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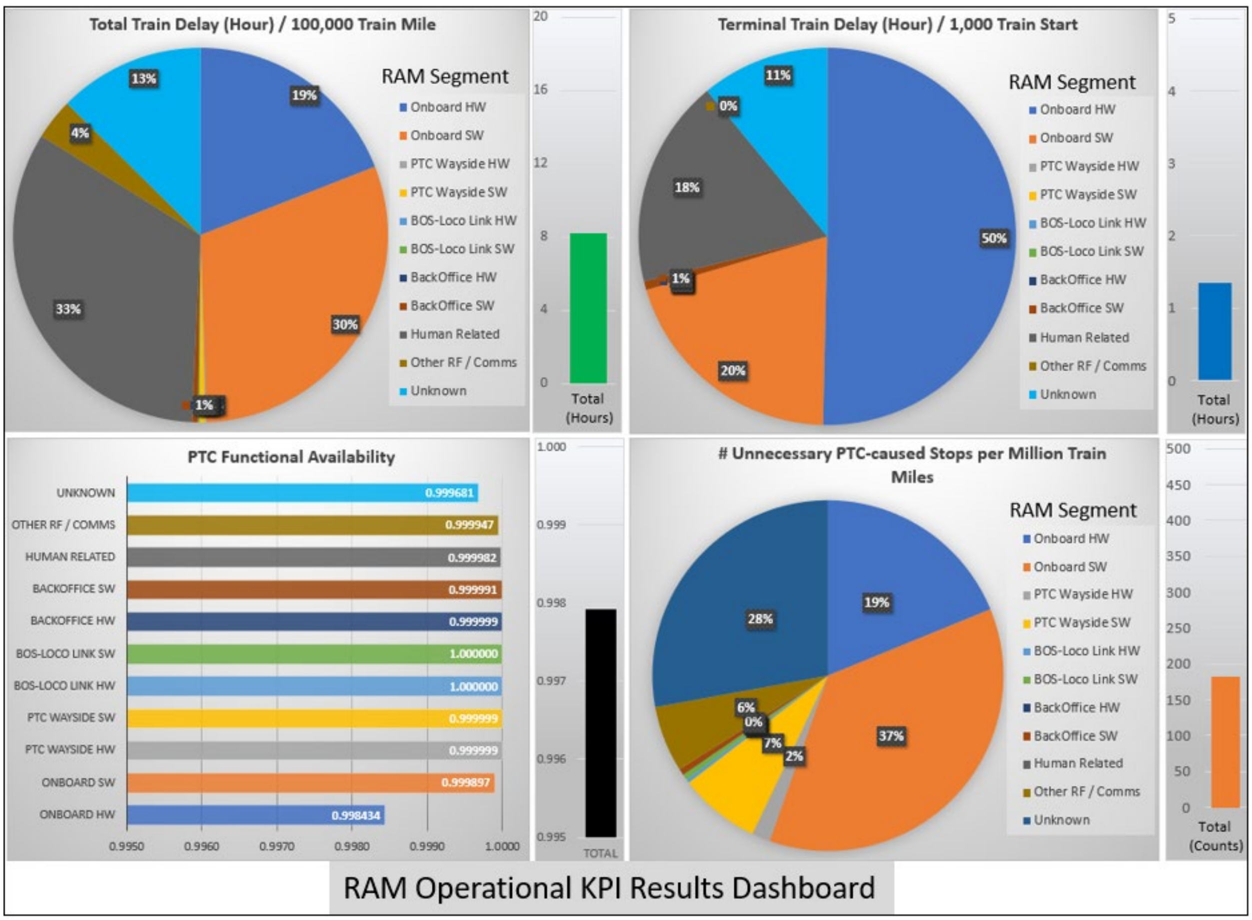
Positive Train Control (PTC) Reliability, Availability, and Maintainability (RAM) Study – Phase 2



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14. ABSTRACT
Between September 2018 and November 2021, the Federal Railroad Administration (FRA) sponsored a research team from Transportation Technology Center, Inc. (TTCI), now MxV Rail, to investigate and address areas of Reliability, Availability, and Maintainability (RAM) that are critical to the long-term sustainability and operation of Positive Train Control (PTC) systems. Although today's PTC systems provide safety benefits, they can significantly impact railroad operations when they stop or slow trains unnecessarily. The research team developed methods and tools to analyze and quantify the negative impact of PTC-related events and applied them to data collected from actual PTC operations to produce RAM growth recommendations.

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Executive Summary

Between September 2018 and November 2021, the Federal Railroad Administration (FRA) sponsored a research team from Transportation Technology Center, Inc. (TTCI), now MxV Rail, to investigate and address areas of Reliability, Availability, and Maintainability (RAM) that are critical to the long-term sustainability and operation of Positive Train Control (PTC) systems. Although today's PTC systems provide safety benefits, they can significantly impact railroad operations when they stop or slow trains unnecessarily. The research team developed methods and tools to analyze and quantify the negative impact of PTC-related events and applied them to data collected from actual PTC operations to produce RAM growth recommendations.

The analysis of the data collected from participant railroads indicates that not all railroad PTC systems are at the same stage of RAM maturity. Overall, the greatest operational impacts experienced by most railroads are due to human errors during system operation, followed by errors in the onboard systems. Railroads also experience issues that prevent trains from leaving a terminal with the PTC onboard system in the Active state, which can cause operational impacts. The analysis also identified multiple issues with the consistency and quality of the data collected, which is currently one of the primary focus areas for railroads.

Table 1 shows the aggregate results per RAM segment for the RAM Key Performance Indicators (KPI) based on ticket data collected from four participant railroads.

Table 1. Aggregate RAM KPI Results per RAM Segment

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability*	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	1.566	0.680	0.998434	34.4
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	8.217	1.350	0.997928	182.7

*Percentage of time that PTC is protecting train operation (i.e., PTC onboard in Active state)

The RAM quantification analysis indicates that the Mean Time Between Downing Events (MTBDE) for onboard software showed a steady increase throughout 2020. The MTBDE for human operator and onboard hardware is also increasing, albeit not as significantly as onboard software. The number of events that cannot be associated with a particular RAM segment (i.e., unknown) due to limitations either during data collection or post-event investigation has been declining over time, but unknown events are still a significant contributor in all RAM KPIs.

The RAM sensitivity analysis indicates that an increase of 2.5 times in the MTBDE for human-related events could cause a reduction of more than 18 percent in the overall aggregate train delay caused by PTC operation. The RAM sensitivity analysis also indicates that an increase of 2.5 times in the MTBDE for onboard hardware events would cause a reduction of 45 percent in the aggregate PTC functional unavailability.

The methods and tools developed for RAM analysis under this project can provide a comprehensive RAM assessment of the PTC system. However, due to issues related to the quality of the available ticket data, the RAM recommendations developed under this project cannot yet be used as a fully reliable and actionable RAM Program Plan.

Moving forward, the following potential steps can be explored:

- Railroads can use the methods and tools developed in this research to create their own analysis and prepare RAM growth plans.
- Researchers can continue the development of an industry-wide PTC-RAM growth program.

Future PTC-RAM efforts should focus on improving input data, including:

- Using data sources more reliable than raw ticket data (e.g., automated log data collection and processing from PTC system components)
- Automating data gathering/processing
- Standardizing RAM data contents among railroads

1. Introduction

Between September 2018 and November 2021, the Federal Railroad Administration (FRA) sponsored a research team from Transportation Technology Center, Inc. (TTCI), now MxV Rail, to investigate and address areas of Reliability, Availability, and Maintainability (RAM) that are critical to the long-term sustainability and operation of Positive Train Control (PTC) in the United States.

The research team developed methods and tools to analyze and quantify the negative impacts of PTC-related events using data collected from actual PTC operations to identify the main contributors to PTC unavailability and train delay. The team then used this information to prepare RAM growth recommendations. The team also documented these methods and tools and made them available to railroads so they can develop and implement RAM growth plans that address their specific needs.

1.1 Background

Today's PTC systems can significantly impact railroad operations when they stop or slow trains prematurely or unnecessarily. These events can also impact safety because the PTC equipment may no longer provide its intended safety functionality when it fails.

The impacts to railroad operations caused by PTC can include the following:

- Equipment/system failures – e.g., hardware failures or hardware or software design errors
- Message communication failures – e.g., loss of over-the-air or backbone messages, excessive communications latency, or insufficient throughput
- Global Positioning System (GPS) issues – e.g., loss of signal or errors that could result from multi-path, diminished satellite geometric dilution of precision (GDOP) or satellite outage
- Incorrect data – e.g., track data, consist characteristics, or configuration parameters
- Operator error – e.g., errors occurring during initialization or operation of the PTC system

These events can delay trains and reduce railroad capacity at a time when railroads are approaching capacity limits in many areas. The degradations are greatest in high traffic density areas where improvements are needed the most. Further, these locations are where delays in one train are most likely to cause delays in other (e.g., following) trains.

Understanding the effect of PTC impact events on the safety and efficiency of railroad operations is critical for the success of PTC operations. It is also fundamental for railroads to identify which components of the PTC system contribute most to railroad inefficiencies and unsafe operations and investigate how modifications to the system or its operation can reduce negative impacts.

Keeping the growing freight, passenger, and commuter traffic flowing efficiently, smoothly, and safely is critical to the nation's economy and its businesses, as well as citizen safety and well-being. Consequently, there is value in understanding the reliability of today's train control systems, and how capacity may be affected, especially in areas of high traffic density.

1.2 Objectives

This project was intended to address the following industry objectives:

- Quantify the impact of PTC on operations

- Identify the main contributors to reduced operational availability
- Develop PTC system and operational impact targets
- Develop PTC RAM targets allocated to RAM segments
- Develop RAM growth recommendations
- Develop a high-level RAM program plan

This research included a comprehensive analysis of PTC elements that was used to accurately portray the overall impact of PTC on railroad operations for ITC-compliant systems. A railroad industry PTC RAM model was developed to analyze log data containing train operations using PTC. The PTC RAM model and the additional tools and methods used in this project were provided to the participant railroads so the individual railroads can adapt them for use in their own operations.

1.3 Overall Approach

Researchers held regular meetings with the project's advisory group (AG) to present the progress of the project, discuss and make decisions about project-related issues, discuss technical concepts, obtain technical guidance, and present and review the results of technical analyses. The work was conducted through a combination of the following tasks:

- The collection and analysis of railroad log data containing PTC-related impact events
- The quantification of RAM parameters based on data collected from railroads
- The development of RAM Key Performance Indicators (RAM KPIs)
- The development of a comprehensive RAM modeling tool that includes all PTC system segments, including system operators
- The analysis of the main contributors to train operation impacts based on the quantified RAM parameters and the results from the comprehensive RAM modeling
- Sensitivity analysis of the RAM KPIs and the development of RAM growth recommendations based on the results obtained
- The development of a high-level RAM program plan documenting the methods and tools used in this project

1.4 Scope

The scope of the project included the following:

- Modeling the RAM characteristics and the behaviors of the ITC-compliant PTC segments of today's Overlay PTC (O-PTC) system in response to PTC impact events that include PTC system components (e.g., Back Office, onboard system, and Wayside Interface Unit), human operators, and communication system components (including external elements such as comms interference and GPS service)
- Analysis of log data containing train operations with PTC to characterize the frequency and duration of PTC-related impact events
- Proposal of the standard RAM data contents and related discussion with railroad participants

- Development of procedures to convert the proprietary railroad log data format to the standard RAM data format used in the RAM model
- Identification and modeling of operational RAM KPIs, as defined by the AG
- Identification of the main contributors that impact train operation based on the analysis of RAM KPIs
- Development of the sensitivity analysis and RAM growth recommendations based on the analysis of improvements in the RAM parameters of the main contributors

The scope of the project did not include the following:

- RAM modeling/analysis of the underlying systems (such as the signaling system)
- RAM modeling/analysis of potential new train control methods as defined in the Higher Reliability and Capacity Train Control program [1]
- Return on Investment (ROI) analysis of RAM growth recommendations

1.5 Organization of the Report

The report is divided into sections that cover the tasks included in the scope of the project, as listed below:

- Section 2 describes the tasks related to engagement with the industry regarding RAM efforts. It includes tasks such as the identification of RAM KPIs and the definition of RAM standard data collection strategies.
- Section 3 contains an overview of the methods and processes used for the RAM analysis developed in this project.
- Section 4 describes the technical details of the comprehensive RAM model developed for this project.
- Section 5 contains an overview of the RAM Program Plan process.
- Section 6 describes the process developed for the collection and analysis of railroad operational data.
- Section 7 describes the processes developed for the collection of RAM data and the quantification of RAM parameters.
- Section 8 contains the RAM growth recommendations based on analysis of the RAM modeling results obtained from the RAM and operational data provided by the railroads.
- Section 9 contains the research conclusions.
- Appendix A contains the draft vendor engagement plan that was developed (see Section 2).
- Appendix B contains the draft RAM Evaluation Questionnaires (see Section 2).
- Appendix C contains a detailed description of the typical operational scenarios that were used to generate the default configuration parameters used in the RAM model.
- Appendix D contains a detailed description of the RAM modeling design for three representative components of the system.

- Appendix E contains a description of the concepts used as principles for the modeling of the communication segment between the office and trains.
- Appendix F contains a description of the fundamental communication system characteristics used in the modeling of communication segments.
- Appendix G contains a description of the method used for the definition and the modeling of train traffic volumes.
- Appendix H contains a description of how the effects of PTC-related impact events are designed in the simulation tool and used to support and compare with the results produced by the RAM model developed for this project.
- Appendix I contains the High-Level RAM Program Plan that includes documentation of the methods and tools used during the development of this project.

2. Railroad and Supplier Engagement

An initial project task focused on initiating discussions with railroads and key PTC suppliers to define the RAM parameters required to develop the subsequent project tasks. The team interacted with vendors and railroad staff to help quantify RAM parameters based on methods and processes used during the development and implementation of PTC.

Researchers developed the initial tasks to engage key railroad suppliers and prepared a draft approach for vendor engagement (see Appendix A). However, after discussions with the AG, the team decided to indefinitely postpone this effort for the following reasons:

- The accuracy and quality of the data being collected during railroad operations were not sufficient to clearly identify which components of the PTC system were main contributors to PTC unavailability, particularly when trying to identify the root cause of a PTC impact event to correlate that event to a system component.
- The railroads and their vendors were focused on resolving several high-priority issues related to meeting PTC implementation deadlines and were concerned about the potential impact the demands of this project would have on these critical items.

The AG agreed that these efforts could be resumed at a later stage, as appropriate.

The initial progress made on this task is described in the following sub-sections. Note that the progress made to the definition of standard RAM data contents was shared with the participant railroads. This progress is described in Section 2.3.

2.1 PTC RAM Performance Metrics and Targets

The team, working with the AG, defined the following RAM KPIs:

- Total Train Delay per 100,000 Train-Miles of operation (TTDTM)
- Terminal Train Delay per 1,000 Train Starts (TTDTS)
- Number of Unnecessary PTC-caused Stops per 1,000,000 Train Miles of operation (UPSTM)
- PTC Functional Availability (PTCFA) – percentage of time PTC is protecting train operation (i.e., PTC onboard in Active state)

The RAM KPIs are calculated considering the train operation where the PTC is implemented. The RAM KPIs TTDTM, TTDTS, and UPSTM are related to railroad efficiency, PTCFA is related to safety, while the UPSTM is a variation of a historical PTC performance metric that had a goal of no more than one false enforcement per 1,000,000 train miles. This metric was refined to consider events that cause not only actual enforcements (e.g., a hardware failure of the onboard system) but events that also cause a train to stop (e.g., a stop target due to a non-communicating Wayside Interface Unit (WIU)).

These RAM KPIs are calculated by the Comprehensive RAM model (detailed in Section 4.6) and used to help identify the main contributors to impact regarding railroad efficiency and safety.

Initial discussions about targets for the RAM KPIs were held with the AG, though no conclusions were made throughout the development of the project, and industry metrics have not yet been established.

2.2 RAM Evaluation Questionnaire

In collaboration with the AG, the team developed questionnaires to assess railroads' and suppliers' existing processes and procedures, as well as existing reliability parameters such as Mean Time Between Failure (MTBF) and Mean Time To Restore (MTTR) for applicable components (see Appendix B). The team used the questionnaires to evaluate the RAM maturity of vendors and their products and to produce RAM scorecards. Based on those scorecards, the team developed theoretical RAM parameters for system components provided by vendors. The questionnaires were not sent to vendors because of the previously mentioned decision to postpone vendor engagement efforts.

2.3 Standard RAM Data Collection Strategy

Researchers prepared and presented to the AG a long-term data collection strategy for RAM analysis and continuous improvement of overall PTC availability. This strategy was based on the definition of standard RAM data contents that railroads periodically provide based on data collected from actual train PTC operation. The standard RAM data contents do not define specific data formats, just the contents of the information to be provided.

Once the required information is made available, interfaces convert the railroad data from the provided format to a standardized RAM database. The standard data is processed to generate RAM results (e.g., RAM KPIs) that can be used to define RAM growth actions. Figure 1 illustrates the proposed RAM Growth Data Collection strategy.

The proposed long-term strategy can be adopted by a railroad industry committee as part of a continuous RAM growth plan in which joint actions can be defined and implemented. The analysis of RAM data can also produce individual RAM actions when the analysis indicates that potential actions can be implemented for specific cases.

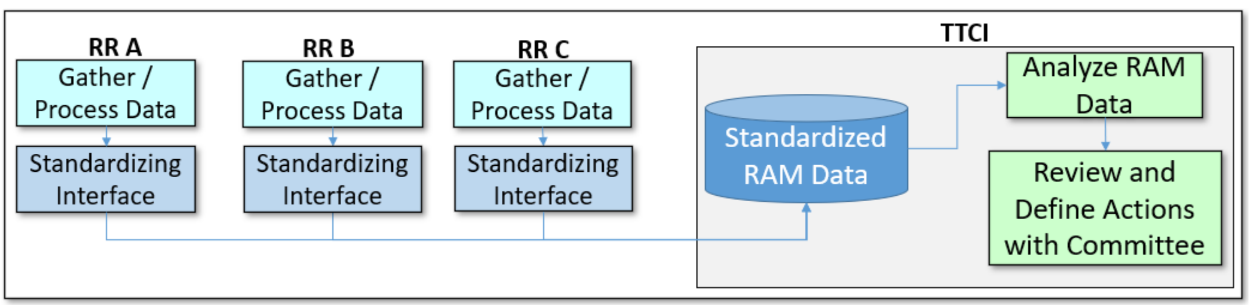

Figure 1. Standard RAM Data Collection Strategy

During the initial working sessions, researchers gathered samples from the PTC operation data that each railroad collects, typically in the format of ticket data created by the railroad's help desk center.

The team analyzed of the sample data collected from the railroads and found the following:

- The data quality was dependent on the capacity of a railroad to assign resources to collect and analyze the data.
- The railroads were at different levels of maturity regarding data collection and data quality.
- The criteria for qualifying an event were not uniform.
- The system component breakdown of impact events was not uniform.

- Several events could not be assigned readily to a PTC RAM segment or a specific root cause.
- Many fields contained free text information instead of pre-defined categories.

Based on the proposed long-term strategy, the information collected, and the requirements for RAM modeling, the team prepared and presented a proposal for standard RAM data contents that would contain the minimum information required for RAM analysis. A working group composed of members from participant railroads was established in mid-2019 to discuss and define the standard RAM data contents, but the group made limited progress.

In the beginning of 2020, the project focused on finalizing the comprehensive RAM model and processes around it. Results obtained from the RAM model were discussed with individual railroads to develop an understanding of the RAM model data input needs, the benefits of providing quality data, and the benefits of standard RAM data contents.

During the last quarter of 2020, the team revisited the discussions with each railroad individually, to verify the gaps between the data being provided and a new proposed standard RAM contents, as shown in Table 2.

Table 2. Standard RAM Data Contents Proposed by TTCI

Event Id	Timestamp	Direct Impact	Event Resolution	Terminal or En route	RAM Segment	Component
Parameters required for RAM Analysis:						
Event Id: RR identification of the event, such as a sequence number						
Timestamp of the event: Date/time when the event occurred						
Direct Impact: The immediate impact to a train, such as disengagement, enforcement; or to the system, such as WIU failure or Office down						
Event Resolution: The action(s) taken to resume train operation or to restore the component, i.e., did the train leave disengaged, was the locomotive rebooted, replaced, etc..						
Terminal/Enroute: Did the event take place at the terminal or en route?						
RAM Segment: Indicates which RAM segment a particular event belongs to, such as onboard hardware, onboard software, human-related, etc.						
Component: Identification of the component that caused the event, ideally at a Line Replacement Unit (LRU) level. Granularity of this information will provide a more targeted analysis.						

Due to ongoing efforts at each railroad, particularly regarding data gathering and processing, agreement on standard RAM data contents was not achieved during this project. To continue the project, the team collected and processed data from each railroad using the format and the quality level that each railroad could make available. The processing procedure included converting data collected from each railroad to the standard RAM format used by the team's RAM model. Section 7 contains details on the data collected and how it was used in the subsequent steps of the RAM analysis. The conclusions presented in Section 9 of this report contain proposed steps related to the standardization of RAM data contents that would allow the progress of an industry RAM program plan for PTC.

3. RAM Modeling and Analysis Overview

3.1 Objectives of RAM Modeling

The objective of the RAM modeling effort was to provide a single, comprehensive model that rolls up the RAM of individual PTC components or subsystems into the bottom-line railroad impacts, namely the availability of PTC to perform its primary safety function (i.e., PTC functional availability) and the quantification of those impacts on overall train delay (i.e., railroad network delay).

The RAM model allows near-instantaneous what-if analyses of bottom-line railroad impacts as various RAM parameters/assumptions are changed (i.e., the model does not require the running of railroad network simulations that typically require numerous iterations for a single data point). The RAM model also does not necessarily require the implementation of Reliability Block Diagram (RBD) models that can predict the expected RAM behavior of a system/system components, although the RAM model accepts results from RBD models as input parameters.

3.2 PTC RAM Modeling Stages

RAM modeling can be implemented at multiple stages as described in Table 3.

Table 3. RAM Modeling Stages

Stage	Description	Key Output	Tool Example
1) Quantification of RAM Parameters	Quantification of RAM system/sub-system parameters based on the inter-dependency of system components and their RAM parameters	MTBDE, MTTR	RAPTOR™
2) Estimation of RR Network Train Delay	Estimation of total train delay caused by downing events that impact the operation of trains operating with PTC for given operational scenarios	Train Delay	RTC™, Arena®
3) Calculation of RAM KPIs	Estimation of overall impact caused to the entire railroad network operation, considering infrastructure characteristics and train traffic volumes of each railroad's subdivisions	Operational RAM KPIs	

Each RAM modeling stage has specific objectives and outputs as described below:

1) Quantification of RAM Parameters: A RAM model can be implemented to calculate/estimate the behavior of a system/sub-system from the RAM perspective, or produce the expected availability of the system itself based on the architecture of the system (i.e., the interdependency among system components) and the reliability and maintainability parameters of the system components. Such a model can produce key outputs such as Mean Time Between Downing Events (MTBDE)[1] and MTTR[2]. An example of a RAM modeling tool for this stage is Rapid Availability Prototyping for Testing Operational Readiness (RAPTOR™).

[1] The PTC system includes components that cause functionalities to become unavailable not only because of the failure of the components but also due to human interaction/operation so MTBDE is used instead of MTBF.

[2] The RAM analysis in this project considers the time that it takes for train operations to restore, and not necessarily the time that it takes to repair a system component. For example, if the PTC onboard hardware fails, the train delay calculation considers the time that it takes to restore train operations with a failed onboard system, instead of the time that it would take to fix the onboard system.

2) Estimation of Railroad Network Train Delay: A railroad network modeling tool can be used to estimate the overall network train delay caused by a downing event in the PTC system for a given operational scenario. Such a model can be configured to trigger the downing events of system components based on the RAM parameters (MTBDE and MTTR) of those events. The results of the network operation, including downing events, can be compared with the operation of the network without downing events to calculate the network train delay. Such a model can be implemented with either simulation or analytical methods. Examples of discrete-event simulation tools that can be used for railroad network simulations are Rail Traffic Controller (RTC™) and Arena®.
3) Calculation of RAM KPIs: The final stage of RAM modeling includes the calculation of operational RAM KPIs. The results of network train delays for given operational scenarios are extrapolated to the overall railroad operation (i.e., multiple subdivisions), considering the infrastructure configuration and train traffic volumes of each railroad subdivision. RAM KPIs are typically based on the proportion of train delays per train miles of operation and/or the availability of key system functionality per train miles of operation.

The RAM modeling tool produced for this project includes stages 2 and 3 in Table 3. The details of the comprehensive RAM modeling are included in Section 4. The details of the RAM modeling tool developed for this project are included in Appendix D.

3.3 PTC Impact Event

A PTC Impact Event (PTCIE) is any event resulting from a PTC operation that causes a train delay or PTC functional unavailability. The correct modeling of PTCIEs is critical for the development of a RAM modeling tool. PTCIEs can be:

- The hardware or software failure of a PTC component, such as the onboard computer, WIU, or a radio
- The failure of a non-PTC component that a PTC component depends upon, such as locomotive interfaces
- The external factors that affect the performance of PTC components, such as radio frequency (RF) message losses
- A human error made during operation or configuration

PTCIEs do not include delays in train operation that would have been incurred without PTC operation. For example, if a signaling system wayside signal fails, the PTC system will enforce an unplanned train stop, but the train would have stopped due to the failed signal regardless of whether PTC was implemented or not. On the other hand, if a wayside signal is cleared but the status of that signal is not received by the onboard system due to a radio failure, a train stop will be enforced due to the PTC.

