a distance of 36m, the algorithm can decide that the first balise encountered at $p_{est} = -81$m is the -100m balise, and the second one encoutered at $p_{est} = -45$m is the -64m balise.

VI. Evaluation

As in Section IV for the existing HOA train controller, we implement our proposed hybrid controller (Figure 6) in Matlab/Simulink to assess its performance. An ideal controller will be able to minimize stopping error and stopping time with and without the presence of cyberattacks. With the conservative controller there is an inherent tradeoff between the two objectives, since v_{min} is low. However, as we show below, once the jog time is considered even this slower-acting controller performs strongly against HOA in a relative sense.

A. Evaluating Availability Attacks

In the absence of countermeasures, simply making one or more balises unavailable as an automated train stops can have serious operational consequences. From the analysis in Section IV, in over 95% of the evaluated stopping scenarios the train failed to reach its target by over or undershooting. We now examine those same attacks after implementing the countermeasures outlined in the previous section.

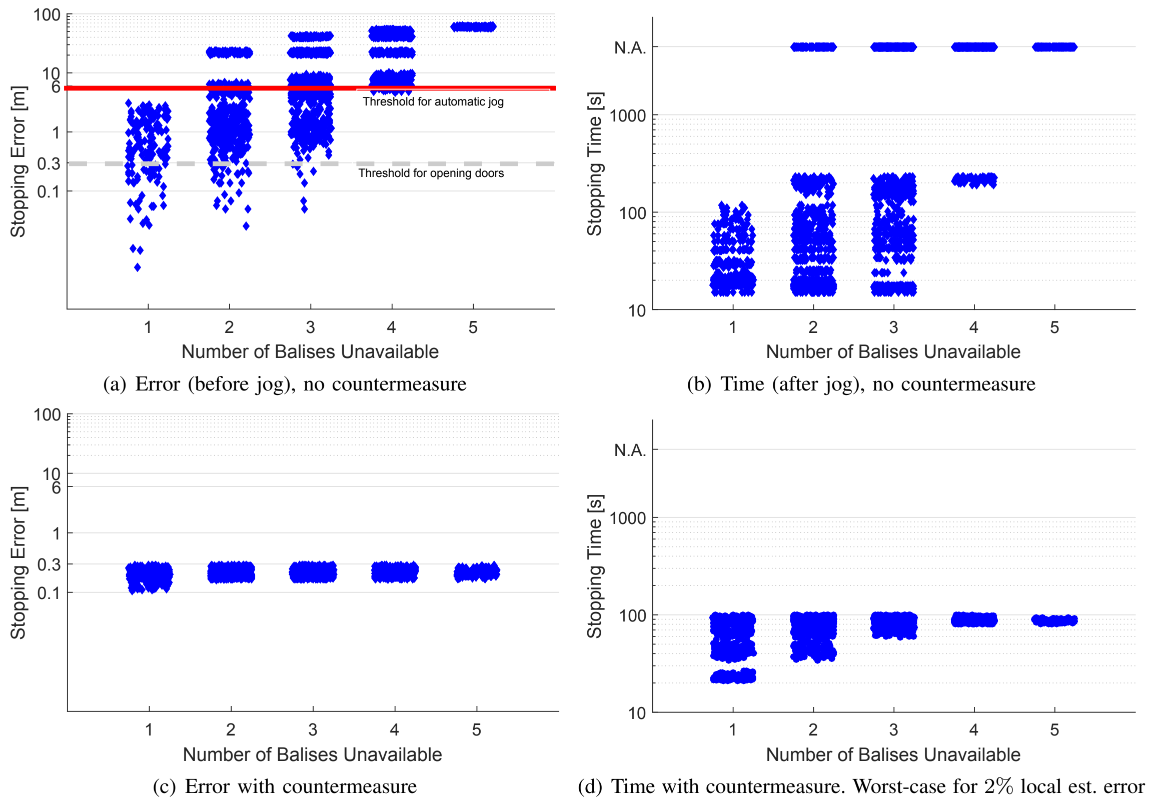
In Figure 7 we contrast the performance with and without the conservative controller, assuming 2% position estimation error. Subfigures (a) and (b) show the impact of attacks with no countermeasures, as discussed in Section IV. Below, in subfigures (c) and (d), we show results from the same 3100 availability attack scenarios after the countermeasures (anomaly detection & correction with a conservative controller) have been implemented. In *every case* the conservative controller ensures that the stopping error is within the acceptable ± 0.3m range, as indicated in Figure 7 (c). The other key metric, stopping time, is shown in Figure 7 (d) for the worst case situation where the train's local position estimate is off by 20 meters. In other words, using its onboard sensors the train estimates that its position is -80m when its actual position is -100m, therefore it slows down to v_{con} more than 20m away from the actual stopping point and it could take around 100s to stop. Note that, the average case stopping time can be much smaller than this worst case, since the stopping time reduces linearly with reduced local estimation error.