A detailed list of PTCIEs is included in Section 4.5.

3.4 PTC RAM Segments

For RAM modeling, the PTC system was divided into the following 10 distinct RAM segments:

1) Human-related: Includes all personnel that can interact with the system and cause a PTCIE either in the office or in the field (e.g., dispatchers, train crew, and staff responsible for the configuration and maintenance of the system)

2) Back Office Hardware: All office hardware components

3) Back Office Software: All office software components

4) Back Office Server (BOS)-Loco Link Hardware: All hardware that provides a connection between the locomotive and the office

5) BOS-Loco Link Software: All software that provides a connection between the locomotive and the office

6) PTC Wayside Hardware: All wayside hardware that supports Wayside Status Message (WSM) broadcast

7) PTC Wayside Software: All wayside software that supports WSM broadcast

8) Onboard Hardware: All onboard hardware that enables PTC operation

9) Onboard Software: All onboard software that enables PTC operation

10) Other RF/Comms Related: Includes RF/communications-related events that cannot be allocated to any of the other RAM segments, such as en route loss of GPS signal (due to lack of service), WSM message loss due to interference, fade, ducting and other external factors.

Figure 2 illustrates the PTC RAM segments.

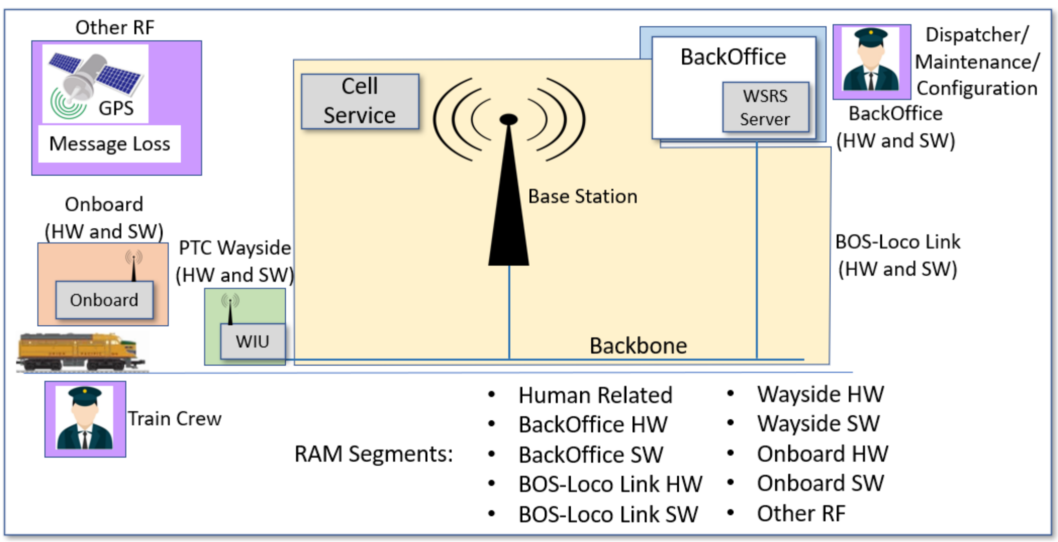

Figure 2. Illustration of PTC RAM Segments

Besides the 10 RAM segments shown in Figure 2, an unassigned RAM segment is also included in the model to accommodate for downing events whose cause is not identified.

3.5 RAM Modeling Process, Inputs and Outputs

The RAM modeling process developed for this project can be organized into three components: the inputs to the model, the modeling tool itself, and the outputs produced by the model. The model created for this project is identified as PTC RAM Impact Analysis (RAMIA).

As inputs, RAMIA requires the following:

- Configuration of Operational Scenarios: Detailed description/configuration of a railroad operational scenario, such as total route miles, number of sidings, track configuration (single, double, triple), signaled or not, and number of base stations

- Train Traffic Volumes for each Operational Scenario: Total number of trains operated over a period and the types of trains, such as freight, expedited, or passenger
- Quantification of RAM Parameters for the PTC RAM segments: MTBDE and MTTR for RAM segments or, if available, lower-level components, i.e., Line Replacement Units (LRU)

Note that RAMIA can be used to analyze multiple operational scenarios with their associated train traffic volumes either from a single railroad or from multiple railroads. The RAM quantification can be calculated with either simulated models (e.g., RBD models) or based on actual historical data. As outputs, RAMIA produces operational RAM KPIs and detailed results for each of the RAM segments and/or LRU components (if configured in the model). Figure 3 illustrates the RAM process with RAMIA and its inputs/outputs. The following sub-sections contain detailed descriptions of the required inputs and outputs produced by RAMIA. Appendix I contains a detailed description of the RAMIA tool.

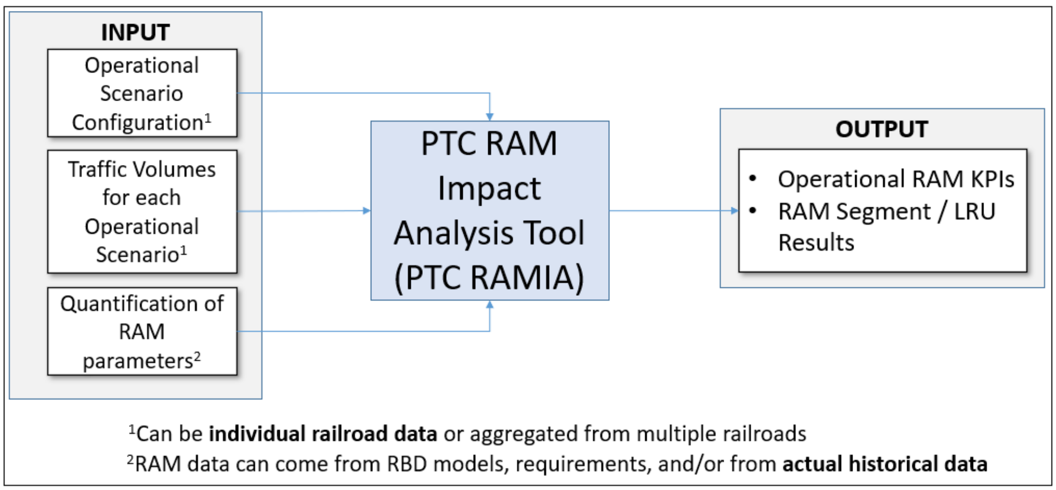

Figure 3. Illustration of RAMIA Inputs and Outputs

The characteristics and the volume of train traffic in the operational scenarios are extremely important because of the indirect impacts caused by the occurrence of a PTCIE. If, for example, the PTC onboard system fails in a train that is operating in single-track territory and the PTC onboard is cutout, that train will operate at reduced speed. This can affect following trains and trains in the opposite direction. Section 4.1 contains details on how this is implemented in the RAM model.

Train traffic volumes for an operational scenario can be configured for a single territory (e.g., a subdivision) or for a group of territories with the same characteristics (e.g., multiple subdivisions with similar physical characteristics, such as signaled single-track with similar siding spacing and characteristics, and volume of train traffic or average number of daily trains). Section 5 contains a description of how train traffic volumes were developed for this project.

The model produces the four operational RAM KPIs defined in Section 2.1 (TTDTM, TTDTS, UPSTM, and PTCFA) as main outputs.

The RAM KPIs are calculated per PTCIE and can be applied to RAM segments as well as at the overall system level. Details about the RAMIA tool and its inputs/outputs are provided in Appendix I.

Besides the RAM KPIs, RAMIA also calculates the average overall train speed reduction caused by PTC. Section 4.6 contains details of the calculation of RAM KPIs in RAMIA.

4. Comprehensive RAM Modeling

The RAM model considered two distinct modeling aspects to accurately reflect the overall impact of PTC on railroad operations. The two distinct aspects of the RAM model are:

- Railroad network operation: The reaction of train operation when a PTCIE occurs, including trains that are directly and indirectly affected by a PTCIE
- RAM parameters: How the primary RAM parameters – MTBDE and MTTR – are considered to determine train delay and PTC functional availability over a time period

The following subsections provide further details on how these modeling aspects are considered in the RAM model developed for this project.

4.1 Modeling Principles for Railroad Network Operation

The foundation of railroad network modeling relies on the behavior of a train that is directly affected by a PTCIE. Depending on the type of PTCIE, a train stop may be enforced, or the PTC system on a train may disengage, or the train may have to stop and/or cutout the PTC. Based on the behavior resulting from the PTCIE, the founding elements for the determination of impacts in efficiency and safety can be calculated.

Figure 4 illustrates the train speed profile for a hypothetical scenario where a PTCIE causes a PTC brake enforcement. After the train stops, the train engineer recovers from the enforcement and resumes operation with PTC disengaged, and PTC re-engages after some time. The diagram shows the time unprotected (that leads to the calculation of PTCFA) and the train delay (that leads to the calculation of TTDTM) caused by the PTCIE to that train.

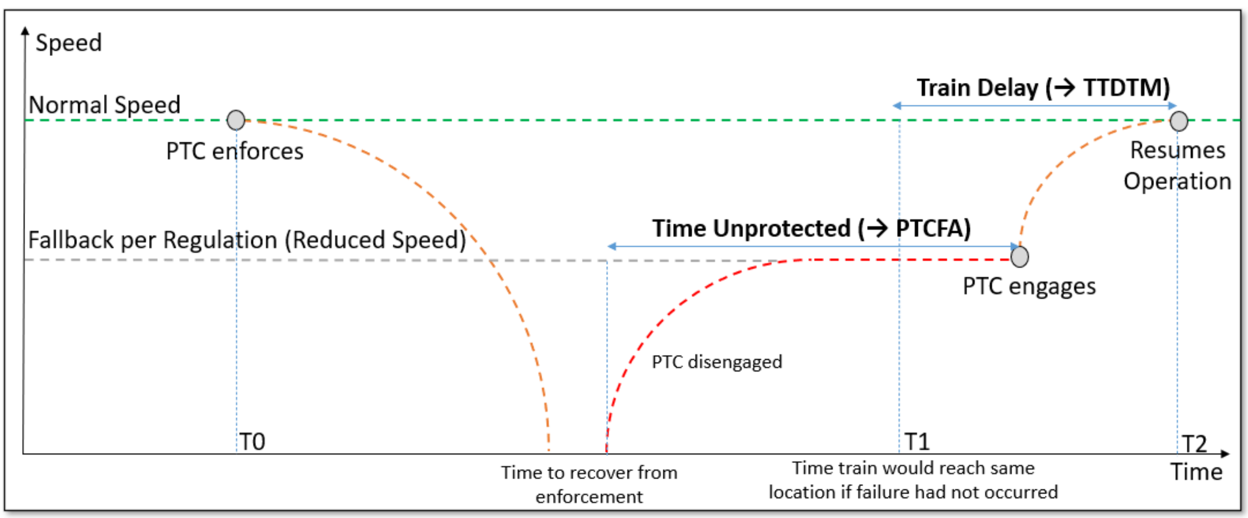

Figure 4. Illustration of Operational and Functional Availability Impacts Caused by the Occurrence of a Hypothetical PTCIE

When a train is affected by a PTCIE, the result of the impact on that train may also affect the operation of other trains in the vicinity. Following trains may have to reduce speed if the separation between the directly affected train and the following train reaches a minimum train separation. This sequence of events may affect multiple trains, not only the train immediately behind, but also other trains behind in a chain effect depending on how close trains are operating. If the directly affected train must operate at a reduced speed due to the PTCIE (e.g., when PTC is disengaged or cutout) a decision may be made to let the trains behind pass or have the lead locomotive of the directly affected train replaced (or have the failed onboard component fixed). The trains operating in the opposite direction of the directly affected train may also be affected, typically due to meet-pass encounters.

Figure 5 shows the time-distance diagram of a hypothetical single-track scenario where a train (TRAIN1) is affected by a PTCIE that causes the train to operate at a fallback velocity instead of at a normal average speed (e.g., an unrecoverable onboard failure). In this case, TRAIN1 will have a delay as indicated by D1. D1 is the result of the comparison of the time that train would have arrived at its destination if the PTCIE had not occurred and the actual arrival time of TRAIN1. Trains behind TRAIN1 (TRAIN2 through TRAIN6) will be indirectly affected since those trains would have to pass TRAIN1 when a minimum headway separation (indicated as Hm in Figure 5) is reached. Additionally, TRAIN1 could also have meet-pass encounters with trains in the opposite direction (represented as black lines) that would not have happened if the PTCIE had not occurred. In this example, it was assumed that TRAIN1 stops for the resolution of the meet-pass encounters with trains in the opposite direction (TRAIN1 stops for trains in the opposite direction are not shown in the diagram but instead are indicated with the red/yellow circles where they would occur). This example shows that the total network train delay will be the direct train delay for TRAIN1 (D1) plus the sum of all indirect train delays for the other trains (D2+D3+D4+D5+D6) and additional meet-pass encounters with trains in the opposite direction.

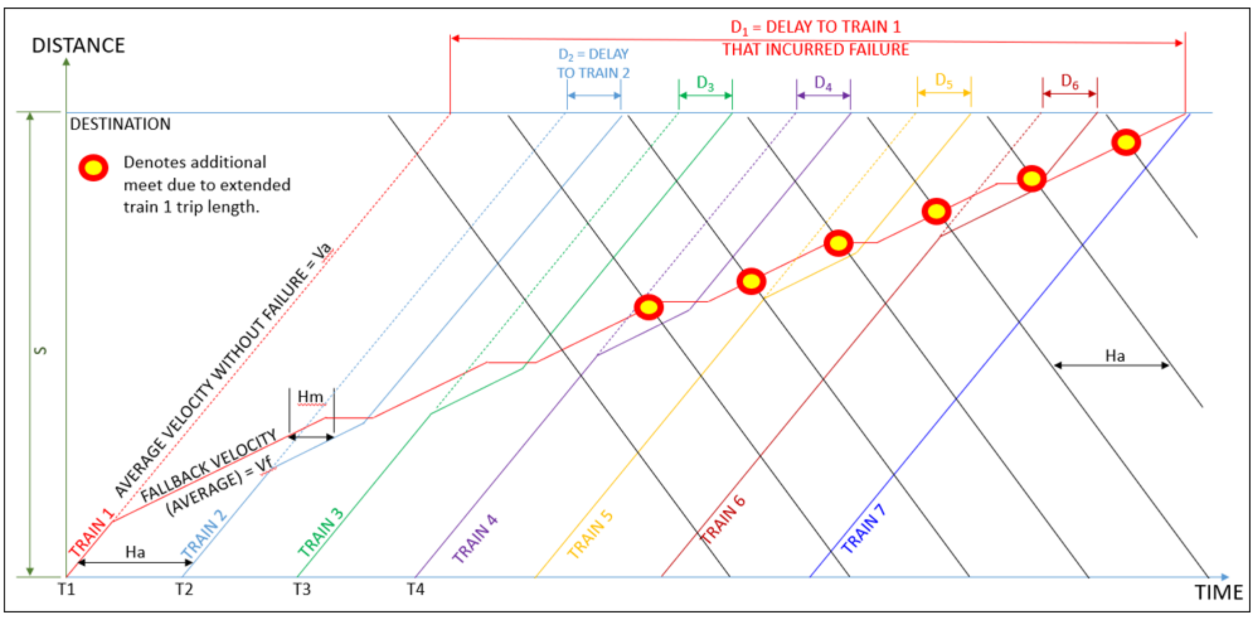

Figure 5. Train Delays Caused to the Network due to a Train Operating with PTC Onboard Cutout

The concepts illustrated above are applied to the multiple types of PTCIE according to the circumstances of each occurrence. For example, some types of PTCIE directly affect only one train, (e.g., an onboard failure or train engineer operation error) while other types of PTCIE may affect multiple trains (e.g., a base station or a WIU failure). Section 4.5 contains details of how each PTCIE affects train operation.

The effect on trains also depends on the track configuration type. For example, in a single-track configuration, trains operating in the opposite direction are more likely to be indirectly affected, while in double- and triple-track configurations, indirect effects may not occur or may cause less impact. The RAM model includes four different track types: signaled single track, signaled double-track, signaled triple-track, and non-signaled single track. Appendix C contains the details of the default operational scenario configuration included in RAMIA and used in RTC simulations.

4.2 Modeling Principles for RAM Parameters

The RAM parameters – MTBDE and MTTR – are used at different stages of the modeling process. MTTR is used to calculate direct train delays. For example, when calculating the impact caused by a WIU outage (due to a failure), the time that the WIU is down (i.e., MTTR) is used to determine how many trains would have passed by that WIU based on average train headway separation. Similarly, if the event occurs at a terminal, the time to restore the train to normal operation from that event (i.e., MTTR) is considered as a direct train delay.

MTBDE is used to calculate train delay or the unavailability of PTC functionality proportional to the time that the system component related to a PTCIE is in operation. For trains, the total time that the trains operated during a certain period is used with the MTBDE to determine how many times a PTCIE would have occurred during that period. For example, if the total train miles operated in one year for a given subdivision is 1,000,000, and trains operate on average at 25 mph, the total hours of train operation would be 40,000 hours. If the MTBDE of a certain PTCIE is 10,000 hours, the number of events for that PTCIE in one year would be four, and the total delay caused by that PTCIE in one year would be four times the delay caused by the occurrence of one event. Analogous calculations are done for all the RAM KPIs and all RAM segments. Appendix D contains a detailed description of RAM KPI calculations for selected PTCIE examples.

4.3 Analysis of Events from a Train vs. Component Perspective

The analysis of the train operation impact due to PTC-related events can be developed from the perspective of the train or from the perspective of PTC system components that affect train operation (e.g., a WIU, a base station, or office components). The failure of a WIU, for example, can be analyzed from events reported by the trains that were directly affected by that event when the analysis is based on data that reports what trains have experienced during operation. When the analysis is done based on a theoretical assumption or from theoretical models, such as an RBD model, a component perspective can be used instead. For example, if there is no sufficient operational data to determine the RAM parameters of the Back Office hardware, theoretical parameters can be used to characterize Back Office hardware outages.

The RAM model includes PTCIEs that evaluate impacts on train operation from both the train and system component perspective; PTCIEs that are analyzed from the perspective of a component are referred to as "outage" PTCIEs. The RAM model supports the analysis of PTCIEs from either perspective. However, for the same type of event, (i.e., a WIU failure) the analysis should not include both perspectives because it could result in double-counting the impacts for that type of event.

4.4 Train Dynamics Modeling

The RAM model includes functions to account for the dynamics of trains (i.e., train acceleration, deceleration, and train speeds) to calculate the effects of PTCIEs on train operation. Three types of trains are included in the RAM model: Freight, Expedited, and Passenger. For each operational scenario included in the RAM model, the percentage of each train type is required as an input to the model. For each of the train types with a percentage of trains greater than zero, the train dynamic parameters described in the following subsection must be provided to the RAM model. The RAM model uses the percentages of the three train types to calculate one weighted average train dynamic configuration that is used in train acceleration/deceleration formulas for a given operational scenario.

4.4.1 Train Speeds

The RAM model includes parameters for three target speeds: Maximum Authorized Speed (MAS), Reduced Speed, and Restricted Speed Restriction (RSR). These speeds are used in conjunction with the train acceleration and deceleration rates to determine the amount of time lost during an operation at these speeds and other specific scenarios when trains are not operating with PTC active.

Depending on the type of event, the RAM model uses different average speeds:

- The RAM model uses average train speeds (Normal and Reduced) for the calculation of train delay due to a PTCIE, such as train disengagement or train cutout non-recoverable that causes a train to operate for long distances at Reduced Speed, and includes delays caused by meet-pass encounters and the effects of the track profile. Figure 6 illustrates the calculation based on average speeds.

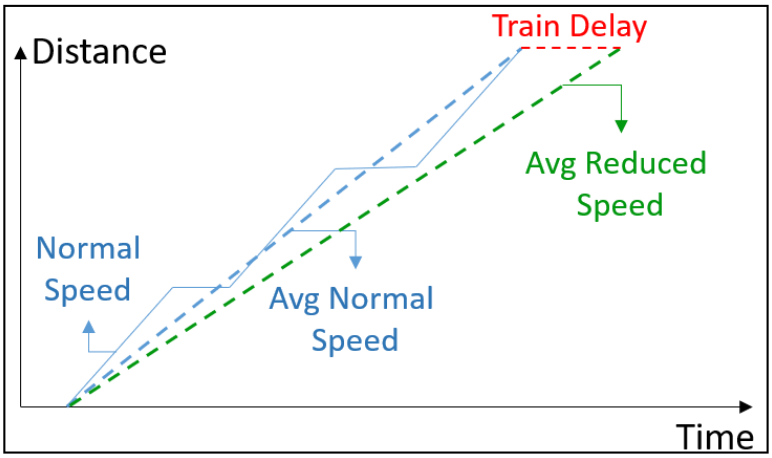

Figure 6. Illustration of Train Delay Based on Average Train Speeds

- The RAM model uses the speed limits specified for the train types to calculate the delay caused by a PTCIE that causes a train to operate for a short distance at Reduced Speed or RSR, such as when a train is authorized to pass a red signal and operate at RSR through the next block. Figure 7 illustrates this scenario, including the effects caused by the acceleration and deceleration of the train impacted by the PTCIE.

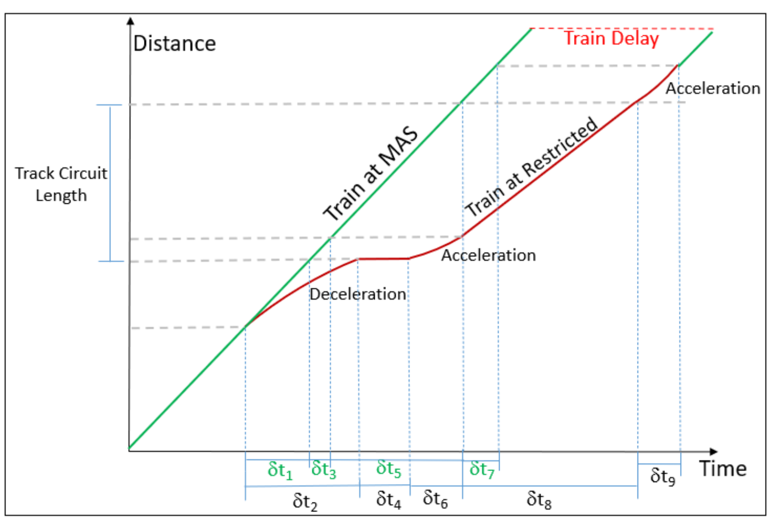

Figure 7. Illustration of Train Delay Calculation due to a PTCIE that Causes a Train to Stop and Proceed at a Control Point

4.4.2 Train Acceleration and Deceleration Rates

The RAM model uses six specific train acceleration rates for different sets of initial-to-target speeds and train models:

- 0 mph to Reduced Speed
- 0 mph to RSR
- 0 mph to MAS
- RSR to Reduced Speed
- RSR to MAS
- Reduced Speed to MAS

Three types of train braking operation are modeled to simulate the operation of PTC:

- Full-service application: Used to decelerate a train for an enforcement, such as when the PTC onboard hardware fails
- Normal service application with PTC target: Used by the crew to decelerate a train to comply with PTC enforced targets, such as a Stop Signal or RSR
- Emergency application: Used to decelerate a train due to a PTC emergency application

The RAM model requires the configuration of braking rates for the three types of braking operation described above.

4.5 RAM Segment and PTCIE Modeling

Multiple PTCIEs are configured for each of the RAM segments described in Section 3.4.

PTCIEs can occur at a terminal or en route. The model considers that per PTC regulation trains are not allowed to depart from a terminal without the PTC active, and for that reason terminal events result in train delay but do not contribute to PTC unavailability. An event such as an onboard hardware failure that prevents PTC from becoming Active on a train will require the replacement of the lead locomotive with a functioning onboard PTC segment for that train. Train delays due to terminal events are included in the calculation of the RAM KPI related to train starts (TTDTS), as well as in the calculation of the RAM KPI related to total train delay (TTDTM). PTCIEs that occur en route can result both in train delay and PTC unavailability.

The following subsections describe the modeling concepts for the different types of PTCIEs that can occur in each RAM segment.

4.5.1 Onboard Hardware RAM Segment

The RAM model assumes that an onboard failure occurs at a location half the distance from origin to destination (i.e., the average distance) and calculates total train delay (direct and indirect). In the single-track configuration, it is assumed that trains behind will pass the failed train. In double- and triple-track territory, the RAM model assumes that trains behind do not pass since the total train delay, including the additional delay in the opposite direction, would be higher than not passing. The RAM model considers that when the onboard system is cutout it can proceed at Reduced Speed according to Subpart I of 49 CFR§ 236 [2]. The RAM model includes one type of PTCIE due to failure at an origin terminal that requires the replacement of the lead locomotive, as it is assumed that trains can only leave a terminal with the PTC active, per Subpart I of 49 CFR§ 236 [2]. The model assumes that only the train itself is delayed (i.e., no indirect delays to other trains). There is no differentiation between the impact of different PTC components (i.e., no difference between a failure in the onboard computer or the interface to the 220 MHz radio) for a given RAM segment and PTCIE. In the conventional system configuration, certain components of a system segment are typically combined as LRU, a set of components that are replaced together when a failure occurs. The RAM model allows the configuration of individual RAM parameters (MTBDE and MTTR) for the LRUs of a RAM segment. If the LRU RAM parameters are provided, the RAM model uses them to calculate the RAM parameters of that RAM segment.

For en route events, the RAM model requires MTBDE input from the user. MTTR is calculated based on the sequence of events needed to restore train operations (e.g., the time that it takes for the train to come to a stop following an enforcement and the time to restore PTC operation) so there is no need for MTTR input from the user.

Table 4 contains the PTCIEs included in the Onboard Hardware (HW) RAM segment.

Table 4. List of PTCIEs for the Onboard Hardware RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route Onboard HW Non-recoverable with Enforcement	Onboard hardware failure that causes immediate enforcement. Onboard is cutout, and train resumes operation at Reduced Speed for the rest of the trip.	*En route*
En route Onboard HW Non-recoverable without Enforcement	Onboard hardware failure that does not cause enforcement (such as display failure) but requires crew-to-cutout PTC. Crew stops train, cuts out PTC, and proceeds at Reduced Speed for the rest of trip	*En route*
Terminal Onboard HW Recoverable with Replacement	Onboard hardware failure that cannot be recovered and lead locomotive is replaced. Train is delayed, and then resumes normal operation	*Terminal*

4.5.2 Onboard Software RAM Segment

For en route events, the RAM model requires MTBDE input from the user. MTTR is calculated based on the sequence of events to restore train operations (e.g., the time that it takes for the train to come to a stop following an enforcement and the time to restore PTC operation) so there is no need for MTTR input from the user.

There are two types of failure events at terminal. The model assumes that these events cause delay only to the train itself (i.e., no indirect delays to other trains):

1) Recoverable SW failure that requires locomotive to be replaced – the model does not require MTTR input for this PTCIE
2) Recoverable with SW restart (no locomotive replacement) – the model requires MTTR input for this PTCIE

The RAM model does not differentiate between different types of onboard SW components.

Table 5 contains the PTCIEs included in the Onboard Software (SW) RAM segment.

Table 5. List of PTCIEs for the Onboard Software RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route Onboard SW Recoverable with Enforcement	Onboard software failure causing enforcement. Train recovers air, crew reboots software, and train resumes normal operation.	*En route*
En route Onboard SW Recoverable with Disengagement	Onboard software event that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software, and train resumes normal operation.	*En route*
En route Onboard Data Corruption Recoverable with Enforcement	Onboard software failure caused by corrupted data, causing enforcement. Crew cuts PTC out, train proceeds to next siding at Reduced Speed. Onboard software is updated, and train resumes normal operation.	*En route*
En route Onboard SW Recoverable with Emergency Brake	Onboard software failure causing emergency brake application. Crew walks the train, reboots software, and train resumes normal operation.	*En route*
En route Onboard SW Recoverable with Train Delay Only	Onboard software failure that causes train to reduce speed, but PTC remains active and does not impose a speed restriction. Train resumes normal operation after crew resolves issue.	*En route*
En route Onboard SW Recoverable with Train Stop	Onboard SW failure that causes train to stop, but PTC remains active and does not impose a speed restriction. Train resumes operation after stop.	*En route*
En route Onboard SW Non-recoverable with Disengagement	Non-recoverable onboard software failure that causes disengagement (no enforcement), but crew is required to cutout PTC. Train proceeds to next siding at Reduced Speed. Crew cuts PTC out and train proceeds at Reduced Speed for the rest of trip.	*En route*
En route Onboard SW Non-recoverable with Enforcement	Non-recoverable onboard software failure that causes enforcement. Crew cuts out PTC, and train proceeds at Reduced Speed for the rest of trip.	*En route*
En route Onboard SW WIU-Loco Link Error with Enforcement	Enforcement caused by WSMs not being received, and the cause is onboard software. Train stops, crew contacts dispatcher, and train resumes normal operation.	*En route*
En route Onboard SW WIU-Loco Link Error resulting in a required stop	Train must stop because WSMs are not being received, and the cause is the onboard software. Train stops at the signal or the monitored switch, proceeds at RSR through next block.	*En route*
En route Onboard SW Synch Error with Disengagement	Synch error event caused by Onboard SW that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software, and train resumes normal operation.	*En route*
En route Onboard SW Synch Error with Enforcement	Synch error event caused by Onboard SW that causes enforcement. Train stops, crew reboots software, and train resumes normal operation.	*En route*
En route Onboard SW Recoverable with Unmap/Map	Error in the onboard SW that causes the system not to receive indication from the field. Train stops and crew resolves the issue by unmapping and remapping the track in the onboard SW.	*En route*
Terminal Onboard SW Recoverable with Replacement	Onboard software failure that cannot be fixed with restart. Lead locomotive is replaced. Train is delayed, and then resumes normal operation	*Terminal*
Terminal Onboard SW Recoverable with Restart	Onboard software event that is recoverable with software restart. Causes train delay at terminal.	*Terminal*
Terminal Onboard SW Update	Onboard software update at terminal.	*Terminal*

4.5.3 PTC Wayside Hardware RAM Segment

Distinct models were developed for three types of WIU: Control Point Signal, Intermediate Signal, and WIU at a monitored switch in Non-Signaled territory. At a failed Intermediate Signal WIU, the train stops and then proceeds through the block at RSR. At a Control Point WIU, time is added for the Dispatcher authorization process. For a WIU at a monitored switch in Non-Signaled territory, it is assumed that the crew will be able to see the position of the switch when the train is at a configurable distance from the switch (default parameter set to 500 feet) and confirm it is properly aligned, allowing the train to resume normal operation.

For the outage PTCIEs, the RAM model uses the MTTR and train separation to calculate the impact to all trains that would have passed by that WIU during failure. In multiple track territory, it is assumed that all tracks are affected. There is no differentiation between impacts based on the type of PTC component within the wayside segment. The default MTBDE and MTTR are the same regardless the type of WIU or component that has failed.

Table 6 contains the PTCIEs included in the PTC Wayside Hardware RAM segment.

Table 6. List of PTCIEs for the PTC Wayside Hardware RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
PTC Wayside HW Outage at Control Point or automatic interlocking	PTC Wayside hardware failure that causes train not to receive WSM (or to receive an overly restrictive WSM) from a WIU at a Control Point. Train stops before signal, crew contacts dispatcher, obtains authorization, and proceeds to next signal at Restricted Speed. When train reaches next signal, it resumes normal operation. Multiple trains affected until PTC Wayside hardware is restored.	*En route*
PTC Wayside HW Outage at Intermediate Signal	PTC Wayside hardware failure that causes train not to receive WSM (or to receive an overly restrictive WSM) from a WIU at an Intermediate Signal. Train stops before signal and proceeds to next signal at Restricted Speed. When train reaches next signal, it resumes normal operation. Multiple trains affected until PTC Wayside hardware is restored.	*En route*
PTC Wayside HW Outage (e.g., in non-signaled territory)	PTC Wayside hardware failure at controlled switch, monitored non-controlled switch, or another monitored wayside device. Crew starts speed reduction to stop before switch (or monitored device) until it is 500 feet from switch/device and then resumes normal operation.	*En route*
PTC Wayside HW Failure at Control Point or automatic interlocking	Same as PTC Wayside SW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
PTC Wayside HW Failure at Intermediate Signal	Same as PTC Wayside SW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
PTC Wayside HW Failure (e.g., in non-signaled territory)	Same as PTC Wayside SW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*

4.5.4 PTC Wayside Software RAM Segment

The PTCIEs for the PTC Wayside Software RAM segment are equivalent to those defined for PTC WIU Hardware – the only difference in terms of RAM modeling are the RAM parameters used. Typically, software components will have shorter MTTR than hardware components.

Table 7 contains the PTCIEs included in this RAM segment.

Table 7. List of PTCIEs for the PTC Wayside Software RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
PTC Wayside SW Outage at Control Point or automatic interlocking	PTC Wayside software failure that causes train not to receive WSM (or to receive an overly restrictive WSM) from a WIU at a Control Point. Train stops before signal, crew contacts dispatcher, obtains authorization, and proceeds to next signal at Restricted Speed. When train reaches next signal, it resumes normal operation. Multiple trains affected until PTC Wayside software is restored.	*En route*
PTC Wayside SW Outage at Intermediate Signal	PTC Wayside software failure that causes train not to receive WSM (or to receive an overly restrictive WSM) from a WIU at an Intermediate Signal. Train stops before signal and proceeds to next signal at Restricted Speed. When train reaches next signal, it resumes normal operation. Multiple trains affected until PTC Wayside software is restored.	*En route*
PTC Wayside SW Outage in non-signaled territory	PTC Wayside software failure at controlled switch, monitored non-controlled switch, or another monitored wayside device. Crew starts speed reduction to stop before switch/device until it is 500 feet from switch/device, and then resumes normal operation.	*En route*
PTC Wayside SW Failure at Control Point or automatic interlocking	Same as PTC Wayside HW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
PTC Wayside SW Failure at Intermediate Signal	Same as PTC Wayside HW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
PTC Wayside SW Failure (e.g., in non-signaled territory)	Same as PTC Wayside HW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*

4.5.5 BOS-Loco Link Hardware RAM Segment

For the PTCIEs that cause an outage, the model calculates the impact caused by the unavailability of one base station (i.e., it assumes that one base station is not communicating with the back office). The unavailability can be caused either by a failure of a base station or the communications backbone. A failure of the backbone that would affect multiple base stations is not modeled. In addition to assuming a single base station failure, it was also assumed that there is base station redundant coverage. Typically, base station coverage redundancy varies per type of scenario (i.e., triple-track territory typically has higher coverage redundancy than double-track territory, which has more than a single track, and that can be configured as such in the RAM model). The RAM model also considers that cell communication may be available for the BOS-Loco link and combines the probability of both communication paths (i.e., 220 MHz radio and cell comms). Appendix E provides details of how the BOS-Loco link communication path is modeled.

The unavailability of communication between the loco and the BOS causes different impacts to train operations, based on the type of WIU:

- WIUs with direct RF comms: The train still communicates with WIUs directly and obtains WSMs, and the impact in train operations is due to the lack of heartbeat messages sent from BOS (i.e., a train will disengage after a timeout with a default parameter set at 6 mins after entering a coverage gap and will restore normal operation after passing the gap). It is assumed that the train crew acknowledges the disengagement warning issued onboard (i.e., train is not enforced due to non-acknowledgment from crew).

- WIUs with WSRS only: Assuming the most restrictive condition, i.e., trains will stop receiving WSMs from base stations within the coverage gap area and will be impacted due to the lack of WSMs in direct RF territory.

The RAM model includes the following features:

- For WIUs with direct RF, because a train only disengages after not communicating with the Back Office for a pre-defined period (see Appendix F for details), the RAM model discounts this time to determine the duration of time that the train will be disengaged. It is possible that the coverage gap is small enough that a train will regain coverage and not be affected when operating through a coverage gap.
- The model uses the proportion of Zone 1 length (see Appendix F for details on Zone 1 definition) to average block sizes to determine the probability that a coverage gap will impact train operation.
- For WIUs with direct RF, the model calculates the impact of gaps caused by planned WSRS that would not be received by trains when the link is down. It also uses the Zone 1 length probability to calculate the impact. The impact caused by this type of gap is typically very small but could become more noticeable in areas that depend more on planned WSRS messages.
- The cell service redundancy path has been included in the model. It includes two parameters (i.e., cell coverage and cell service availability) that are applied to the entire operational scenario to average numbers for the scenario.

The model uses MTTR and train separation to define how many trains will be affected (i.e., how many trains will encounter the gap).

Table 8 contains the PTCIEs included in the BOS-Loco Link Hardware RAM segment.

Table 8. List of PTCIEs for the BOS-Loco Link Hardware RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
BOS-Loco link HW Outage - WIUs with direct RF comms	Failure will cause a coverage gap. Trains will continue to receive WSMs directly from WIUs but will disengage PTC if it does not receive heartbeat messages (assumed 6 minutes as worst case). If/when disengaged, trains will operate at Reduced Speed through the remainder of the gap, and then resume normal operation.	*En route*
BOS-Loco link HW Outage - WIUs with WSRS only	Failure will cause a coverage gap. Trains stop receiving WSMs from WIUs and will be impacted the same way as if a WIU failure occurs. Failure varies depending on the type of WIU (Control Point, Intermediate, or Non-signaled territory) as explained for the WIU failure events.	*En route*
BOS-Loco link HW Failure with Enforcement	Like BOS-Loco link HW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
BOS-Loco link HW Failure with Red Fence	Like BOS-Loco link HW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*

4.5.6 BOS-Loco Link Software

The PTCIEs for the BOS-Loco Link Software RAM segment are equivalent to those defined for the BOS-Loco Link Hardware RAM segment; the only difference in terms of RAM modeling are the RAM parameters.

Table 9 contains the PTCIEs included in this RAM segment.

Table 9. List of PTCIEs for the BOS-Loco Link Software RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
BOS-Loco link SW Outage - WIUs with direct RF comms	Failure will cause a coverage gap. Trains will continue to receive WSMs directly from WIUs but will disengage PTC if it does not receive heartbeat messages (assumed 6 minutes as worst case). If/when disengaged, trains will operate at Reduced Speed through rest of the gap and then resume normal operation.	*En route*
BOS-Loco link SW Outage - WIUs with WSRS only	Failure will cause a coverage gap. Trains stop receiving WSMs from WIUs and will be impacted the same way as if a WIU failure occurs. Failure varies depending on the type of WIU (Control Point, Intermediate, or Non-signaled territory) as explained for the WIU failure events.	*En route*
BOS-Loco link SW Failure with Enforcement	Like BOS-Loco link SW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*
BOS-Loco link SW Failure with Red Fence	Like BOS-Loco link SW Outage, but affecting just one train (i.e., impact perceived from the perspective of the train).	*En route*

4.5.7 Office Hardware RAM Segment

For the Office Hardware RAM segment, two distinct models were developed for office components that resulted in different impact characteristics. One model accounts for the failure of the office components that will cause all trains in the scenario to disengage for not receiving heartbeat messages (i.e., it assumes that all trains in that scenario are connected to that Back Office). There is no breakdown of the office components for this segment.

Another model was developed for the WSRS server. The failure of the WSRS server causes an impact on all trains/territory in the subdivision. It causes the same impact as a failure in the BOS-Loco link related to the delivery of WSMs to trains. If the WIUs serviced by the WSRS server that failed have direct RF communication (i.e., have 220 MHz radios), the impact on train operations is attributed to the gaps caused by WSM relays pre-planned in the RF network design, as described in the RF Network Design for Dense Urban Report [3]. The model uses an "average WSRS gap size" (i.e., the average size of WSRS gaps for an operational scenario) as input to estimate the impact on trains for this case.

Table 10 contains the PTCIEs included in this RAM segment.

Table 10. List of PTCIEs for the Office Hardware RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route Back Office HW Outage	Trains operating in the subdivisions controlled by the failed Back Office will disengage (for not receiving heartbeat messages) and operate at Reduced Speed until Back Office is restored. When Back Office is restored, PTC is engaged, and trains resume normal operation.	*En route*

PTCIE	Consequence to Train Operation	En route/Terminal
WSRS Server HW Outage - WIUs with direct RF comms	Failure will cause coverage gaps where WSRS is required to resolve coverage not satisfied by direct WIU transmission. Trains will stop receiving WSMs from WIUs and will be impacted the same way as if a WIU failure occurs. This varies depending on the type of WIU (Control Point, Intermediate or Non-Signaled territory) as explained for the WIU failure events.	*En route*
WSRS Server HW Outage - WIUs with WSRS only	Failure will cause trains traveling along the territory where the WSRS server provides service to not receive WSMs. Trains on those territories will stop, cutout PTC, and proceed at Reduced Speed until WSRS server is restored.	*En route*
Terminal Back Office HW Outage	Trains cannot Initialize and would not leave terminal until Back Office is restored.	*Terminal*

4.5.8 Back Office Software RAM Segment

The PTCIEs for the Back Office Software RAM segment contain multiple types of impact due to Back Office software failure. Some events can cause delay only to the train operation, but no train enforcement nor disengagement. Train disengagements due to Back Office software synchronization failure are tracked separately from other types of disengagement. Back Office software outages can be configured separately for software failures or software maintenance events.

Table 11 contains the PTCIEs included in this RAM segment.

Table 11. List of PTCIEs for the Office Software RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route Back Office SW Outage	Trains operating in the subdivisions controlled by the failed Back Office will disengage and operate at Reduced Speed until Back Office is restored. When Back Office is restored, PTC is engaged, and trains resume normal operation.	*En route*
En route Back Office SW Maintenance Outage	Trains operating in the subdivisions controlled by the Back Office will disengage and operate at Reduced Speed until Back Office maintenance is complete. When Back Office is restored, PTC is engaged, and trains resume normal operation.	*En route*
En route Back Office SW Failure Recoverable with Disengagement	Synch error event caused by Back Office that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software, and train resumes normal operation.	*En route*
En route Back Office SW Failure Recoverable with Enforcement	Synch error event caused by Back Office that causes enforcement because train engineer did not respond to acknowledgment prompt triggered by the Back Office software failure. Train stops, crew reboots software, and train resumes normal operation.	*En route*
En route Back Office SW Failure Recoverable with Red Fence	Error in the Back Office SW that causes a train to see an incorrect Stop Target (signal is cleared). Train must stop and proceed at signal.	*En route*
En route Back Office SW Failure Recoverable with Train Stop	Error in the Back Office SW that causes train engineer to stop the train and then proceed with normal operation.	*En route*
En route Back Office SW Failure Recoverable with Delay Only	Error in the Back Office SW that does not cause train to stop or to be enforced but causes delay in operation.	*En route*
En route Back Office SW Failure Non-recoverable with Enforcement	Error in the Back Office SW that causes train enforcement, and PTC operation is not recoverable. Train cuts out PTC and proceeds at Reduced Speed until the end of trip.	*En route*

PTCIE	Consequence to Train Operation	En route/Terminal
En route Back Office SW Synch Error with Disengagement	Synch error event caused by Back Office that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software and train resumes normal operation.	*En route*
En route Back Office SW Synch Error with Enforcement	Synch error event caused by Back Office that causes enforcement because train engineer did not respond to acknowledgment prompt. Train stops, crew reboots software, and train resumes normal operation.	*En route*
WSRS Server SW Outage - WIUs with direct RF comms	Failure will cause coverage gaps where WSRS is required to resolve coverage not satisfied by direct WIU transmission. Trains will stop receiving WSMs from WIUs and will be impacted the same way as if a WIU failure occurs. This impact varies depending on the type of WIU (Control Point, Intermediate or Non-Signaled territory) as explained for the WIU failure events.	*En route*
WSRS Server SW Outage - WIUs with WSRS only	Failure will cause trains travelling along the territory where the WSRS server provides service to not receive WSMs. Trains on those territories will stop, cutout PTC, and proceed at Reduced Speed until WSRS server is restored.	*En route*
Terminal Back Office SW Outage	Trains cannot Initialize and would not leave terminal until Back Office is restored.	*Terminal*
Terminal Back Office SW Failure Recoverable	Failure in the Back Office that causes delay to a single train.	*Terminal*

4.5.9 Human-related RAM Segment

The model includes events that can be caused by human interaction with the system. The two groups interacting with the system are train crews and maintenance/configuration personnel in the Back Office.

Table 12 contains the PTCIEs included in this RAM segment.

Table 12. List of PTCIEs for the Human-Related RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
Terminal Crew Operation Delay	User-caused delays such as incorrect password or any other. Causes delay to train departure. Train eventually departs in normal operation.	*Terminal*
En route Crew Error - Braking Curve Enforcement	Train crew does not reduce speed per braking curve causing enforcement. Train resumes normal operation after stop, contacting dispatcher, and recovering air.	*En route*
En route Crew Error - Emergency Application	Train crew does not reduce speed per braking curve causing enforcement and triggering the Emergency brakes. Train resumes normal operation after stop, contacting dispatcher, walking the train, and recovering air.	*En route*
En route Crew Error - Other Enforcement	Other crew errors that cause an enforcement, e.g., incorrect track selection, incorrectly reporting the position of a non-monitored switch or going active when too close to a switch, when interacting with the system. Train resumes normal operation after stop, contacting dispatcher, and recovering air.	*En route*
En route Crew Error - Disengagement	Crew error causing disengagement. Train resumes operation after some typical time.	*En route*
En route Crew Error - Train Stop	Crew error that requires a train stop (no enforcement by PTC). Train resumes normal operation after stop.	*En route*
En route Crew Error - Delay Only	Crew error while operating system that causes train delay, but PTC remains active and does not impose any additional restriction.	*En route*

PTCIE	Consequence to Train Operation	En route/Terminal
En route Dispatcher Error - Train Stop	Dispatcher error that requires a train stop (no enforcement by PTC). Train resumes normal operation after stop.	*En route*
En route Maintenance Subdiv File Update	The subdiv file of a subdivision needs to be updated to fix an incorrect configuration or to reflect changes in the field. Every train operating in the subdivision will disengage and operate at Reduced Speed until the onboard subdiv file is updated. Train does not have to stop. After update, PTC is engaged, and trains resume normal operation.	*En route*
En route Maintenance Consist Error	Consist error not detected at departure time but detected during train operation en route. The error may have occurred at point of origin or after a pickup or setout en route. Crew stops train, fixes consist data, and train resumes normal operation.	*En route*
En route Maintenance Map Error	Configuration error in the subdiv file that causes enforcement at a signal location. Train proceeds to next signal at Restricted Speed and resumes normal operation.	*En route*
Terminal Dispatcher Error	Error (such as incorrect Bulletin) caused by dispatcher, causing departure delay.	*Terminal*
Terminal Crew Consist Error	Errors made by the crew related to train consist data entry that cause train delay at terminal.	*Terminal*
Terminal Maintenance Consist Error	Train consist error detected at departure time. Causes train delay. Train eventually departs in normal operation.	*Terminal*
Terminal Maintenance Other Error	Include other types of errors in system configuration/database, such as missing PIN, etc.	*Terminal*

4.5.10 Other RF/Comms RAM Segment

The Other RF/Comms RAM segment includes RF/communications-related events that cannot be associated to any of the other RAM segments, such as en route loss of GPS signal (due to lack of service), WSM message loss due to interference, fade, ducting, and other external factors. This segment also includes communication errors in the path between a WIU and the locomotive.

Table 13 contains the PTCIEs included in this RAM segment.

Table 13. List of PTCIEs for the Other RF/Comms RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route loss of GPS Signal	Intermittent GPS coverage loss or poor-quality signal. Train will continue for some distance until it will disengage. Train resumes normal operation when GPS signal returns (value TBD, based on analysis of data).	*En route*
En route WSM Message Loss	Intermittent PTC message loss due to interference, fade, ducting, and other external factors that cause messages not to arrive at destination. It is assumed that this message loss affects WSMs (i.e., messages originated at WIUs to trains) and the effect is the same as WIU failure. See Appendix F for modeling details of this PTCIE.	*En route*
En route Comms Synch Error with Disengagement	Synch error event caused by the comms link that affects just one train and causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software and train resumes normal operation.	*En route*
En route Comms Synch Error with Enforcement	Synch error event caused by the comms link that affects just one train and causes enforcement because train engineer did not respond to acknowledgment prompt. Train stops, crew reboots software, and train resumes normal operation.	*En route*

PTCIE	Consequence to Train Operation	En route/Terminal
En route Comms WIU-Loco Link Error with Emergency Brake	Train stops receiving WSMs when already close to signal (within Zone 1), causing emergency brakes to be applied. Train resumes normal operation after train crew walks the train.	*En route*
En route Comms WIU-Loco Link Error with Enforcement	Enforcement caused by WSMs not being received because of the comms link between loco and the WIU. Train stops, contacts dispatcher, and resumes normal operation.	*En route*
En route Comms WIU-Loco Link Error with Red Fence	Train stop is enforced because WSMs are not being received and the cause is the comms link between loco and the WIU. Train stops at the signal, proceeds at RSR through next block.	*En route*
En route Comms Synch Error with Emergency Brake	Train stops receiving WSMs when already close to signal (within Zone 1), causing emergency brakes to be applied. Train resumes normal operation after train crew walks the train.	*En route*

4.5.11 Unassigned Segment

The unassigned segment includes impact events that cannot be associated to a RAM segment due to lack of complete diagnostics of root causes.

Table 14 contains the PTCIEs included in this RAM segment.

Table 14. List of PTCIEs for the Unassigned RAM Segment

PTCIE	Consequence to Train Operation	En route/Terminal
En route Unknown Synch Error with Disengagement	Synch error event that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software and train resumes normal operation.	*En route*
En route Unknown Synch Error with Enforcement	Synch error event that causes enforcement because train engineer did not respond to acknowledgment prompt. Train stops, crew reboots software, and train resumes normal operation.	*En route*
En route Unknown Synch Error with Emergency Brake	Train stops receiving WSMs when already close to signal (within Zone 1), causing emergency brakes to be applied. Train resumes normal operation after train crew walks the train.	*En route*
En route Unknown WIU-Loco Link Error with Enforcement	Enforcement caused by WSMs not being received and the cause is unknown (i.e., it could be the WIU, radio, backbone, WSRS, base station, or the loco radio). Train stops, contacts dispatcher, and resumes normal operation.	*En route*
En route Unknown WIU-Loco Link Error with Red Fence	Train stop is enforced because WSMs are not being received and the cause is unknown (i.e., it could be the WIU, radio, backbone, WSRS, base station or the loco radio). Train stops at the signal, proceeds at RSR through next block.	*En route*
En route Unknown WIU-Loco Link Error with Emergency Brake	Train stops receiving WSMs when already close to signal (within Zone 1), causing emergency brakes to be applied. Train resumes normal operation after train crew walks the train.	*En route*
En route Unknown Enforcement Recoverable	Unknown or unidentified event that causes enforcement. Train stops, crew contacts dispatcher, reports issue, reinitializes onboard, and train resumes normal operation.	*En route*
En route Unknown Disengagement Recoverable	Unknown or unidentified event that causes onboard to disengage (no enforcement). Train proceeds to next siding at Reduced Speed. Crew reboots software, and train resumes normal operation.	*En route*
En route Unknown Emergency Brake Recoverable	Train stops receiving WSMs when already close to signal (within Zone 1), causing emergency brakes to be applied. Train resumes normal operation after train crew walks the train.	*En route*

PTCIE	Consequence to Train Operation	En route/Terminal
En route Unknown Enforcement Non-Recoverable	Unknown or unidentified event that causes enforcement and cannot be recovered. Train stops, crew obtains authorization from dispatcher, cuts PTC out, and train resumes operation with Reduced Speed until destination.	*En route*
Terminal Unknown Failure Recoverable with Replacement	Unknown failure that requires the locomotive to be replaced (or a major fix/replacement in the onboard).	*Terminal*
Terminal Unknown PTC System Delay	Initialization process takes longer than usual due to problems with system (not user), but the cause is unknown.	*Terminal*
Terminal Unknown Train Delay	Unknown or unidentified event that causes delay at departure.	*Terminal*
Terminal Unknown Synch Error	Synch Error during initialization causing delay in terminal/yard.	*Terminal*

4.6 RAMIA Modelling Tool

RAMIA is an analytical, deterministic modeling tool developed in this research that implements the RAM model described in the previous sections. Appendix I contains a detailed description of RAMIA functionalities.