Figure 7 also shows that when some balises are available, our algorithm can derive trusted information from them, and use that to reduce the stopping time. In comparison, while HOA (with potential additional automatic jogs), i.e., the original scheme without any countermeasure, can sometimes stop faster, there are 1083 (out of 3100) settings where the train overshoots by more than 6m, so it cannot be jogged back to the current station (marked as N.A. in the figure). There are an additional 290 cases where the train takes more than 150 seconds (including jog time) to stop. Even for the case when the attacker only makes a single balise at -16m unavailable, the stopping time of HOA can be as long as 157 seconds, 50% worse than the worst case stopping time with our countermeasure. The gap further increases when more balises are made unavailable.

B. Evaluating Advanced Attacks

We also evaluate our countermeasure under advanced attacks, where an attacker can combine both availability and integrity compromises. Our evaluation confirms that our countermeasures are able to detect and discard all manipulated balise values, making advanced attacks equivalent to the case where an attacker simply launches availability attacks. Revisiting the attacks from Section IV-B, the integrity attack on B_1 (Figure 5(a)) has its stopping error reduced from $-43.7m$ to an acceptable $0.15m$; the corresponding elimination of jog time reduces the stopping time from $1646.4s$ to $19.8s$. Similarly, the integrity attack on two balises (Figure 5(c)) reduces stopping error and time from $-29m$ and $1098.8s$ to $0.15m$ and $19.8s$, respectively.

The final advanced attack, combining availability and integrity attacks (Figure 5(d)) illustrates the performance trade-off of the conservative controller in terms of stopping time. The countermeasure successfully reduces stopping error



(a) Error (before jog), no countermeasure

(b) Time (after jog), no countermeasure

(c) Error with countermeasure

(d) Time with countermeasure. Worst-case for 2% local est. error

Fig. 7. Evaluation of train automatic stop control performance in the presence of availability attacks before (top) and after (bottom) our countermeasures.

($-27.6m$ to $0.22m$) and stopping time ($1046.4s$ to $93.2s$). However this stopping time is still slower than under normal operating conditions; therefore we want to understand how the elongated stopping time impacts a rail system.

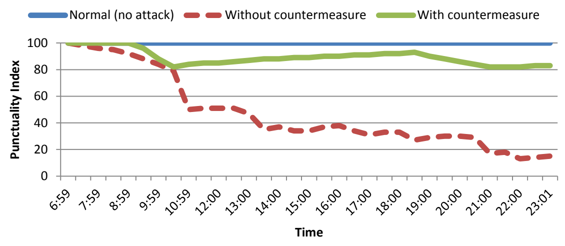
To explore the system-level impact we use our enhanced version of the Open Rails train simulator [6]. We built a model of Shenzhen Metro Line 1 [13], created timetables, and integrated publicly available real-world passenger data [7]. Then, we simulated the advanced attack at one of the busiest stations, Gou Wu Gong Yuan, during the morning rush-hour. Figure 8(a) shows a plot of the system *punctuality index*: a railway metric indicating the percentage of trains on time. This is defined as $P = \frac{t_s - t_l}{t_s} \times 100$ where t_s is the number of scheduled trips within a certain period of time (2 minutes in this work), and t_l is the number of lost or delayed trips. For the final attack scenario above, the worst-case punctuality with the countermeasure is 82%, while in the absence of countermeasures, the service level degrades rapidly to a low of 13%. The difference in passenger delay is also substantial, as shown in Figure 8(b). In the normal case, 4.1% of passengers have travel delays of 15min or longer. This number spikes to 64.7% without countermeasures, while many experience delays over 30min. After introducing countermeasures the performance is close to the normal case, with 4.5% of passengers delayed 15min or longer, and none over 30min.