RAMIA was developed using Microsoft Excel™ as the user interface and Microsoft Visual Basic for Applications™ (VBA) for the development of source code. The tool is self-contained and can be executed in any Microsoft Excel version 2011 (Build 13426.20404) enabled to execute VBA.

RAMIA is composed of three tabs that are visible to the user as shown at the bottom of Figure 8.

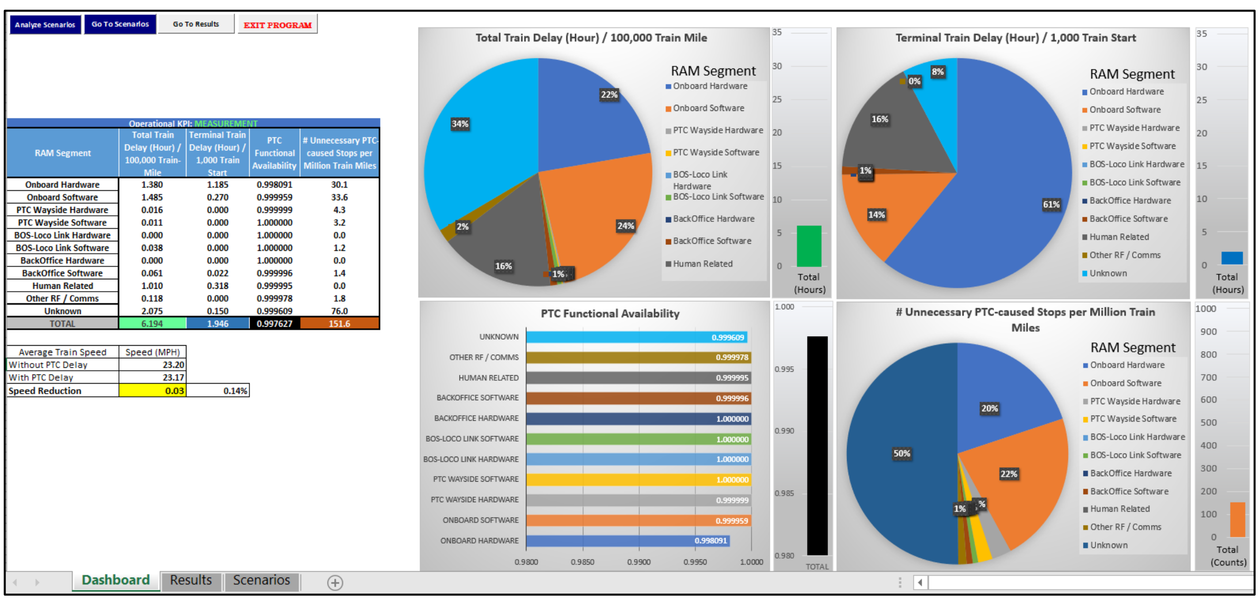

Figure 8. Screenshot of RAMIA's Dashboard

The three tabs are:

1. Dashboard: This tab displays the aggregated RAM KPI results of the selected operational scenarios configured in the tool.
2. Results: This tab contains RAM KPI results of each PTCIE for every operational scenario selected for execution.

3. Scenarios: This tab is where the user configures all the input parameters required for the execution of RAMIA.

The operation/navigation of RAMIA is the same as any Microsoft Excel file. A few navigation functionalities were implemented with VBA code to facilitate the usability of the tool.

Besides the tabs visible to the user, RAMIA contains additional tabs that are used for internal processing and calculations. These tabs are hidden to avoid interfering with the execution of RAMIA. The additional tabs, shown in Figure 9, are:

- Default Parameters: Contains default input parameter for each type of operational scenario. These default parameters are used to load input parameters when a new operational scenario is created.
- LRU_Inputs: Contains default LRU breakdown per PTCIE and default RAM parameters for each.
- OC_Single Track: Processing tab that contains the formulas invoked and the corresponding results for signaled single-track operational scenarios.
- OC_Double-Track: Processing tab that contains the formulas invoked and the corresponding results for signaled double-track operational scenarios.
- OC_Triple-Track: Processing tab that contains the formulas invoked and corresponding results for signaled triple-track operational scenarios.
- Non_Signaled: Processing tab that contains the formulas invoked and the corresponding results for non-signaled operational scenarios.
- LRUProcessing: Processing tab that contains the formulas invoked for the calculation of RAM segment parameters based on LRU breakdown.
- AvailableScenarios: Processing tab containing the configuration parameters used during the processing of operational scenarios.

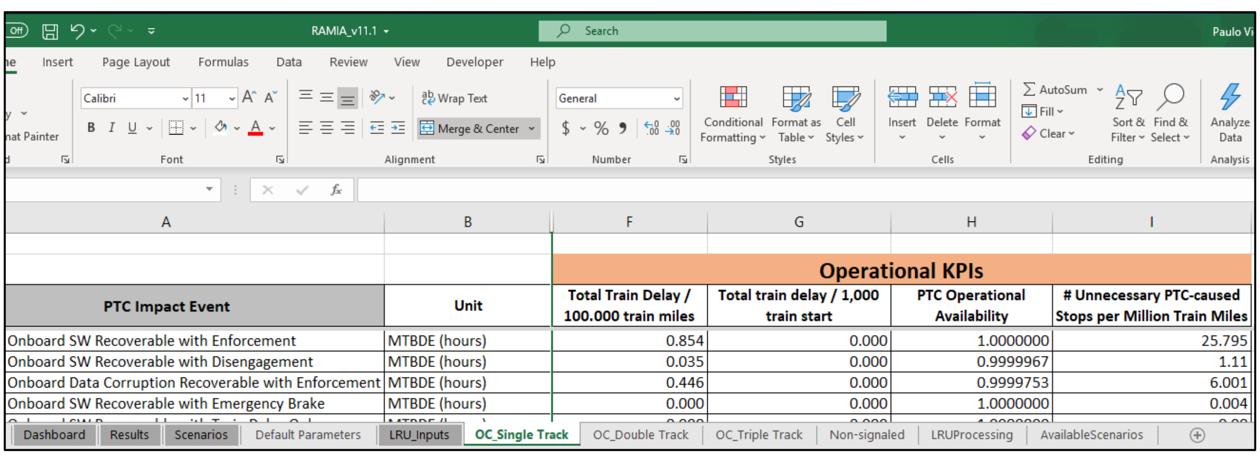

Figure 9. Screenshot of RAMIA's Additional Tabs

The VBA source code is protected from user access and requires a password to unlock, and is placed in multiple modules. The VBA modules, are:

- Macro_FilterAvailableScenerios: Contains the functions used for navigation/creation/editing of operational scenarios.

- Macro_openSceneriosForm: Contains the forms used for navigation/creation/editing of operational scenarios and calculation of results (Results and Dashboard tabs).
- Multipurpose_Functions: Contains functions used in RAM calculations for multiple operational scenarios.
- Single_Track_Functions: Contains functions used in RAM calculations for signaled single-track and non-signaled operational scenarios.
- Double_Track_Functions: Contains functions used in RAM calculations for signaled double-track operational scenario.
- Triple_Track_Functions: Contains functions used in RAM calculations for signaled triple-track operational scenario.

The core design of RAMIA's processing logic is as follows:

- Operational scenarios are created, and input parameters are configured by the user.
- User requests RAMIA to analyze the operational scenarios (see Appendix I for details on how to perform this function).
- For each one of the operational scenarios, RAMIA calculates results according to the following steps:
    - Input parameters of the scenario are copied to the corresponding processing tab (i.e., OC_Single Track, OC_Double-Track, OC_TripleTrack, or Non-signaled)
    - The processing table invokes the corresponding function that calculates the RAM KPI results for each of the PTCIEs.
    - The RAM KPI results are copied to the Results tab.
- After the RAM KPI results are calculated for each PTICE for all operational scenarios, RAMIA compiles the results into RAM Segments and displays them in the Dashboard tab. Results are weighted based on total train miles operated per operational scenario.

4.7 RAM KPI Calculation

RAMIA calculates the RAM KPIs for all PTCIEs for every operational scenario that is selected for execution. It uses the inputs configured in the Scenarios tab and calculates the RAM KPIs for each PTCIE according to the following sequence:

- Calculate total train delay (direct and indirect) caused by that PTCIE (Step 1)
- Calculate total train miles and number of hours of train operation in each operational scenario in one year of operation, based on average train headways and train average speed (Step 2)
- Calculate the number of train starts in each operational scenario in one year of operation, based on average train headways (Step 3)
- Calculate the time that trains operate unprotected (i.e., not Active) when a PTCIE occurs (Step 4)
- Calculate the number of unnecessary PTC train stops that occur in one year of operation (Step 5)

- Calculate the RAM KPIs:
  - TTDTM using (1), (2) and the PTCIE MTBDE
  - TTDTS using (1), (3) and the PTCIE MTBDE
  - Number of UPSTM using (2) and (5) and the PTCIE MTBDE
  - PTCFA using (2) and (4)

The RAM KPI results are presented under two tabs in RAMIA:

- Results: Contains the RAM KPI results of every PTCIE for each of the selected operational scenarios
- Dashboard: Contains the aggregated[3] RAM KPI results of all operational scenarios per RAM segment

The Results tab contains the results of the four RAM KPIs for every PTCIE for each operational scenario selected for execution. It also contains the total train delay caused by one occurrence of that PTCIE in each operational scenario.

Figure 10 shows one illustrative example of the Results tab with a partial list of PTCIEs for one operational scenario.

Go To Scenarios / Clear Results	TUL 102 Single Track				
PTC Impact Event	Total Train Delay (hours)	Total Train Delay / 100.000 train miles	Total train delay / 1,000 train start	PTC Operational Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Enroute Onboard HW Non-recoverable with Enforcement	0.556	0.515	0.000	0.9989663	16.388
Enroute Onboard HW Non-recoverable without Enforcement	0.493	0.000	0.000	1.0000000	0.004
Terminal Onboard HW Recoverable with Replacement	1.680	0.582	0.171	1.0000000	6.126
Enroute Onboard SW Recoverable with Enforcement	0.451	1.134	0.000	1.0000000	44.479
Enroute Onboard SW Recoverable with Disengagement	0.424	0.029	0.000	0.9999965	1.196
Enroute Onboard Data Corruption Recoverable with Enforcement	1.120	0.272	0.000	0.9999823	4.297
Enroute Onboard SW Recoverable with Emergency Brake	0.752	0.017	0.000	1.0000000	0.401
Enroute Onboard SW Recoverable with Train Delay Only	0.200	0.162	0.000	1.0000000	0.000
Enroute Onboard SW Recoverable with Train Stop	0.451	0.884	0.000	1.0000000	0.004
Enroute Onboard SW Non-recoverable with Disengagement	0.800	0.000	0.000	1.0000000	0.638
Enroute Onboard SW Non-recoverable with Enforcement	0.556	0.020	0.000	0.9999598	0.638
Enroute Onboard SW Synch Error with Disengagement	0.100	0.008	0.000	0.9999901	0.000
Enroute Onboard SW Synch Error with Enforcement	0.300	0.156	0.000	0.9999877	9.182
Enroute Onboard SW WIU-Loco Link Error with Enforcement	0.120	0.008	0.000	0.9999997	1.108
Enroute Onboard SW WIU-Loco Link Error with Red Fence	0.338	0.111	0.000	0.9999983	5.800
Enroute Onboard SW Recoverable with Unmap/Map	0.208	0.003	0.000	1.0000000	0.000
Terminal Onboard SW Recoverable with Replacement	1.680	0.001	0.000	1.0000000	0.000
Terminal Onboard SW Recoverable with Restart	0.180	0.429	0.126	1.0000000	0.000
Terminal Onboard SW Update	0.050	0.004	0.001	1.0000000	0.000

Figure 10. Screenshot of "Results" tab with Partial List of PTCIEs and Associated RAM KPI Results

The Dashboard tab contains several groups of information:

1. A tabular display of the aggregated RAM KPI results per RAM segment for all operational scenarios included in the analysis. It also includes the accumulation of the RAM KPI results of all operational scenarios. Figure 11 shows one example of a tabular RAM KPI aggregate results.

[3] Individual RAM KPIs results of all operational scenario are average weighted based on the total train-miles operated per year in each operational scenario

Operational KPI: MEASUREMENT				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC caused Stops per Million Train Miles
Onboard Hardware	0.970	0.077	0.998947	22.5
Onboard Software	2.771	0.058	0.999907	67.7
PTC Wayside Hardware	0.004	0.000	0.999999	1.6
PTC Wayside Software	0.013	0.000	0.999999	15.1
BOS-Loco Link Hardware	0.000	0.000	1.000000	0.9
BOS-Loco Link Software	0.000	0.000	1.000000	0.7
BackOffice Hardware	0.002	0.000	0.999999	0.0
BackOffice Software	0.003	0.000	1.000000	0.1
Human Related	3.043	0.061	1.000000	0.0
Other RF / Comms	0.426	0.000	0.999948	19.3
Unknown	0.447	0.013	0.999855	19.9
TOTAL	7.679	0.208	0.998654	147.9

Figure 11. Screenshot of RAM KPI Results per RAM Segment in Tabular Format in the Dashboard

2. The calculation of the reduction in average network speed caused by PTC, based on the total train delay calculated for the aggregated operational scenarios and the average railroad speed. Figure 12 shows an example of the Speed Reduction display.

Average Train Speed	Speed (MPH)	
Without PTC Delay	23.20	
With PTC Delay	23.16	
Speed Reduction	**0.04**	**0.18%**

Figure 12. Screenshot of the Speed Reduction Display in the Dashboard

3. A graphical display of the proportional contribution to a RAM KPI from each RAM segment, as well as the total RAM KPI calculation (i.e., all segments combined) for the following KPIs:

    a. TTDTM, as shown in Figure 13

    b. TTDTS, as shown in Figure 14

    c. Number of UPSTM, as shown in Figure 15

4. A graphical bar graph display with the PTCFA RAM KPI values per RAM segment, as shown in Figure 16.

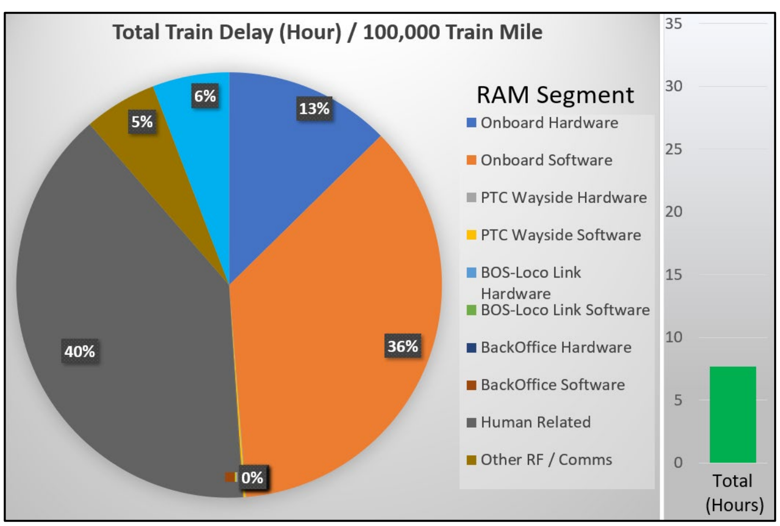

Figure 13. Screenshot of the TTDTM RAM KPI Graphical Display in the Dashboard

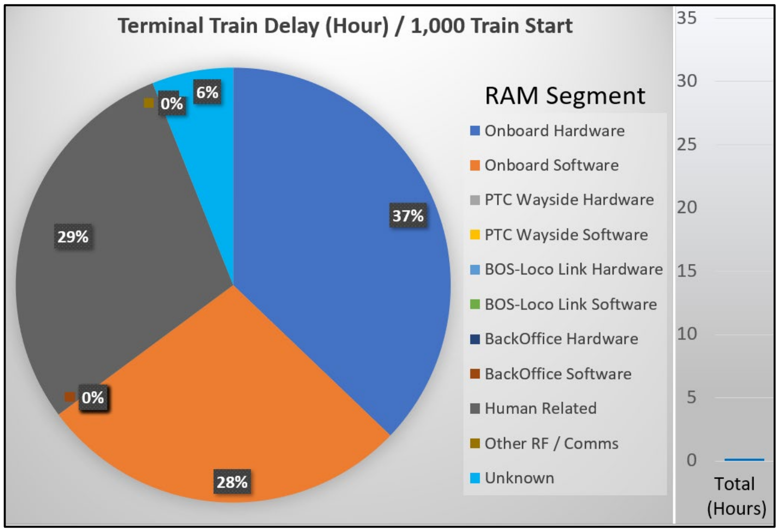

Figure 14. Screenshot of the TTDTS RAM KPI Graphical Display in the Dashboard

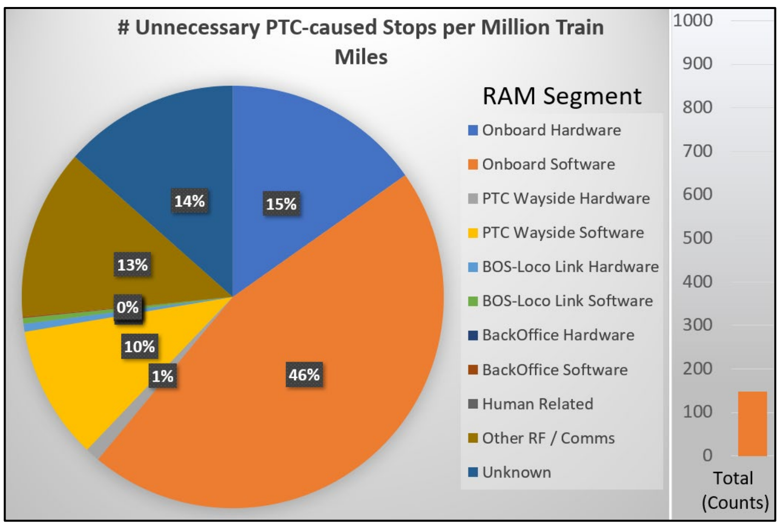

Figure 15. Screenshot of the UPSTM RAM KPI Graphical Display in the Dashboard

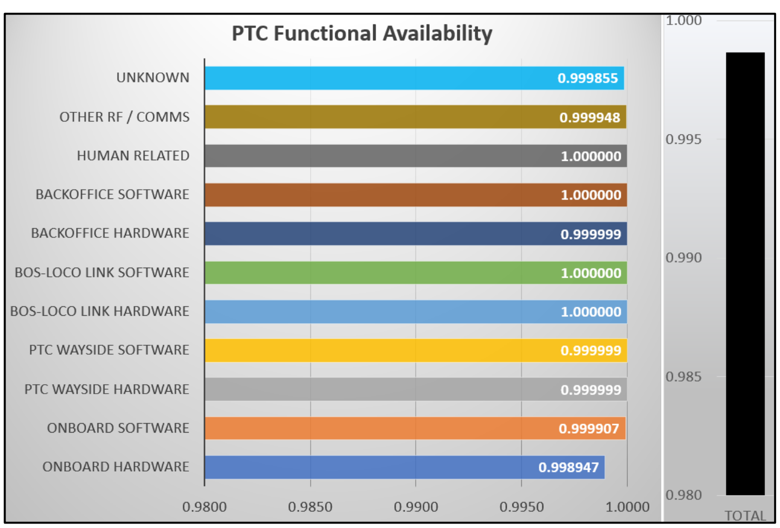

Figure 16. Screenshot of the PTCFA RAM KPI Graphical Display in the Dashboard

4.8 Validation of RAMIA Results

The team compared the RAM modeling results with the results obtained using RTC simulations. RTC is a widely employed railroad network simulation tool used by North American railroads. Its models and configuration parameters have been extensively improved and validated by its users over many years.

The team created RTC models for four operational scenarios including signaled single track, signaled double-track, signaled triple-track, and non-signaled territory. Each RTC model was configured with typical operational parameters including train schedules, train consist, and track layout. Details of each operational scenario are included in Appendix C.

RTC contains functionality to simulate the operation of trains during an occurrence of a PTCIE. This functionality was implemented and validated under the Higher Reliability and Capacity Train Control (HRCTC) project [1]. TTCI configured RTC to trigger individual PTCIEs for each of the operational scenarios and calculated the total train delay (i.e., delay incurred to all trains in the model) in each case, by comparing simulations runs with and without PTCIEs. Appendix H contains details on the use of RTC simulation runs for this purpose.

Researchers selected six representative PTCIEs for the comparison. The selected PTCIEs contain the foundational model components that are inherited either entirely or partially by all other PTCIEs developed in RAMIA. These are:

- En route Onboard Hardware Failure Non-recoverable with Enforcement
- En route Onboard Software Failure Recoverable with Enforcement
- PTC Wayside Hardware Outage at Control Point
- PTC Wayside Hardware Outage at Intermediate Signal
- En route Crew Error- Braking Curve Enforcement
- BOS Hardware Outage

The team configured the same operational scenarios and PTCIEs in RAMIA and produced the results of the total train delay per operational scenario and PTCIEs.

The comparisons were made at 50 percent and 75 percent Track Utilization Levels (TUL). Additionally, researchers ran RTC simulations at 25 percent and 100 percent and the results showed a large standard deviation for the following reasons:

- At 25 percent TUL, the random train departure times in RTC sometimes caused meet-pass encounters where the delay to trains was substantially higher than the average delay caused by the PTCIE.
- At 100 percent TUL, because the operation was close to practical capacity, the operational delays due to the PTCIE often caused RTC to make non-optimal meet-pass decisions that imposed additional train delays, sometimes higher than the delay caused by the PTCIE itself.

During the validation process, the team found several issues that required the revision and adjustment of the RAM models. Table 15 contains the comparative results between RTC and RAMIA after the various adjustment rounds made.

Table 15. RTC and RAMIA Comparative Results

Operational Scenario	Track Utilization Level	PTCIE	Total Train Delay Results (Hour		
			RTC™	RAMIA	Diff.
Single-track	50	En route Onboard HW Failure Non-recoverable with Enforcement	0.43	0.47	9%
		En route Onboard SW Failure Recoverable with Enforcement	0.57	0.59	4%
		PTC Wayside HW Outage at CP	0.41	0.39	5%
		PTC Wayside HW Outage at IS	0.22	0.24	9%
		En route Crew Error- Braking Curve Enforcement	0.23	0.21	8%
		BOS HW Outage	0.74	0.76	2%
	75	En route Onboard HW Failure Non-recoverable with Enforcement	0.39	0.45	14%
		En route Onboard SW Failure Recoverable with Enforcement	0.53	0.57	7%
		PTC Wayside HW Outage at CP	0.70	0.61	13%
		PTC Wayside HW Outage at IS	0.43	0.37	14%
		En route Crew Error- Braking Curve Enforcement	0.21	0.23	10%
		BOS HW Outage	0.94	0.95	1%
Double-track	50	En route Onboard HW Failure Non-recoverable with Enforcement	0.43	0.37	14%
		En route Onboard SW Failure Recoverable with Enforcement	0.63	0.55	13%
		PTC Wayside HW Outage at CP	1.13	1.10	3%
		PTC Wayside HW Outage at IS	0.75	0.76	1%
		En route Crew Error- Braking Curve Enforcement	0.25	0.25	0%
		BOS HW Outage	1.20	1.34	12%
	75	En route Onboard HW Failure Non-recoverable with Enforcement	0.45	0.39	14%
		En route Onboard SW Failure Recoverable with Enforcement	0.66	0.58	12%
		PTC Wayside HW Outage at CP	1.55	1.65	6%
		PTC Wayside HW Outage at IS	1.09	1.14	5%
		En route Crew Error- Braking Curve Enforcement	0.24	0.25	6%
		BOS HW Outage	2.08	1.95	6%
Triple-track	50	En route Onboard HW Failure Non-recoverable with Enforcement	0.28	0.31	11%
		En route Onboard SW Failure Recoverable with Enforcement	0.38	0.39	1%
		PTC Wayside HW Outage at CP	1.32	1.20	9%
		PTC Wayside HW Outage at IS	0.48	0.54	13%
		En route Crew Error- Braking Curve Enforcement	0.12	0.13	8%
		BOS HW Outage	1.88	1.94	3%
		Synch Error Failure (single train)	0.05	0.06	2%
	75	En route Onboard HW Failure Non-recoverable with Enforcement	0.30	0.31	2%
		En route Onboard SW Failure Recoverable with Enforcement	0.43	0.39	10%
		PTC Wayside HW Outage at CP	1.56	1.79	15%
		PTC Wayside HW Outage at IS	1.00	0.86	14%
		En route Crew Error- Braking Curve Enforcement	0.15	0.13	13%
		BOS HW Outage	2.59	2.78	7%
Non-signaled Territory	50	En route Onboard HW Failure Non-recoverable with Enforcement	0.89	0.77	13%
		En route Onboard SW Failure Recoverable with Enforcement	0.41	0.46	12%
		PTC Wayside HW Outage at CP	0.12	0.11	8%
		PTC Wayside HW Outage at IS	0.18	0.18	2%
		En route Crew Error- Braking Curve Enforcement	1.22	1.08	11%
	75	En route Onboard HW Failure Non-recoverable with Enforcement	1.05	0.91	13%
		En route Onboard SW Failure Recoverable with Enforcement	0.46	0.48	4%
		PTC Wayside HW Outage at CP	0.13	0.15	13%
		PTC Wayside HW Outage at IS	0.23	0.20	13%

Table 15 still shows some difference margin in the results that could be investigated and refined through future efforts; however, the results are sufficiently close to be considered reliable. Several RAMIA parameters were configured with average values, and the train operation model uses analytical formulas, so it is expected that the results between RAMIA calculation and RTC simulations will not be exactly the same. The current RAMIA implementation achieved a good compromise between the modeling effort and the quality of results. It is also important to highlight that not necessarily all the RTC results can be taken without question, and further comparison analysis should also investigate the quality of the RTC results.

5. High Level RAM Program Plan

The overall process developed for this project includes the following steps:

- Input data is gathered, including the following:
    - Operational scenario configuration
    - Traffic volumes per operational scenario
    - Quantification of RAM parameters
- Input data is configured in RAMIA.
- RAMIA is executed and RAM KPI results are produced.
- The main contributors to RAM KPIs are identified.
- The sensitivity analysis of the RAM segments/LRUs to the RAM KPIs is developed. The sensitivity analysis includes:
    - RAM parameters (MTBDE and MTTR) are modified for the main contributors.
    - RAMIA is executed, producing new RAM KPI results.
    - Multiple iterations of the two steps above are executed.
    - RAM KPI results of the multiple iterations are compiled producing sensitivity analysis results.
- Based on the results of the sensitivity analysis, RAM improvement targets to achieve improvements in operational parameters (i.e., RAM KPIs) are defined by stakeholders and/or negotiated among them. The stakeholders could be either the entire industry (issues common to all railroads), individual railroads, and/or vendors.
- Based on the chosen improvement targets, specific RAM Growth Actions (short-term, specific items) or RAM Growth Plans (mid- to long-term comprehensive actions) are established and implemented.

Figure 17 illustrates the entire process described above. A detailed description of the methods and tools that support this process are included in Appendix I. Section 6, Section 7, and Section 8 describe how the process was applied to data collected from participant railroads.

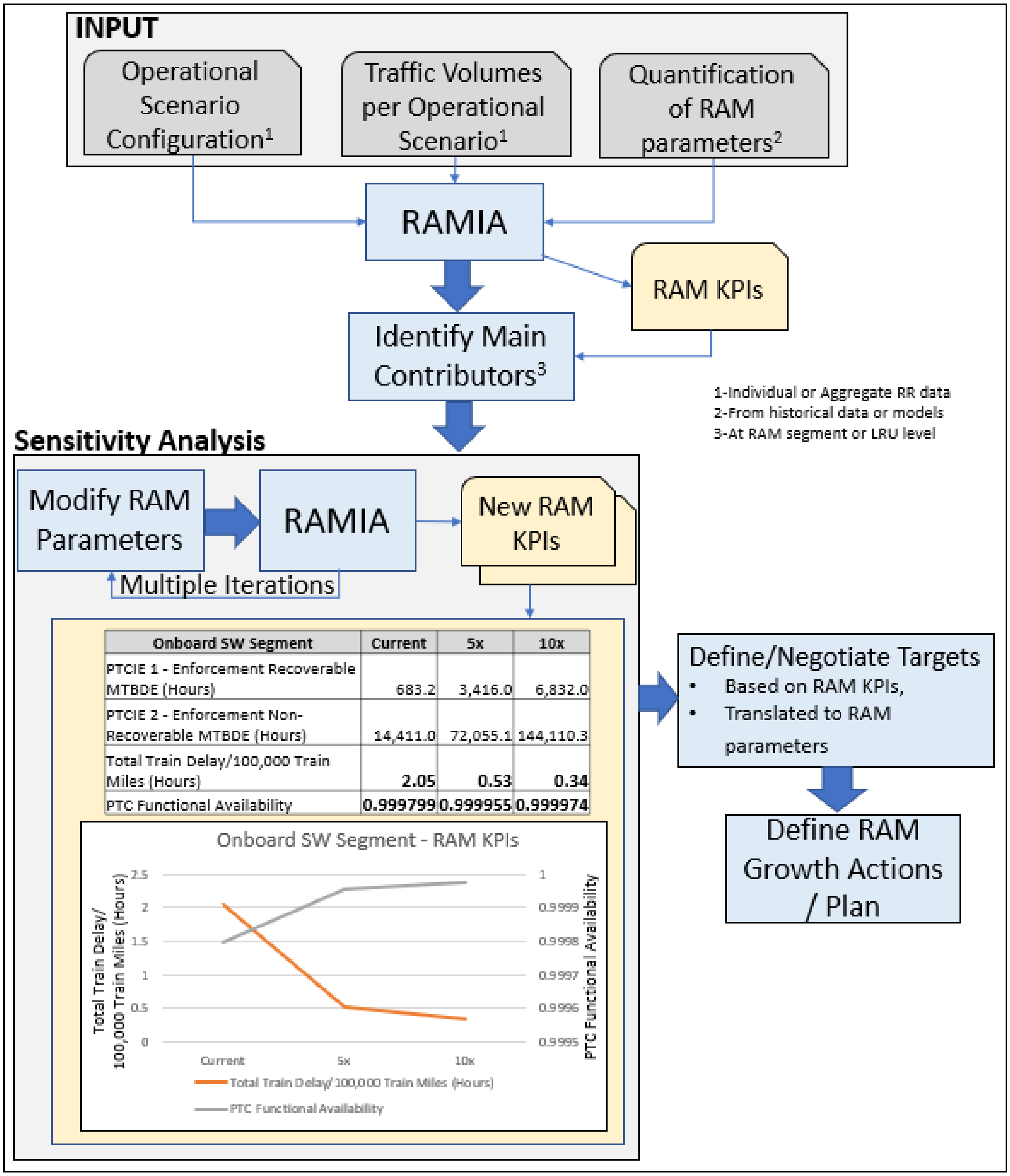

Figure 17. Process to Develop a RAM Growth Plan

6. Railroad Operational Scenarios and Train Traffic Levels

Train traffic volume is defined as a percentage of the maximum practical capacity of an operational scenario, identified as the Track Utilization Level (TUL). Appendix G contains details of the TUL concept and how it is calculated. In the HRCTC project, the research team used four TULs (25, 50, 75, and 100 percent) to analyze the impacts due to PTC operation (see details in the HRCTC report [1]). For this project, the team developed a parametric method to define and use multiple TULs based on the volume of train traffic per subdivision provided by participant railroads, resulting in more accurate analysis.

The data provided by the participant railroads included the total train-miles operated in a year per subdivision and the total route miles per type of track layout (i.e., signaled single, double, triple, and non-signaled). The total train-miles operated per year were proportionally allocated to track types based on the route-miles of each track type in a subdivision.

The allocation of train-miles to track types is based on the capacity of train traffic volume that each track type can withstand at a given TUL (see Appendix G, Table 44 for details). Table 16 shows the proportion of trains/day of signaled double, triple, and non-signaled tracks compared to signaled single track.

Table 16. Proportion of Trains per Day Compared to Signaled Single Track

Signaled Double-Track	Signaled Triple-Track	Non-Signaled
2.37	4.61	0.52

For example, if a theoretical subdivision operates 1,000,000 train-miles per year and has 200 route-miles evenly distributed among the four track types (i.e., 50 miles per track), the distribution of train-miles per track type would be allocated per the proportions shown in Table 16, resulting in the numbers shown in Table 17.

Table 17. Illustrative Example of Proportional Allocation of Train-miles per Type

Subdivision		Single track	Double-track	Triple-track	Non-Signaled	TOTAL
SUB 01	Route-Miles	50	50	50	50	200
	Train-Miles/Yr	117,647	278,824	542,353	61,176	1,000,000

Researchers used the results of the RTC simulations to associate train traffic volume (i.e., train headways and train-miles per year) with TUL levels per type of track configuration. The RTC simulations were developed at four TUL levels (25, 50, 75, and 100 percent) and the results were used to extrapolate the volume of traffic for a given territory to a TUL. Appendix G contains a detailed explanation of the extrapolation methods.

Table 18 shows an example of several hypothetical subdivisions for which the total route-miles per type of track and total train-miles per year are known. These amounts are used to calculate the TUL per subdivision. To facilitate the analysis process, subdivisions operating within a TUL range are combined into a TUL group, where the TUL value of the group is weighted by the total train-miles of each subdivision in the group. In the illustrative example shown in Table 18, four TUL groups are calculated and indicated with different colors.

Table 18. Example of TUL Calculations per Subdivision and Track Configuration

Subdivision	Route Miles					Total Train Miles/ Year	TUL	TUL Group	TUL
	Signaled Single-Track	Signaled Double-Track	Signaled Triple-Track	Non-Signaled	Total				
Sub 1	50.0	0.0	0.0	0.0	50.0	430,000	72%	1	72%
Sub 2	24.0	0.0	0.0	0.0	24.0	140,000	49%	2	46%
Sub 3	65.0	15.0	0.0	0.0	80.0	565,000	46%		
Sub 4	0.0	20.0	0.0	0.0	20.0	250,000	42%	3	38%
Sub 5	0.0	40.0	11.0	0.0	51.0	750,000	41%		
Sub 6	12.0	0.0	0.0	0.0	12.0	60,000	42%		
Sub 7	40.0	23.0	0.0	0.0	63.0	440,000	38%		
Sub 8	0.0	42.0	0.0	0.0	42.0	480,000	38%		
Sub 9	100.0	10.0	5.0	0.0	115.0	620,000	35%		
Sub 10	0.0	18.0	15.0	0.0	33.0	450,000	32%	4	30%
Sub 11	125.0	0.0	0.0	0.0	125.0	470,000	31%		
Sub 12	37.0	0.0	0.0	0.0	37.0	130,000	29%		
Sub 13	45.0	15.0	10.0	0.0	70.0	435,000	28%		

Based on the grouped TULs per type of track configuration, nine operational scenarios with a distinct TUL per type of track configuration were created from the 13 subdivisions, as shown in Table 19. If the TUL grouping method was not used, 22 operational scenarios would have to be analyzed for those same subdivisions, producing the same results.

Table 19. Example of Operational Scenarios Based on Grouped TUL

TUL	Type of Track Configuration	Average Headway (hours)	Train-miles / Year	Route-Miles
72	Signaled Single track	2.02	430,000	50.0
46	Signaled Single track	3.17	496,511	89.0
46	Signaled Double-track	1.27	496,511	15.0
38	Signaled Single track	3.84	699,710	152.0
38	Signaled Double-track	1.54	1,548,322	135.0
38	Signaled Triple-track	0.80	351,968	16.0
30	Signaled Single track	4.86	752,156	207.0
30	Signaled Double-track	1.95	298,747	33.0
30	Signaled Triple-track	1.02	434,097	25.0

The method described above was used to define operational scenarios for the railroads that provided data for this project and subsequently configured in RAMIA for RAM analysis. Table 20 shows the number of subdivisions analyzed by the team and the number of operational scenarios produced for each railroad. The names of railroads are not disclosed, but are identified as A, B, C, and D.

Table 20. Number of Subdivisions and Operational Scenarios per Railroad

Railroad	Total	A	B	C	D
Number of Subdivisions	366	129	17	88	132
Number of Operational Scenarios	84	35	12	37	37

7. Data Collection and Quantification of RAM Parameters

The research team developed the quantification of RAM parameters based on participant-railroad-provided historical logs that contained PTC train operation data.

The following data was requested from the railroads:

1) Total PTC train-miles per month that were operated in subdivisions that required PTC and recorded over a period of time (such as the last 12 or 24 months)
2) Ticket data containing PTC-related events for the PTC-equipped trains that operated on the same subdivisions and time period used in item #1
    a. Include events for the same trains that are included in the calculation of #1
    b. Include events for trains that were ready to depart with PTC (i.e., PTC-equipped and crew-trained) but, for any reason, departed with PTC cutout (i.e., missed opportunity)

    The ticket data should ideally contain the following information:

    a. Identification of PTC RAM segment
    b. Direct effect on train operation and its resolution
        i. Direct effect, such as Enforcement, Disengagement, Terminal delay, etc.
        ii. Resolution, such as Cutout PTC, restore active, restore disengaged, etc.
    c. Location of event (i.e., terminal or en route)
    d. Timestamp of the event
3) Number of successful PTC train starts during the same period of time as item #1.

Four railroads provided usable log data containing the requested information. Three other railroads provided partial sets of data; however, the team was not able to use that data, because it did not contain sufficient information to allow for the calculation of the RAM KPIs defined for this project.

The number of total PTC train miles was used for the calculation of the RAM KPIs related to total train-miles of operation, or TTDTM, Number of UPSTM, and PTCFA, while the number of train starts was used to calculate the KPI related to the number of train starts, i.e., TTDTS.

The data was collected from the railroads between the beginning of 2018 and the 3rd quarter of 2020. Two railroads provided data for 2020 only, while the other railroads provided data prior to 2020. Table 21 shows the range of data collected. The four railroads are identified in this report as Railroad A, B, C, and D.

Table 21. Data Range of Collected Ticket Data

Railroad	From	To
A	January 2018	June 2020
B	January 2018	June 2020
C	January 2020	July 2020
D	January 2020	October 2020

The ticket data provided by the participant railroads contained the list of events that impacted the operation of PTC-equipped trains. This list was generated mostly using human input, gathered typically from operators in the help desk centers. Some railroads implemented automated processes to generate an entry in their help desk systems when an event occurred, such as when a PTC enforcement occurred and the onboard notified the office. The identification of the cause and resolution of the event, however, still required human input.

The research team addressed multiple issues with the ticket data to make it usable for the project. These issues included:

- The quality of the data varied among the railroads. In some cases, the ticket data reflected the best information that could be collected by human operators at the time the event occurred. In other cases, the ticket data was updated as investigation of the event occurred, improving the quality of that data.
- Criteria for qualifying an event in the ticket data was not uniform. Sometimes events were reported in a similar fashion among railroads, but the information referred to different types of events.
- Data formats and contents were not uniform among railroads. In some cases, the contents of the ticket data were organized and contained information that was easier to convert to the input required for RAMIA, such as the identification of RAM segments, types of PTCIEs, the impact caused to the train, and how the train restored operation. In other cases, the organization of data and its contents were very difficult to convert to the required RAMIA inputs and many times required interpretation and assumptions. These issues resulted in a non-uniform conversion of ticket data to RAMIA input data among railroads.
- Overall, the collected ticket data was often uncertain and subject to interpretation. The uncertainty, in many instances, centered around which RAM segment or PTCIE should be assigned the event. Many fields, for example, contained free text information instead of pre-defined categories.
- Most events could not be associated to an LRU, constraining the analysis at the RAM segment level, and sometimes it was not even possible to assign an event to a RAM segment. For example, an onboard software failure could have been caused by multiple components, such as the PTC onboard system itself, an interface, or an external component that provided input data to the PTC onboard system.

The resolution of the issues identified during the analysis of ticket data required intense analysis of the data and multiple reviews with the railroads who provided the data to produce usable and relatively accurate RAMIA inputs.

Figure 18 shows an example of the association made regarding ticket data events and PTCIEs. Columns A, B, and C in Figure 18 contain ticket data from one of the railroads, while Column F contains the PTCIE associated with the ticket data event.

A	B	C	F
EVENTDATE	PTCSD_SYMPTOM	PTCSD_ROOT_CAUSE	PTCIE
4/16/2020	Enforcement - Work Zone	Unidentified Cause	Enroute Unknown Enforcement Recoverable
4/16/2020	Enforcement - Signal	C&S – Sig – Signal	Non-PTC related
4/16/2020	Enforcement - Signal	Locomotive - GPS	Enroute loss of GPS signal
4/16/2020	Enforcement - Signal	No Trouble Found	Enroute Unknown Enforcement Recoverable
4/16/2020	Enforcement - Signal	Training - Crew - Training	Enroute Crew error 1
4/16/2020	Enforcement - Switch Unknown	C&S - MOW - Switch	Non-PTC related
4/16/2020	Enforcement - Signal	Locomotive - GPS	Enroute loss of GPS signal
4/16/2020	Enforcement - Switch Unknown	No Trouble Found	Enroute Unknown Enforcement Recoverable
4/16/2020	Enforcement - Unexpected Exit From Active	Training - Crew - Training	Enroute Crew error 1
4/16/2020	Enforcement - Track Warrant Authority	Training - Crew - Training	Enroute Crew error 1
4/16/2020	Other - Not listed issue	Training - Crew - Training	Enroute Crew error 1
4/16/2020	Enforcement - Permanent Speed Restriction	No Trouble Found	Enroute Unknown Enforcement Recoverable
4/16/2020	Enforcement - Signal	C&S - Sig - Switch	Non-PTC related
4/16/2020	Enforcement - Signal	OPR - Init/Active too close to Signal	Enroute Crew error 3
4/16/2020	Init - Failed	No Trouble Found	Terminal Unknown Delay

Figure 18. Example of Association of Ticket Data Events to PTCIE

The ticket data analysis shows that the quality of the information provided by the railroads has improved over time. As an example, the percentage of unknown events (i.e., events for which a root cause RAM segment cannot be identified) found in Railroad A's data is above 30 percent in the beginning of 2020, but the percentage reduced throughout the year, as shown in Figure 19.

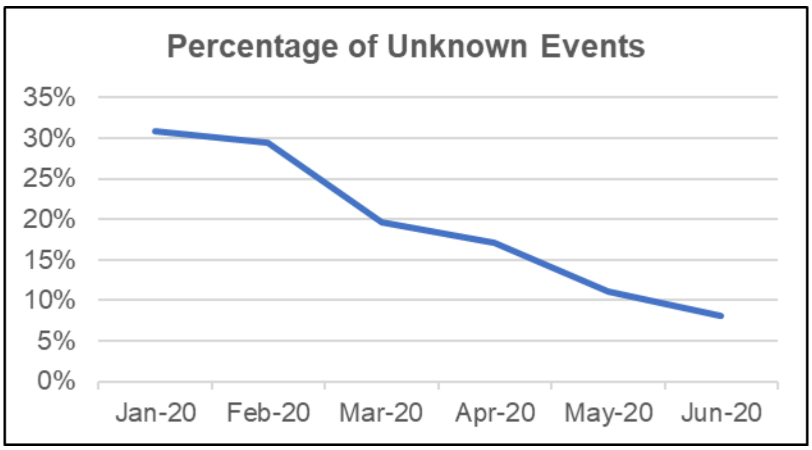

Figure 19. Percentage of Unknown Events in the Ticket Data Provided by Railroad A

A proportional reduction in the number of unknown events was also observed in the data provided by the other three railroads.

Once the association between ticket data and PTCIEs was made, the team calculated the number of events for each PTCIE monthly. The MTBDE then was calculated using the total PTC train-miles of operation and the average normal train speed of 24.6 MPH[4].

Despite the quality issues with input data provided by the railroads, the contents of the ticket data were still usable in performing a meaningful RAM analysis that included the following:

- Comparative analysis of the overall RAM performance of RAM Phases 1 and RAM Phase 2 projects

[4] Average normal train speed reported by BNSF, CN, NS, and UP for a 53-week period from 12/24/2016 to 12/29/2017, weighted according to the cars-on-line metric for each railroad for the same time period.

- Individual analysis of the performance of RAM segments and PTCIEs
- Identification of trends and exceptional events during MTBDE calculation

The granularity of the ticket data, for the most part, was not sufficient to determine root cause to the LRU level, and the RAM analysis in this project was developed at a RAM segment level that does not allow for the analysis to discriminate between the contribution of each component to RAM performance. For example, when an onboard software failure occurs, it could be due to multiple software components in the onboard system. A similar issue was observed with hardware components.

The MTBDE analysis of the events included in the ticket data showed that the overall RAM for the PTC system had grown in comparison to the RAM Phase 1 project; the aggregate PTCFA of the PTC system grew from 0.9523 to 0.9979. In the RAM Phase 1 project, it was estimated that the aggregate PTCFA would reach 0.9961 at a steady state (i.e., by the end of 2020, when PTC was fully implemented) which is comparable to the PTCFA of 0.9979 calculated in this RAM Phase 2 project.

The analysis also shows overall improvement for most railroads throughout the course of the RAM Phase 2 project. Figure 20 shows the MTBDE of all events from January 2019 to June 2020 for Railroad A. The trend shows a steady increase in MTBDE since August 2019, when Railroad A implemented relevant improvements in the onboard system combined with the systematic reduction of operator errors. The drop in both the total PTC train miles and the overall MTBDE in March/April of 2020 was a result of the COVID-19 pandemic. Notice that MTBDE values bounced back in the two months of data following the impact of the pandemic. While the reduction of total PTC train-miles is understandable, an explanation for the reduction in MTBDE during the initial months of the COVID-19 pandemic was not determined.

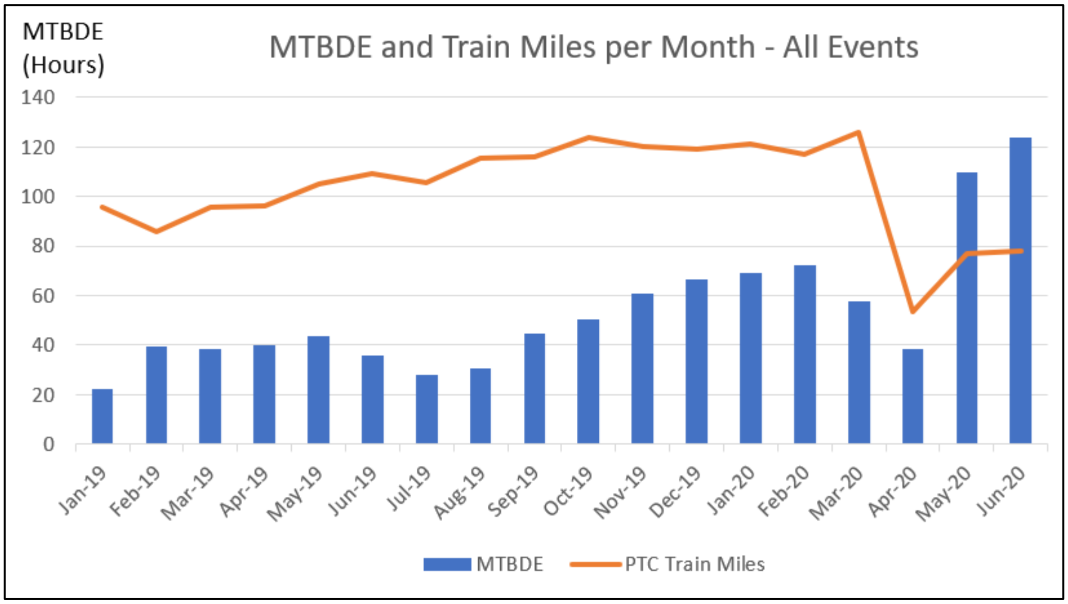

Figure 20. Overall MTBDE Considering All Events from Railroad A

Figure 21, Figure 22, and Figure 23 show the MTBDE trends for the other three railroads.

The team received partial data for the month of July 2020 from Railroad B. The partial data explains the reduction of train miles in that month, as shown in Figure 21.