VII. Related Work and Discussion

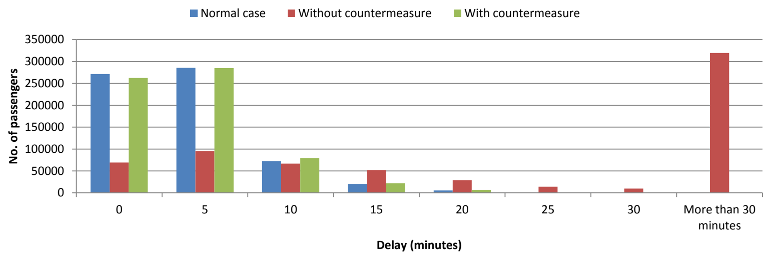
Cybersecurity for rail transit systems has received less attention than other critical infrastructures such as electric power, water/gas distribution, and aviation. However, with proliferation of wireless networking, commercial-off-the-shelf products, and automation in rail systems this is starting to change [14], [15]. In terms of funded research projects, over the last few years some European efforts began to systematically study the cybersecurity [16], [17] and security/safety engineering [18] of railway systems. As far as standards and best practices, security has not been a focus in the past [19], however there is a growing effort to adapt standards and introduce new best practices to improve the security level of railway systems [20].

Much of the existing academic work on railway security has focused on security issues for the ERTMS and GSM-R in particular [21], [22]. Another area of work is on system-level modelling and analysis [23]. Our work adopts lower-level control models, and is not limited to ERTMS, although railway balises are a component of that system. Recent work examining security issues for rail transportation [3], [2], [12] indicates that balises could be a disruptive point of attack, and [4] examines possible attacks and countermeasures. However, to the best of our knowledge, our work is the first systematic investigation of attacks on railway balises using high-fidelity physics-based models.

There are certain limitations in this study that we would like to discuss before we conclude the paper. First, the threat model used in this work assumes that attackers are not able to introduce additional balises into the railway system. One could imagine situations where additional balises, or device imitating



(a) Punctuality index.



(b) Passenger delay.

Fig. 8. Simulation results based on Shenzhen metro data.

balises, could be physically put into the system by determined attackers. Our proposed countermeasure would not directly work under such a threat model. How to defend against such attacks is an interesting open topic for future work. Second, within the context of the availability and integrity attacks considered, our study in this paper focuses on one train brake control algorithm (HOA from [5]) and one specific balise layout, as both are used in real deployment. However, the simulation tools we developed and the countermeasure we designed are not specific to the HOA algorithm or balise layout. One area of future work is to evaluate these attacks and countermeasure with other control logic and balise patterns.

Finally, our proposed software-only countermeasures is just one approach to reduce the damage of balise data attacks. There are other potential solutions that we have not explored. For example, one alternative is replacing existing railway balises with enhanced devices that contain stronger authentication and integrity checking mechanisms. Another important countermeasure is to strengthen the cyber and physical access control to prevent balises from being compromised. In comparison, our software-only solution minimizes changes to the legacy systems, hence could be easier for adoption. It also provides an additional layer of protection even when the balises are compromised.

VIII. Conclusion

We evaluate a train automatic stop controller that is used in real systems and show that it can be disrupted by compromising the availability or integrity of railway balise position data. To mitigate the threat, we propose and evaluate a software-only countermeasure using high-fidelity train braking models in Simulink and a system-level simulator based on the open-source Open Rails software. Our results show that the countermeasure ensures accurate train stopping with only a small extra stopping delay.

Acknowledgments

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