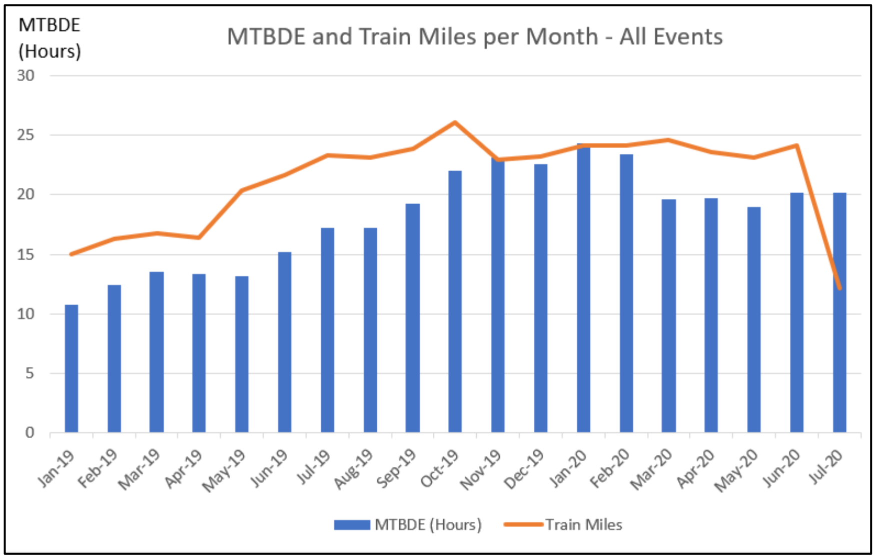

Figure 21. Overall MTBDE Considering All Events from Railroad B

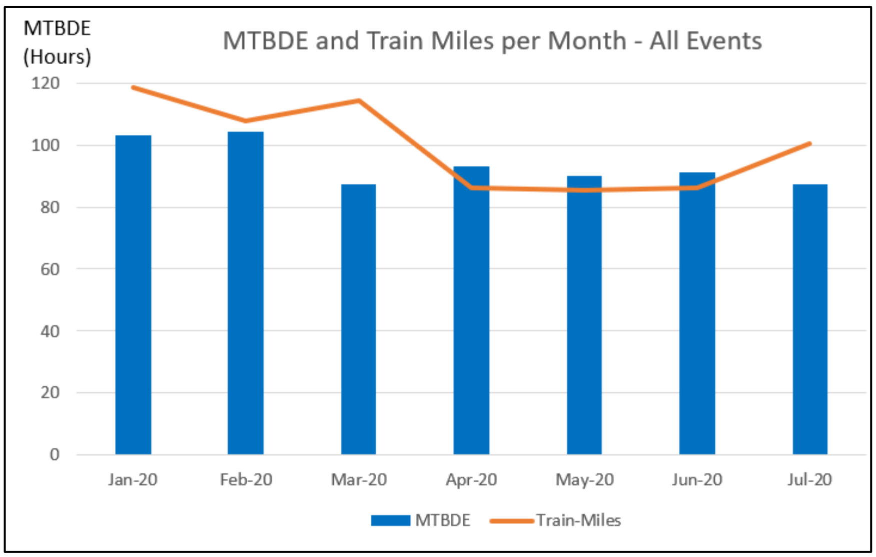

Figure 22. Overall MTBDE Considering All Events from Railroad C

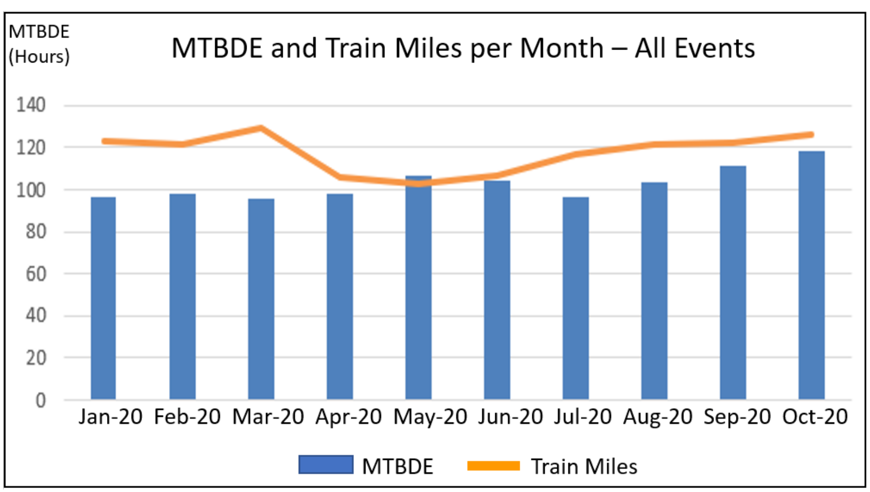

Figure 23. Overall MTBDE Considering All Events from Railroad D

The results obtained from the four railroads show that Railroads A, C, and D reached an overall (i.e., all types of PTC impact events) MTBDE in the range of 100 to 120 hours, while Railroad B's overall MTBDE was around 20 hours. This difference is reflected in the RAM KPI results, and the key contributors for this discrepancy are discussed in Section 8.1.

The analysis of the MTBDE values for the RAM segments over time also shows some expected phenomena in control systems:

- The MTBDE of human-related events also increased over time. Figure 24 shows an example of data collected from Railroad A since 2019, where a slow but steady increase can be observed until the beginning of 2020, just before the COVID-19 pandemic. It is expected that the MTBDE of human-related events should continue to improve as operators become more familiar with the operation of the system and as usability/reliability of the system also continues to improve.
- The MTBDE of onboard software events is increasing consistently and significantly over time. This is an expected phenomena with the maturity of onboard software systems and it should continue to improve until it reaches a steady state. Figure 25 shows an example of the MTBDE of all onboard software events collected from Railroad A since 2019.
- The MTBDE of onboard hardware events is also increasing, although not as significantly as that of onboard software events. This is expected to occur during the initial stages of system deployment and operation, especially with a system like PTC that has multiple hardware components and interfaces. Distinct from software events, however, hardware failure events are expected to increase when the hardware components start reaching their lifetime expectancy. Figure 26 shows an example of the MTBDE of all onboard hardware events collected from Railroad A since 2019.

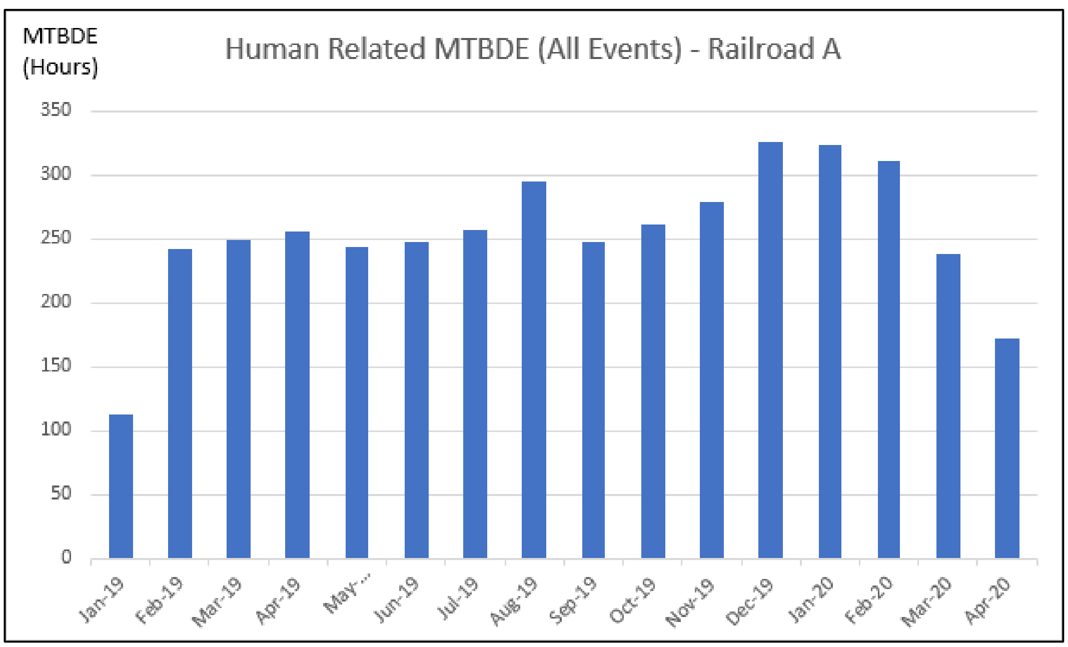

Figure 24. MTBDE of All Human-related Events for Railroad A Since 2019

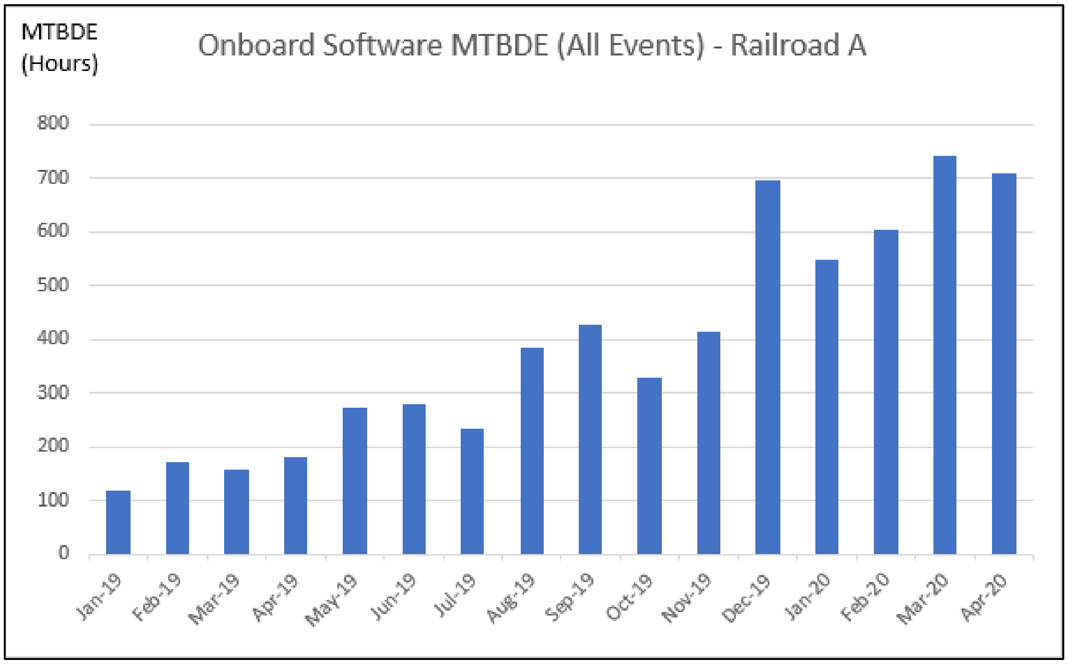

Figure 25. MTBDE of All Onboard Software Events for Railroad A Since 2019

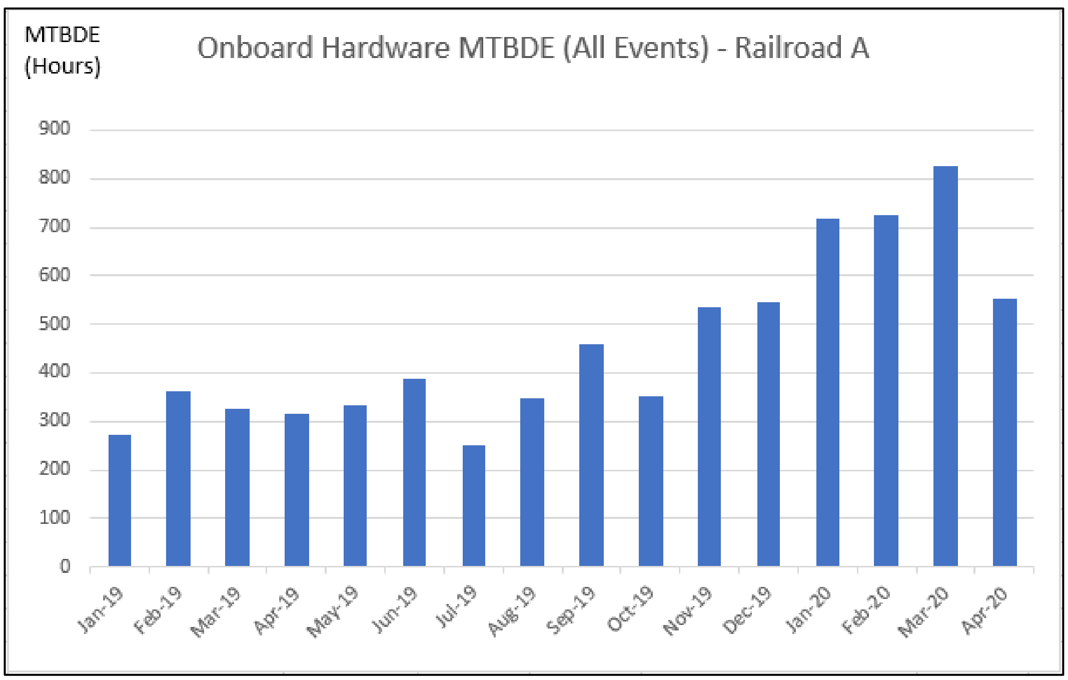

Figure 26. MTBDE of All Onboard Hardware Events for Railroad A Since 2019

The final step in the RAM quantification is the calculation of the MTBDE for each of the PTCIEs. Figure 27 shows an example of the MTBDE calculation for PTCIE "En route Crew Error – Other Enforcement," based on Railroad A's ticket data.

In a conservative approach, the average MTBDE value for the last six months was used to configure RAMIA that was calculated as 1,101 hours, based on the months of January 2020 to June of 2020 (highlighted in yellow), as shown in Figure 27.

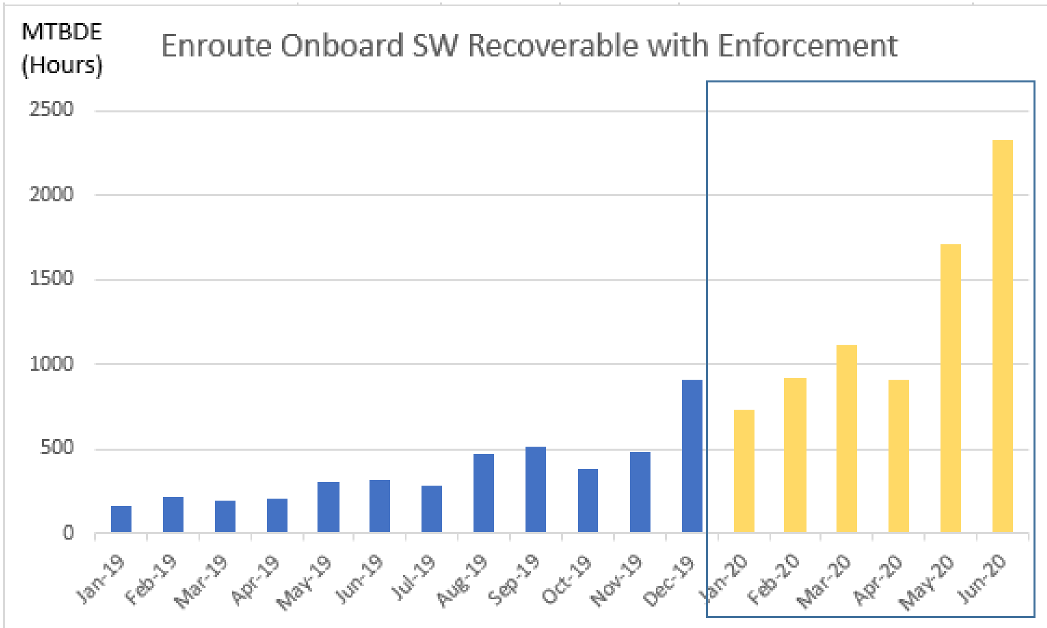

Figure 27. Example of MTBDE Calculation for a Type of PTCIE

8. RAM Modeling and Analysis Results and Strategic RAM Growth Recommendations

8.1 RAMIA Configuration and RAM KPI Results

Researchers configured RAMIA with input data for each of the four railroads and calculated the RAM KPIs, first individually and then aggregately. For the aggregate analysis, the team configured RAMIA with all the operational scenarios from each railroad and their specific train traffic volumes and RAM quantification parameters per operational scenario.

The RAM KPIs and the average speed reduction due to the overall train delay for each of the four railroads are shown in the next set of figures (Figure 28 to Figure 39).

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	2.608	0.719	0.995894	75.0
Onboard SW	1.955	0.078	0.999895	70.4
PTC Wayside HW	0.035	0.000	0.999999	8.8
PTC Wayside SW	0.026	0.000	0.999999	6.5
BOS-Loco Link HW	0.000	0.000	1.000000	0.0
BOS-Loco Link SW	0.049	0.000	1.000000	2.5
BackOffice HW	0.000	0.000	1.000000	0.0
BackOffice SW	0.102	0.015	0.999965	2.8
Human Related	2.284	0.212	0.999915	0.0
Other RF / Comms	0.210	0.000	0.999950	3.8
Unknown	2.707	0.100	0.999156	159.2
TOTAL	9.976	1.124	0.994774	329.0

Figure 28. RAM KPI Calculation for Railroad A

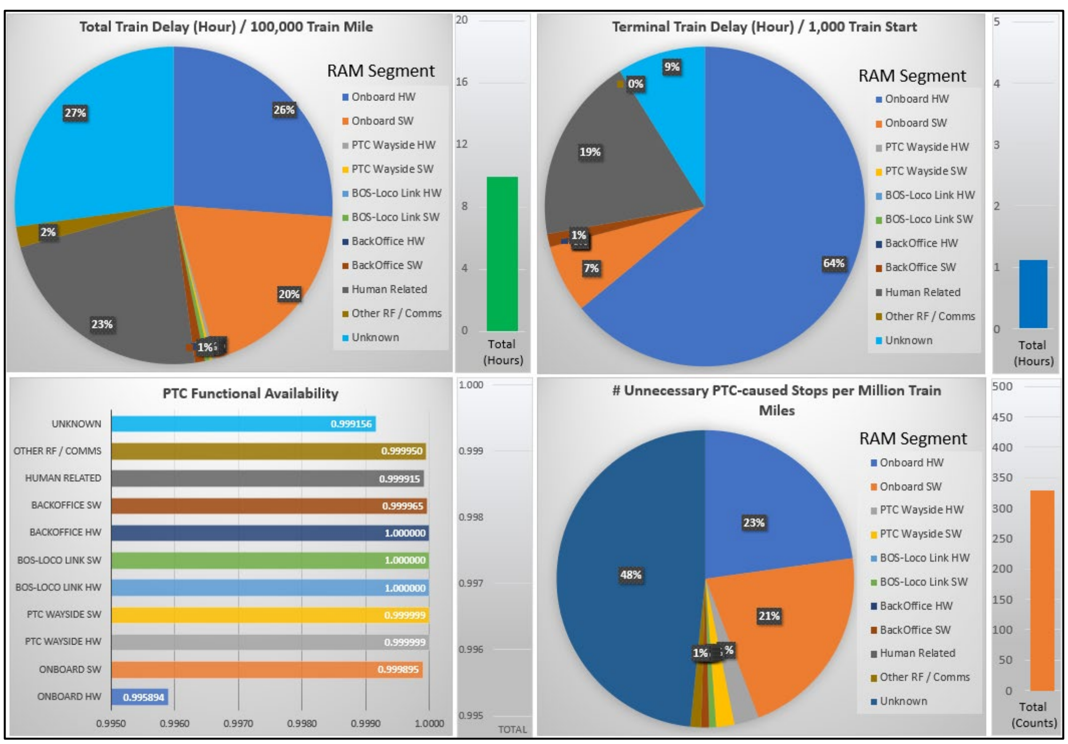

Figure 29. RAM KPI Distribution per RAM Segment for Railroad A

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.54	
Speed Reduction	**0.06**	**0.24%**

Figure 30. Average Speed Reduction for Railroad A

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	12.912	12.480	0.999369	135.5
Onboard SW	6.533	3.758	0.999413	114.3
PTC Wayside HW	0.016	0.000	0.999999	3.0
PTC Wayside SW	0.401	0.000	0.999987	75.1
BOS-Loco Link HW	0.000	0.000	1.000000	0.0
BOS-Loco Link SW	0.000	0.000	1.000000	0.0
BackOffice HW	0.000	0.000	1.000000	0.0
BackOffice SW	0.660	0.261	0.999932	14.5
Human Related	6.719	2.499	0.999989	0.0
Other RF / Comms	0.130	0.000	0.999981	8.1
Unknown	5.646	3.733	0.998858	113.1
TOTAL	33.018	22.731	0.997527	463.6

Figure 31. RAM KPI Calculation for Railroad B

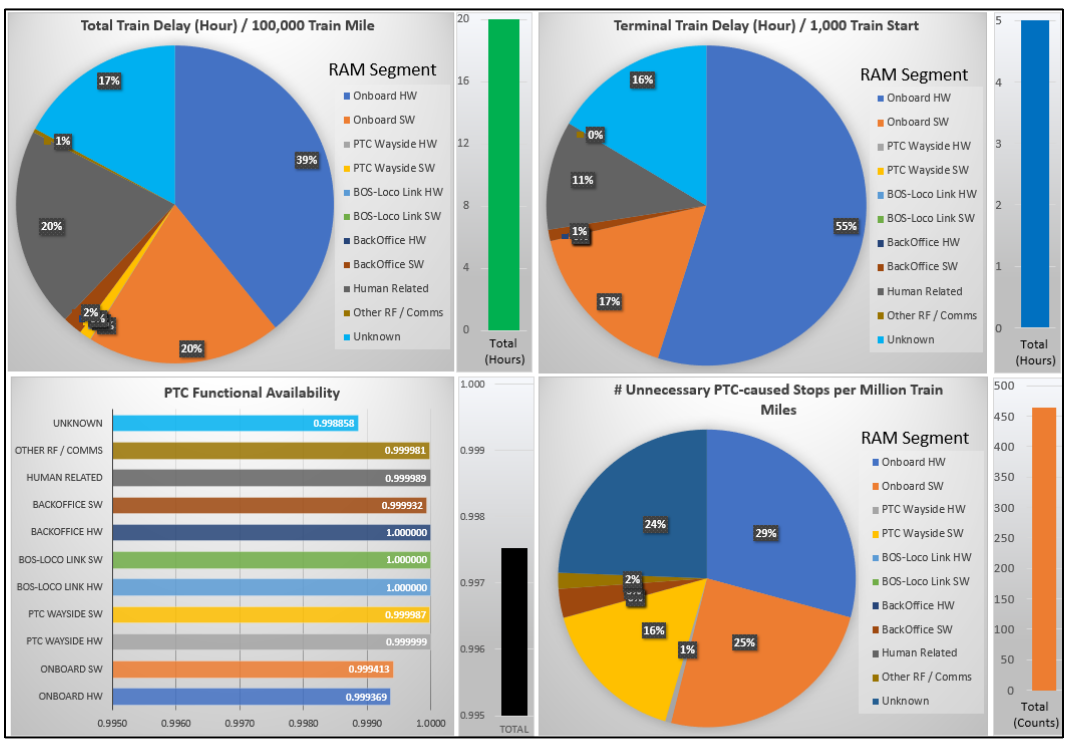

Figure 32. RAM KPI Distribution per RAM Segment for Railroad B

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.40	
Speed Reduction	**0.20**	**0.81%**

Figure 33. Average Speed Reduction for Railroad B

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	0.940	0.213	0.998997	21.2
Onboard SW	2.671	0.159	0.999912	63.9
PTC Wayside HW	0.005	0.000	0.999999	1.5
PTC Wayside SW	0.027	0.000	0.999999	14.0
BOS-Loco Link HW	0.000	0.000	1.000000	0.8
BOS-Loco Link SW	0.000	0.000	1.000000	0.6
BackOffice HW	0.002	0.000	0.999999	0.0
BackOffice SW	0.003	0.000	1.000000	0.1
Human Related	2.772	0.167	1.000000	0.0
Other RF / Comms	0.402	0.000	0.999946	18.2
Unknown	0.435	0.035	0.999860	18.8
TOTAL	7.256	0.575	0.998712	139.2

Figure 34. RAM KPI Calculation for Railroad C

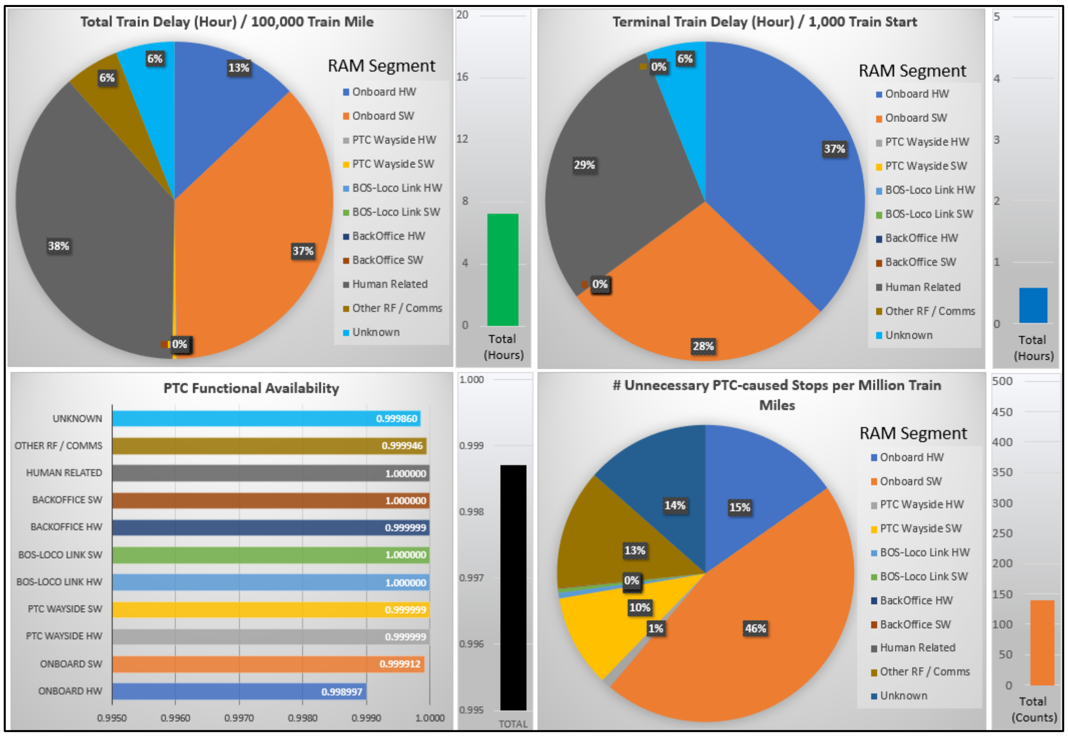

Figure 35. RAM KPI Distribution per RAM Segment for Railroad C

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	**0.18%**

Figure 36. Average Speed Reduction for Railroad C

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	0.818	0.292	0.999201	18.1
Onboard SW	2.344	0.242	0.999917	64.4
PTC Wayside HW	0.006	0.000	0.999999	1.5
PTC Wayside SW	0.036	0.000	0.999999	13.0
BOS-Loco Link HW	0.000	0.000	1.000000	0.8
BOS-Loco Link SW	0.000	0.000	1.000000	0.6
BackOffice HW	0.002	0.000	0.999999	0.0
BackOffice SW	0.003	0.000	1.000000	0.1
Human Related	2.635	0.172	1.000000	0.0
Other RF / Comms	0.234	0.000	0.999943	8.4
Unknown	0.390	0.035	0.999850	19.1
TOTAL	6.468	0.741	0.998907	126.0

Figure 37. RAM KPI Calculation for Railroad D

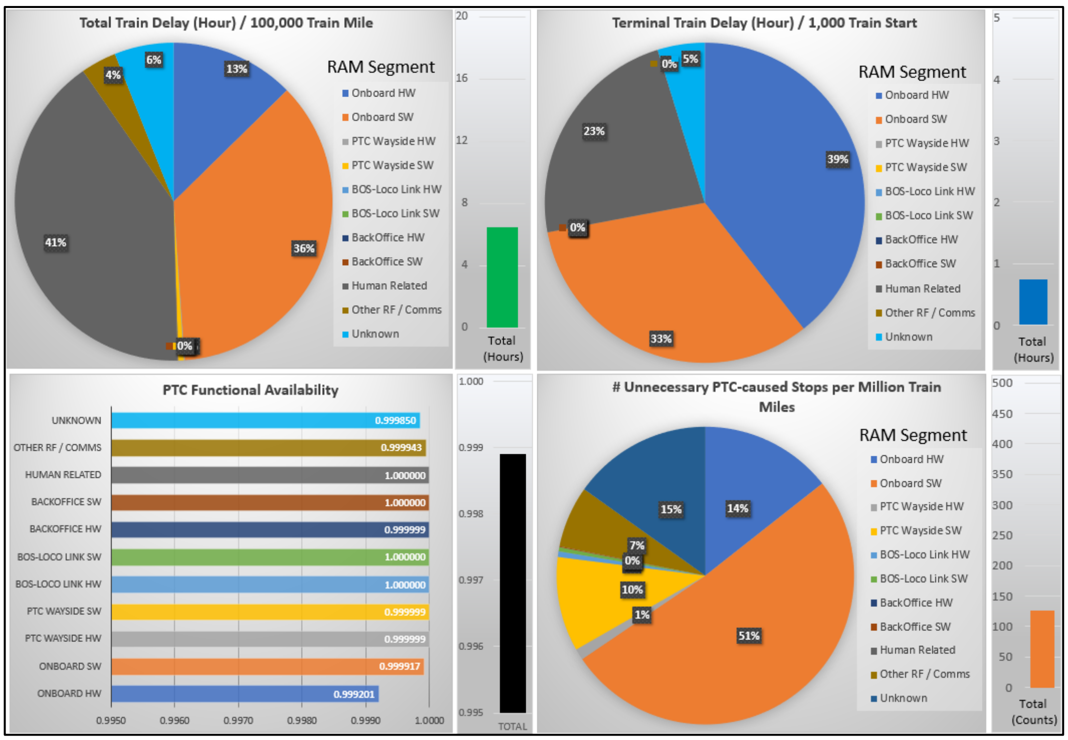

Figure 38. RAM KPI Distribution per RAM Segment for Railroad D

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	**0.15%**

Figure 39. Average Speed Reduction for Railroad D

The aggregate RAMIA results from the four railroads is shown in Figure 40, Figure 41, and Figure 42. Note that the aggregate results are weighted by the total train miles operated in the operational scenarios configured for each railroad in RAMIA.

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	1.566	0.680	0.998434	34.4
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	8.217	1.350	0.997928	182.7

Figure 40. Aggregate RAM KPI Calculation

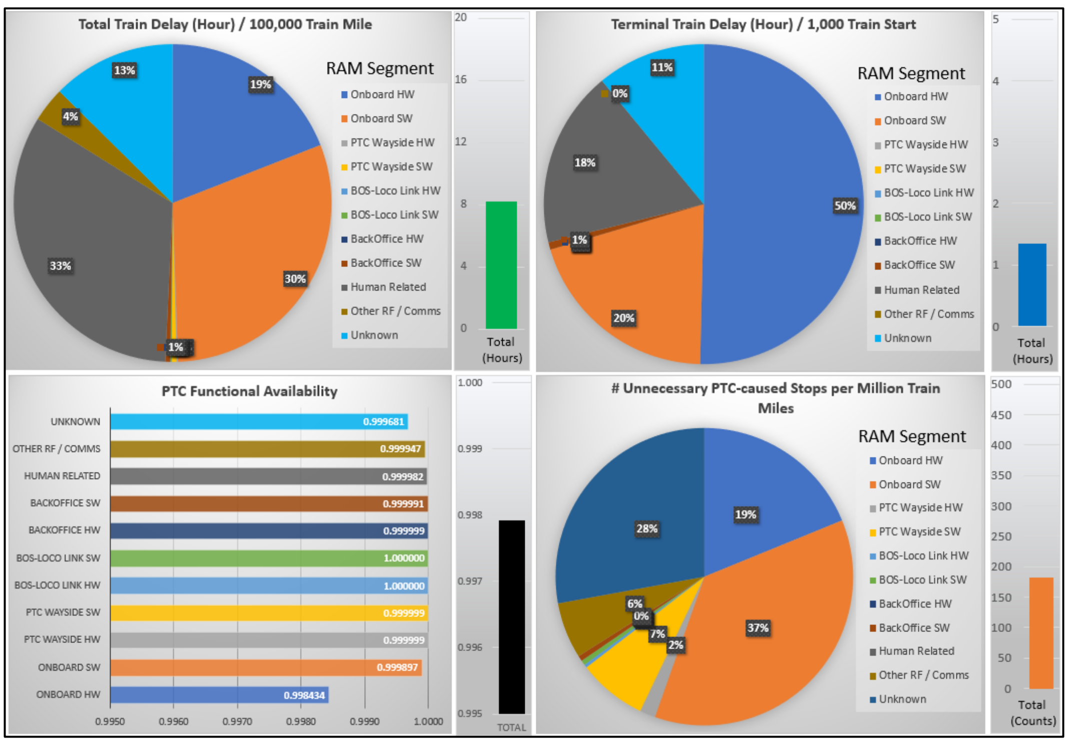

Figure 41. Aggregate RAM KPI Distribution per RAM Segment

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.55	
Speed Reduction	**0.05**	**0.20%**

Figure 42. Aggregate Average Speed Reduction

Table 22 shows the individual and aggregate RAM KPI results and average speed reductions.

Table 22. RAM KPI and Average Speed Reduction - Individual and Aggregate Results

Railroad	RAM KPI				Average Speed Reduction	
	TTDTM	TTDTS	PTCFA	UPSTM	Total (mph)	Percentage
A	9.976	1.124	0.99477	329.0	0.06	0.24
B	33.018	22.731	0.99753	463.6	0.20	0.81
C	7.256	0.575	0.99871	139.2	0.04	0.18
D	6.153	0.567	0.99891	126.0	0.04	0.15
Aggregate	8.217	1.350	0.99793	182.7	0.05	0.20

The individual results show comparable results between Railroads C and D for all calculations. Railroad A shows higher train delay KPI results when compared to Railroads C and D, particularly at the terminal. All railroads show comparable results regarding the availability of the PTCFA, which indicates that the percentage of time that trains operate in an ACTIVE state is comparable between railroads.

The outstanding train delay results of Railroad B are mostly due to two factors:

- Railroad B logged shorter train mileage per trip, on average, than the other railroads. For example, the same operator error that would happen in a 30-mile train trip would result in an MTBDE three times that of a 90-mile train trip.
- Railroad B confirmed they experienced a higher number of onboard events and operator errors than typical when data was collected.

During this project, Railroad B identified issues related to onboard hardware and software problems in one of its interfaces, and addressing these problems was expected to significantly reduce train delays. Figure 43 shows some of the initial improvement results that Railroad B obtained with the improvement of onboard hardware reliability.

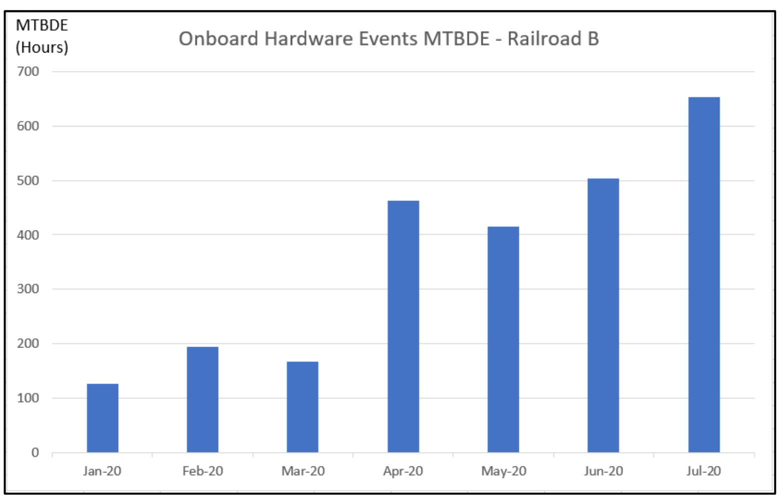

Figure 43. MTBDE of Onboard Hardware Events for Railroad B

Railroad B data also shows a continuous reduction in train crew operation errors throughout the year of 2019 and the beginning of 2020; however, the performance of train crews was affected in the beginning of 2020, as shown in Figure 44. According to Railroad B, one of the factors related to the reduction in the performance of this type of event in 2020 is related to the beginning of the COVID-19 pandemic, as the pandemic affected the availability and performance of human operation.

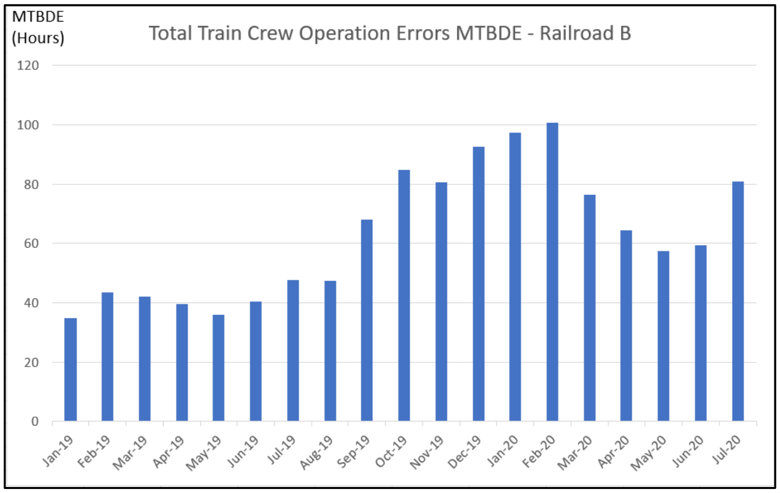

Figure 44. MTBDE of Train Crew Operation Error Events for Railroad B

8.2 Main Contributor Analysis

The analysis of the aggregate results presented in Figure 41 indicate that the main RAM segment contributors per RAM KPI are:

- TTDTM: Human-related
- TTDTS: Onboard hardware
- PTCFA: Onboard hardware
- UPSTM: Onboard software

In the current RAM model, onboard hardware events impact TTDTS significantly because it is assumed that, under full PTC regulation, a train can only depart from the terminal with the PTC active, and the RAM model assumes as default that it takes an average of 90 minutes for the replacement of a lead locomotive (locomotive swap). The PTCFA is also significantly affected by onboard hardware events because it is assumed that these events typically cannot be fixed en route and a train that experiences such an event would have to cut PTC out and operate unprotected until reaching the destination or a repair location,.

The ticket data provided by the railroads still shows a significant number of events that were attributed to the onboard software RAM segment. This data explains why this segment is the highest contributor to UPSTM; however, these events are typically recoverable quickly and do not affect PTCFA and TTDTS as much as onboard hardware events.

8.3 RAM Sensitivity Analysis

The sensitivity analysis indicates how the RAM results change as the RAM parameters of the main contributors improve. Based on the identification of the main contributors, the team developed the sensitivity analysis to both the MTBDE of the two main contributor RAM segments, Human-related and Onboard Hardware, and the MTTR of non-recoverable events that require locomotive swap, to verify how these changes affect the overall RAM KPIs.

The sensitivity analysis based on MTBDE increase illustrates the RAM improvements that are obtainable if actions are taken to reduce the frequency of the occurrence of onboard hardware and human-related events. The sensitivity analysis based on the MTTR of non-recoverable events illustrates the RAM improvements obtainable with the reduction of the average time that it takes to restore train operations when the swap of the lead locomotive is necessary to restore normal PTC operation. Each analysis was developed separately, and the results are presented in the following subsections.

8.3.1 Increase in the MTBDE of Human-related RAM Segment Events

Researchers configured RAMIA with either a 2.5- or 5.0-times increase in the MTBDE of all PTCIEs associated with the Human-Related RAM segment. Figure 45, Figure 46, and Figure 47 show the results obtained with a 2.5-times increase in MTBDE, while Figure 48, Figure 49, and Figure 50 show the results obtained with a 5.0-magnitude increase in MTBDE.

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	1.566	0.680	0.998434	34.4
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	1.089	0.096	0.999993	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	6.583	1.206	0.997939	182.7

Figure 45. Aggregate RAM KPI Results with 2.5-Times Increase in the MTBDE of All Human-related PTCIEs

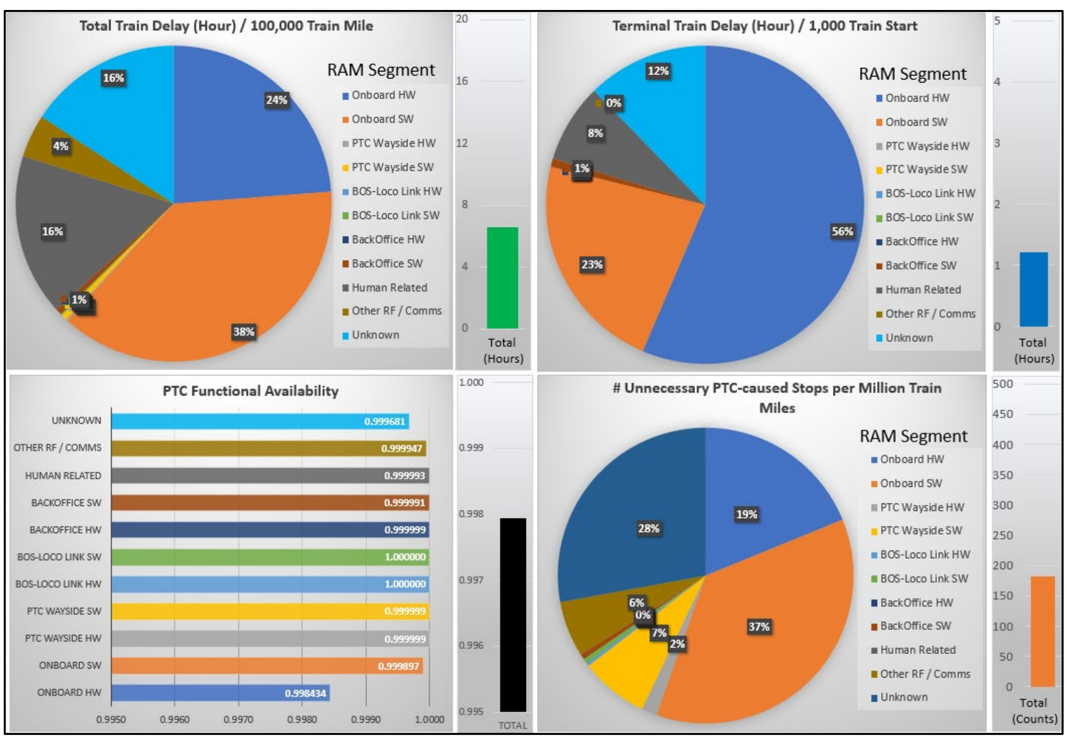

Figure 46. Aggregate RAM KPI Distribution per RAM Segment with 2.5-Times Increase in the MTBDE of All Human-related PTCIEs

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	**0.16%**

Figure 47. Aggregate Average Speed Reduction with 2.5-Times Increase in the MTBDE of All Human-related PTCIEs

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	1.565	0.681	0.998434	34.4
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	0.545	0.048	0.999996	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	6.038	1.158	0.997942	182.7

Figure 48. Aggregate RAM KPI Results with 5.0-Times Increase in the MTBDE of All Human-related PTCIEs

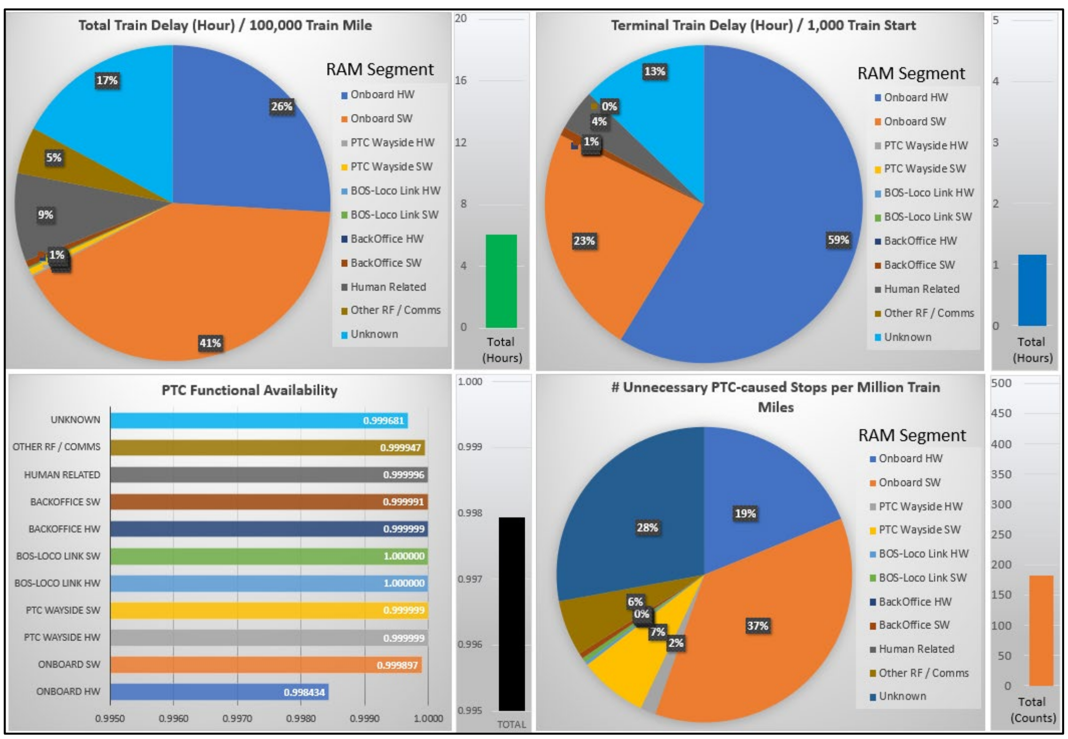

Figure 49. Aggregate RAM KPI Distribution per RAM Segment with 5.0-Times Increase in the MTBDE of All Human-related PTCIEs

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	**0.15%**

Figure 50. Aggregate Average Speed Reduction with 5.0-Times Increase in the MTBDE of All Human-related PTCIEs

8.3.2 Increase in the MTBDE of Onboard Hardware RAM Segment Events

The team configured RAMIA with either a 2.5- or 5.0-times increase in the MTBDE of all PTCIEs associated with the Onboard Hardware RAM segment. Figure 51, Figure 52, and Figure 53 show the results obtained with a 2.5-times increase in MTBDE, while Figure 54, Figure 55, and Figure 56 show the results obtained with a 5.0-times increase in MTBDE.

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	0.626	0.272	0.999374	13.8
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	7.277	0.942	0.998868	162.1

Figure 51. Aggregate RAM KPI Results with 2.5-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

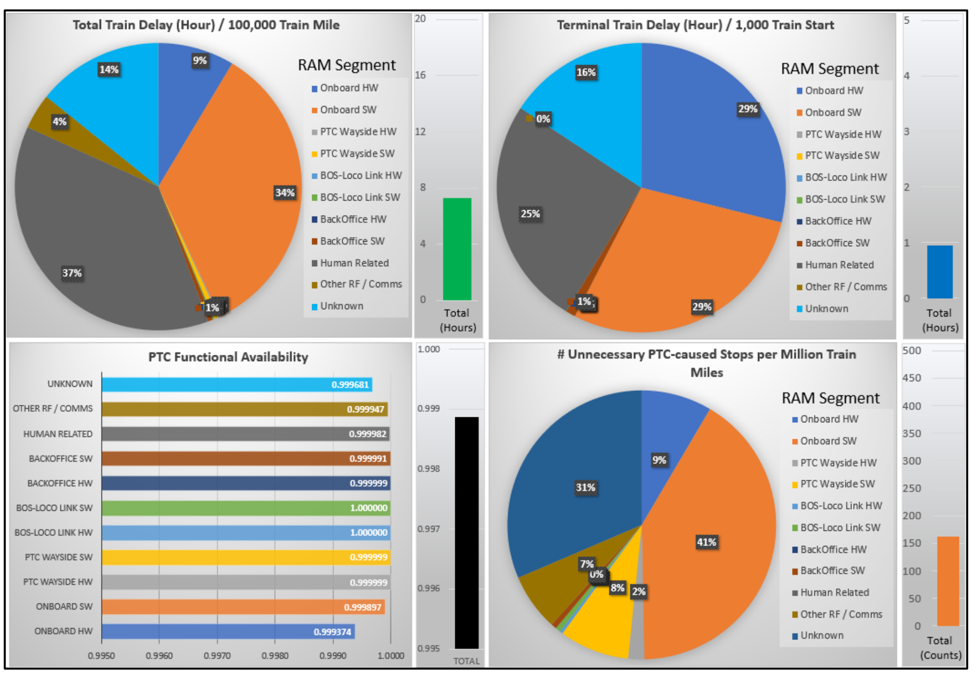

Figure 52. Aggregate RAM KPI Distribution per RAM Segment with 2.5-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	0.18%

Figure 53. Aggregate Average Speed Reduction with 2.5-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	0.313	0.136	0.999687	6.9
Onboard SW	2.498	0.271	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.035	0.148	0.999681	50.9
TOTAL	6.964	0.806	0.999181	155.2

Figure 54. Aggregate RAM KPI Results with 5.0-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

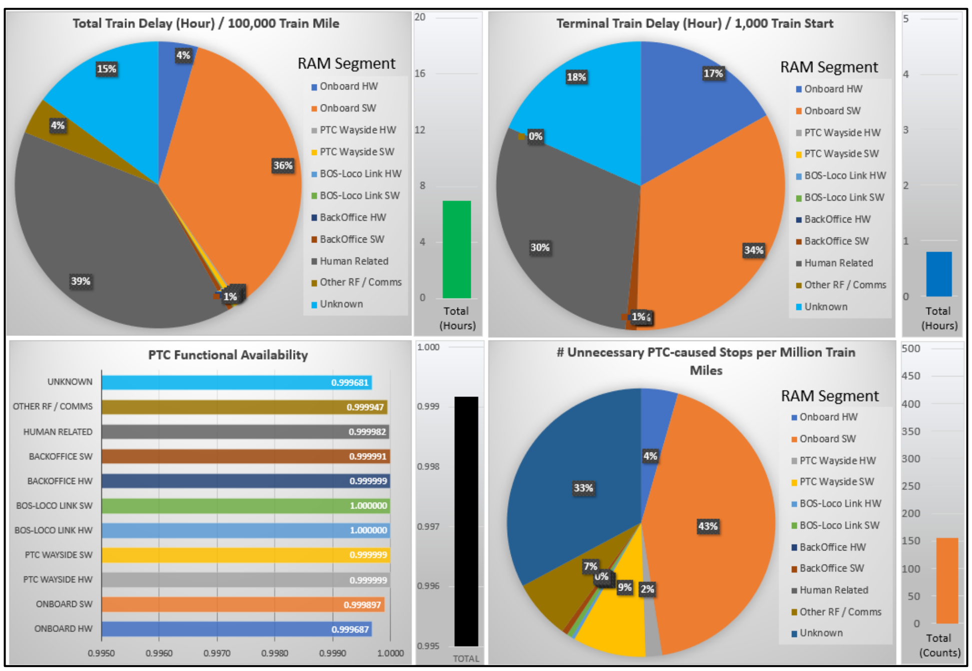

Figure 55. Aggregate RAM KPI Distribution per RAM Segment with 5.0-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.56	
Speed Reduction	**0.04**	0.17%

Figure 56. Aggregate Average Speed Reduction with 5.0-Times Increase in the MTBDE of All Onboard Hardware PTCIEs

8.3.3 Reduction in the MTTR of Events that Require Swap of Lead Locomotive

Researchers configured RAMIA with a reduction in the amount of time that it takes to restore from an event that requires the swap of a lead locomotive from 90 minutes (original configuration) to 60 and 30 minutes, consecutively. Figure 57, Figure 58, and Figure 59 show the results obtained with the reduction of MTTR to 60 minutes, while Figure 60, Figure 61, and Figure 62 show the results obtained with the reduction of MTTR to 30 minutes.

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	1.267	0.478	0.998434	34.4
Onboard SW	2.490	0.263	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	1.009	0.122	0.999681	50.9
TOTAL	7.883	1.114	0.997928	182.7

Figure 57. Aggregate RAM KPI Results with Reduction in the Time to Swap a Lead Locomotive to 60 Minutes

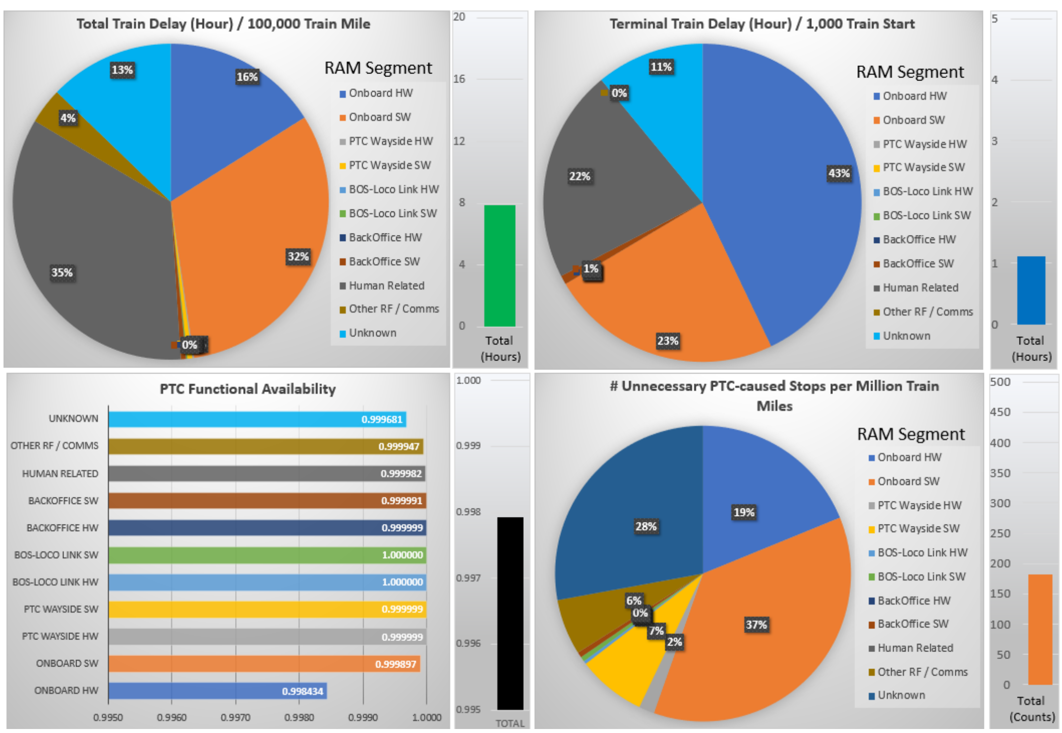

Figure 58. Aggregate RAM KPI Distribution per RAM Segment with Reduction in the Time to Swap a Lead Locomotive to 60 Minutes

Average Train Speed	Speed (MPH)	
Without PTC Delay	24.60	
With PTC Delay	24.55	
Speed Reduction	**0.05**	0.19%

Figure 59. Aggregate Average Speed Reduction with Reduction in the Time to Swap a Lead Locomotive to 60 Minutes

Operational KPI Results				
RAM Segment	Total Train Delay (Hour) / 100,000 Train-Mile	Terminal Train Delay (Hour) / 1,000 Train Start	PTC Functional Availability	# Unnecessary PTC-caused Stops per Million Train Miles
Onboard HW	0.968	0.275	0.998434	34.4
Onboard SW	2.482	0.255	0.999897	66.8
PTC Wayside HW	0.012	0.000	0.999999	3.1
PTC Wayside SW	0.040	0.000	0.999999	13.7
BOS-Loco Link HW	0.000	0.000	1.000000	0.6
BOS-Loco Link SW	0.011	0.000	1.000000	1.0
BackOffice HW	0.001	0.000	0.999999	0.0
BackOffice SW	0.041	0.010	0.999991	1.1
Human Related	2.723	0.241	0.999982	0.0
Other RF / Comms	0.290	0.000	0.999947	11.1
Unknown	0.982	0.096	0.999681	50.9
TOTAL	7.549	0.877	0.997928	182.7

Figure 60. Aggregate RAM KPI Results with Reduction in the Time to Swap a Lead Locomotive to 30 Minutes

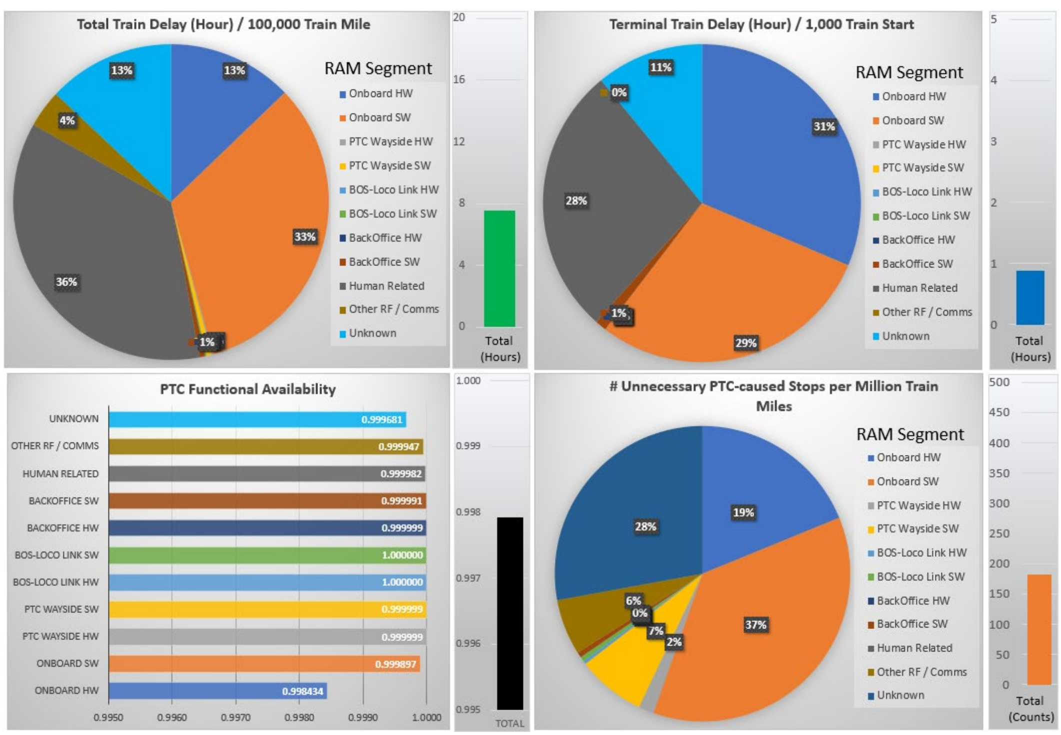

Figure 61. Aggregate RAM KPI Distribution per RAM Segment with Reduction in the Time to Swap a Lead Locomotive to 30 Minutes

Average Train Speed	Speed (MPH)	
Without PTC Delay	**24.60**	
With PTC Delay	**24.55**	
Speed Reduction	**0.05**	**0.19%**

Figure 62. Aggregate Average Speed Reduction with Reduction in the Time to Swap a Lead Locomotive to 30 Minutes

8.3.4 Summary of RAM Sensitivity Results

Table 23 shows the overall results obtained from the sensitivity analysis, where the Baseline shows the aggregate RAM results based on the ticket data analysis. Figure 63 shows a graphical representation of the comparative train delay RAM KPI results (i.e., TTDTM and TTDTS) for the three RAM improvements investigated. Figure 64 shows the improvements obtained for PTCFA (i.e., the percentage of time that trains operate with PTC in ACTIVE state).

Table 23 shows that the increase in the MTBDE of the Onboard Hardware results in the best overall impact on the RAM KPIs, as compared to the other scenarios investigated.

Table 23. Summary RAM Sensitivity Results

Scenario	RAM KPI				Average Speed Reduction	
	TTDTM	**TTDTS**	**PTCFA**	**UPSTM**	**Total (MPH)**	**Percentage**
Baseline	8.095	1.283	0.99793	182.7	0.05	0.20
Human-related 2.5x MTBDE	6.583	1.206	0.99794	182.7	0.04	0.16
Human-related 5x MTBDE	6.038	1.158	0.99794	182.7	0.04	0.15
Onboard HW 2.5x MTBDE	7.277	0.942	0.99887	162.1	0.04	0.18
Onboard HW 5x MTBDE	6.964	0.806	0.99918	155.2	0.04	0.17
Locomotive Swap - 60 Mins	7.883	1.114	0.99793	182.7	0.05	0.19
Locomotive Swap - 30 Mins	7.549	0.877	0.99793	182.7	0.05	0.19

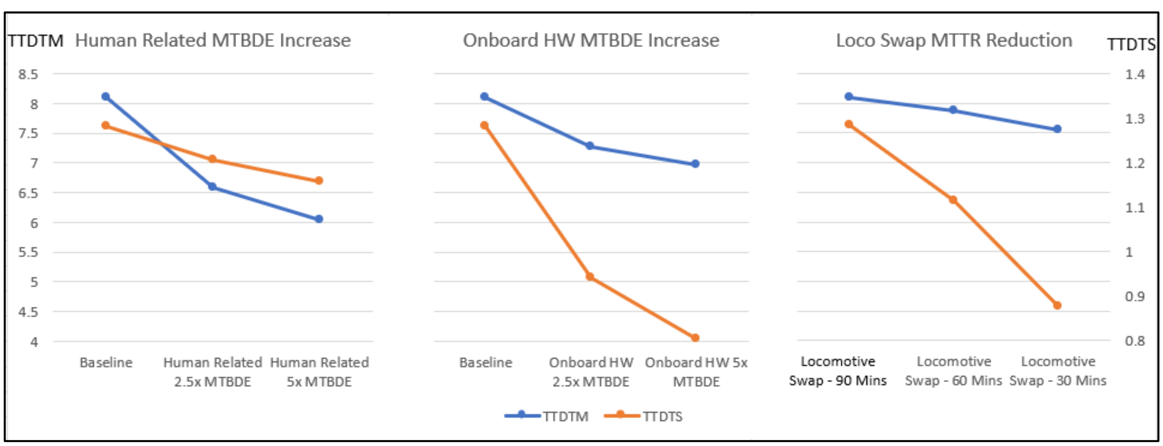

Figure 63. Comparative Train Delay RAM KPI Results Obtained with RAM Improvements

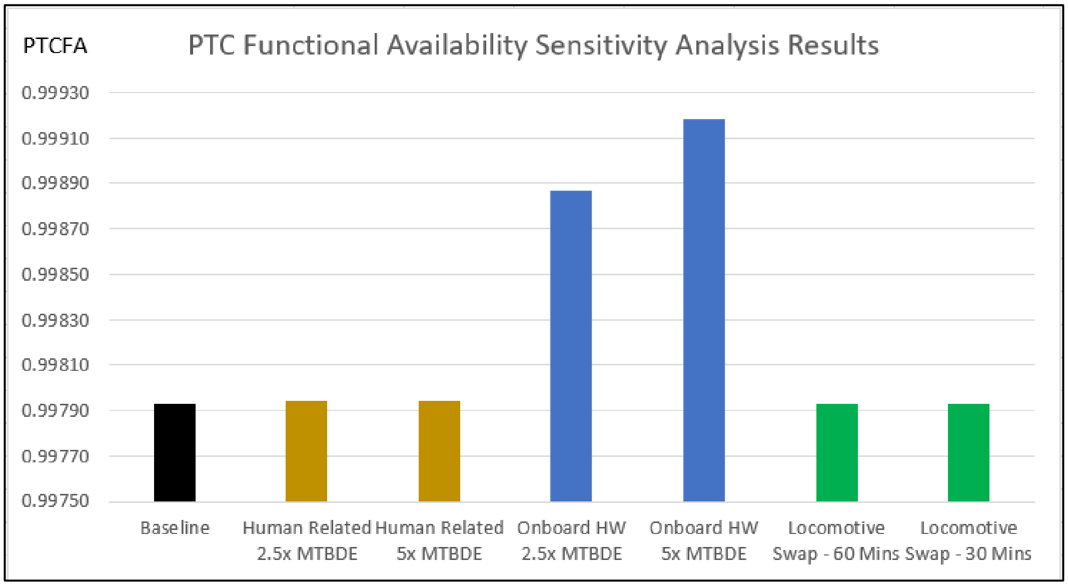

Figure 64. Comparative PTCFA Results Obtained with RAM Improvements

8.4 RAM Recommendations

As previously discussed in Section 7, the RAM analysis was developed at the RAM segment level in this project. Therefore, specific RAM recommendations for the individual PTC components, such as a software or hardware component or LRU, could not be established. The RAM recommendations, however, provide guidance on which RAM segments should be targeted and what magnitude of overall RAM improvements could be achieved.

The results obtained in the RAM analysis indicate that PTCIEs pertaining to the Human-Related RAM segment are the main contributors to overall train delay, followed by the Onboard Software RAM segment. Non-recoverable Onboard Hardware PTCIEs are the main contributors to both train delays at the terminal and PTC functional unavailability.

The analysis of RAM quantification (Section 7) also shows that the MTBDE of human-related events is increasing as expected and should continue, as PTC is now fully deployed and users will continue to become more familiar with the operation of the system. Nonetheless, the sensitivity analysis shows that an increase of 2.5 times in the aggregate MTBDE of all human-related events can produce an overall reduction of more than 18 percent in TTDTM (i.e., overall delay in train operation), which is a significant efficiency improvement. An increase of 5 times in the MTBDE of human-related events would cause a reduction of more than 25 percent in TTDTM. Based on these results, it is strongly recommended that actions related to the reduction of human-related errors (e.g., training, monitoring and mentoring, and system user friendliness improvements) should be considered higher priority from the RAM perspective to improve railroad efficiency.

The sensitivity analysis also shows that an equivalent increase in the MTBDE of the Onboard Hardware PTCIEs can improve overall railroad efficiency, but not as significantly as Human-related PTCIEs. However, it can significantly reduce the overall system unavailability from 0.207 percent (Baseline) to 0.113 percent (2.5x MTBDE) and to .083 percent (5x MTBDE, with a reduction of 45 percent (2.5x MTBDE) and 60 percent (5x MTBDE) of the baseline PTC unavailability. The increase in PTC availability would occur because railroads would operate fewer trains with PTC cutout due to onboard hardware failures. As hardware failures are likely to increase as components reach the end of their life expectancy (as in any system), predictive maintenance procedures will be critical to maintain the reliability of these components, and data logging/analysis will play a major role in generating meaningful predictions.

The reduction in the MTTR of locomotive swap operations to 2/3 and 1/3 of the baseline value (i.e., 90 mins) shows modest overall train delay reduction (2.6 percent and 6.7 percent in TTDTM, respectively) compared to the reduction that could be obtained with the increase in the MTBDE of Human-related PTCIEs. However, the reduction in the MTTR of locomotive swap operations is an improvement that should be considered, and the following operational procedures can be implemented to reduce the MTTR of a locomotive swap operation:

- Performing locomotive testing procedures as early as possible, even before train crew is present
- Maintaining spare sets of locomotives with functional onboard systems tested, ready to replace locomotives with non-functional PTC at key locations
- Maintaining sufficient spare LRUs at key locations

9. Conclusions

Based on 2020 data collected from four railroads, the research team found through RAM analysis that the Human-related and Onboard Software RAM segments are the main contributors to overall train delay, while the Onboard Hardware segment is the main contributor to the unavailability of PTC functionality.

The RAM quantification analysis indicates that the MTBDE of onboard software showed a steady increase throughout 2020. The MTBDE of human operator and onboard hardware also increased during the same period, although not as significantly as onboard software. The number of events that cannot be associated with a particular RAM segment (i.e., Unknown) due to limitations either during data collection or post-event investigation has declined over time, but it is still a significant contributor in all RAM KPIs.

The RAM sensitivity analysis indicates that a 2.5-times increase in the MTBDE of human-related events would cause a reduction of more than 18 percent in the overall aggregate train delay caused by PTC operation, while a 5.0-times increase would cause a reduction of more than 25 percent. The RAM sensitivity analysis also indicates that a 2.5-times increase in the MTBDE of onboard hardware events would cause a reduction of 45 percent in the overall PTC functional unavailability, while a 5.0-times increase would cause a reduction of 60 percent.

The ticket data provided by the railroads contained multiple quality issues, including inaccurate assessments of events causes, non-uniform reporting of events among railroads, incomplete descriptions of events, and low granularity of root-cause identification, all of which constrained the development of the RAM analysis and impacted the accuracy of the RAM results to some extent.

Based on the analysis efforts and discussions with railroads, the research team recommended standard RAM data contents that could reduce or eliminate the issues found with raw ticket data, but a detailed specification for such a standard was not achieved during this project.

During this research, the railroads started developing enhanced methods of data gathering and processing, particularly during 2020, to satisfy requirements from FRA, although the team was unable to explore how these methods could be leveraged in this project.

The team created methods and processes to support the development and execution of a RAM Program Plan. The methods and tools developed for RAM analysis under this project can provide a comprehensive RAM assessment of the PTC system. The results produced were verified in different ways, including:

- Some of the results of the RAM analysis were reviewed with some of the participant railroads to confirm the findings, such as observed variances in RAM parameters due to actions made by railroads (e.g., correction of hardware failures, new software versions, and impacts to human operation).
- The results of the analytical RAM model were compared with the results obtained with the use of a simulation tool (i.e., RTC), and the results were comparable.
- The results were verified through comparison with results from the RAM Phase 1 project (for PTC Functionality Availability).

The RAM analysis process and the model results were reviewed and shared with the participant railroads throughout the project.

Due to the issues related to the quality of the ticket data available from the railroads, the RAM recommendations developed through this project cannot be used as a fully reliable and implementable RAM Program Plan at this time. However, the methods and tools created for the project were shown to be useful in the development of a RAM analysis for an ITC-compliant PTC system and the generation of RAM growth actions.

Moving forward, potential steps such as the following can be explored:

- Methods and tools developed by the research team can be individually used by the railroads.
- Researchers can further expand on the existing project on behalf of the industry to continue development of an industry-wide RAM growth program.

Future RAM efforts will need to focus on improved input data, including the following:

- Using sources of data more reliable than raw ticket data (if available)
- Automating data gathering/processing
- Standardizing RAM data contents among railroads

10. References

[1] Vieira, P. (n.d.). Higher Reliability and Capacity Train Control. *In Press*.

[2] Code of Federal Regulations Title 49CFR, Transportation.

[3] Vieira, P. (2018). PTC Radio Frequency Network Design for Dense Urban Areas (Report No. DOT/FRA/ORD-18/07). Federal Railroad Administration.

[4] Cambridge Systematics, Inc. (2007). National Rail Freight Infrastructure Capacity and Investment Study. Association of American Railroads.

Appendix A.
Draft Vendor Engagement Plan

The research team, in conjunction with the AG, prepared a draft plan for the engagement of vendors in RAM growth initiatives. The draft version was laid out as a set of supporting slides for meetings with vendors as described below.

Motivation

- RAM Growth Plan is a key project objective
  - Failures of PTC SW/HW components are leading drivers of delays
  - Railroad and vendor participation is essential to RAM improvement
- Potential for RAM improvements with current information
  - Identify largest single contributor for initial engagement
  - Identify immediate RAM growth actions
- As the project progresses, detailed modeling and analysis will drive additional recommendations/actions

Objectives of Initial Vendor Engagement

- Make the vendor aware that there are issues, and the situation needs improvement
  - Negatively affecting railroads' operations
  - Will be much worse when railroads can no longer cut out en route and proceed at MAS
- Improve/establish RAM culture and the collaboration between the vendor and the railroads
- Collect information required for RAM modeling
- Produce list of immediate RAM growth actions (low-hanging fruit)
  - Railroads can use list to engage with vendors and to address the RAM issues identified
  - List will be updated throughout project as new items are identified
  - Project scope does not include facilitating implementation

Proposed Approach – Initial Vendor Engagement

- Vendors are currently under pressure
  - Focus is on deployment and tactical bug fixes
  - Any RAM effort is secondary and long-term initiatives are limited
- Discuss in terms of partnership and not vendor-customer relationship, i.e., act as ONE industry
  - There must be long-term benefits for both the industry and the vendors that support it
  - Reduce pressure on vendor by offering help
    - Methodology, tools, expertise, resources, potential funding

    - Show how RAM methodology can benefit all parties
    - Railroads may need to reduce priority of some deployment issues to raise priority of RAM or provide additional resources

Proposed Steps to Engage Vendors

- Meet with vendors to:
    - Explain benefit of active participation into project
    - Explain the scope/objectives of the RAM Phase 2 project
    - Gather RAM information and data
- After the meeting with vendor:
    - Analyze the data/info collected
        - Update RAM evaluation
        - Refine list of immediate RAM growth actions
    - Prepare summary to review with the AG
    - Establish AG consensus and prioritization of short-term RAM improvement actions

Appendix B.
RAM Evaluation Questionnaires

Table B1 contains the RAM Evaluation Questionnaire for hardware components and Table B2 contains the RAM Scorecard for software components.

Table B1. RAM Scorecard for Hardware Components

#	Segment	Instruction	Vendor Notes Current Practice	Vendor Notes Future Improvement Initiatives
1	Hardware Reliability Prediction	Please describe the process (and results) for predicting the mean-time-between-failure for the hardware (each line replaceable unit).		
2	Hardware Operating Life	Please describe the process (and results) for predicting useable life for the hardware (line replaceable unit).		
3	Hardware Design Quality	Please describe the overall End-to-End process for hardware design.		
4	Early Life Failures	Please describe the method (and results) for removing early life hardware issues.		
5	Hardware Fault Management	Please describe the process used for hardware (component) fault detection, alarming and recovery, including transient faults, and failed interfaces. Provide the overall fault coverage percentage for each.		
6	Hardware Failure Containment	Please describe the mechanisms used for hardware failure containment and isolation from other system components.		
7	Failure Diagnostics	Please describe the process to determine which (line replaceable) hardware requires replacing after a failure occurs. This response shall also include the expected duration for changing the failed hardware.		
8	Fault Logging	Please describe the method for logging all hardware errors, describe what is logged, as well as the overall percentage of errors covered by logging.		
9	Power-On Start-Up Test	Please describe the mechanism for determining if the hardware (each line replaceable unit) is functioning properly after power-on start up.		

Table B2. RAM Scorecard for Software Components

#	Segment	Instruction	Vendor Notes Current Practice	Vendor Notes Future Improvement Initiatives
1	Process	Describe general process for improving software quality (e.g., availability, reliability, and maintainability) to evaluate a new design across its life cycle: requirements, design, implementation, and in-service.		
2	CMMI	Provide CMMI assessment level or a self-assessment of their current CMMI level.		
3	Release Management	Describe the method used to declare the release acceptance criteria.		
4	Configuration Management	Describe the process and plan for Software Configuration and branching strategy.		
5	Documentation	Describe the types of documentation provided initially and with subsequent release.		
6	Code Coverage	Describe the process/tool used for static and dynamic code analysis and code coverage.		
7	Code Inspections	Describe the process used for code inspection.		
8	Requirements Traceability	Describe the process used to ensure Software Requirements are traceable to both System Requirements and Test Requirements and Results.		
9	In-service Software Upgrades	Describe the process for planned and unplanned software upgrades. This response shall include the process for reversion if the software upgrade fails or is aborted.		
10	Software Reliability	Describe the process to resolve and minimize field issues and other defects; release over release.		
11	OAM Capability	Describe how OAM and remote management access is handled.		
12	OAM Preserving	The software shall provide sufficient computing and memory resources to support stable OAM operation without impacting system availability.		
13	Software State Audits	Describe how self-diagnostics are performed to verify the operation of critical and non-critical functions of the software.		
14	Testing	Demonstrate how they validate their software using unit, integration, system, regression, fault insertion, robustness and quality testing of features and fixes.		
15	Soak Testing	Describe the process used for soak testing the software (note: duration and capacity levels).		
16	Fault Insertion Testing	Describe their fault insertion (FITS) program.		

#	Segment	Instruction	Vendor Notes Current Practice	Vendor Notes Future Improvement Initiatives
17	Configuration Testing	Describe how configurable parameters are tested and validated.		
18	Test Escapes	Demonstrate how they produce defect density statistics (weighted by severity of defects) of escaped defects by internal architecture area of software (e.g., classes, subsystems); this includes demonstrating how they adjust software test coverage in each new release to improve test coverage in highest defect density areas. The Vendor shall demonstrate continuous improvement in the area of predicting latent escaped defects by software area.		
19	Re-inserted Defects	Show how statistics on re-inserted defects by software area are tracked and adjusted with each release, software regression test coverage to better detect re-inserted defects prior to delivery. Demonstrate how they measure re-inserted defect rate for each new release.		
20	Fault Management	Describe the fault detection, isolation and accommodation/recovery capability of the software and describe how faults are alarmed, logged. Include the percentage of recoverable software faults detected.		
21	Failure Recreation	Describe the mechanism for capturing (and preserving) critical de-bugging data after a failure. Note: the intent of this data is to better understand the failure so it can be recreated and fixed.		
22	Overload and Resource Management	Describe how the mechanism use by the software for handling overloads and managing (and preserving resources) (i.e., memory, CPU). State current levels of CPU and Memory usage		
23	Power Outage	Explain how the software recovers after a power outage.		

Appendix C.
Configuration of Default Operational Scenarios

The configuration of the default RAM operational scenarios was based on selected subdivision configurations defined for the HRCTC project [1]. These same operational scenarios were configured in RTC for the validation of the RAMIA results. Table C1 shows a summary of the primary configuration parameters per operational scenario.

Table C1. Primary Operational Scenario Configuration Parameters

Operational Scenario	Track length (miles)	Number of WIUs	Number of sidings or crossovers
Signaled single track	204	99	20
Signaled double-track	204	162	27
Signaled triple-track	109	108	25
Non-signaled territory	204	99	20

For RTC simulations, the scenarios needed additional information to be fully configured, specifically:

- Length of sidings in the single-track and dark territory scenarios
- Spacing between sidings in single-track and dark territory scenarios
- Spacing between crossovers in the double- and triple-track scenarios
- Track circuit length in the single, double-, and triple-track, as well as dense urban area scenarios
- Track altimetry in all the scenarios
- Track curvature in all the scenarios
- Switch characteristics
- Train consist make up and schedule for all the trains in all the scenarios

Configuration details for each operational scenario (e.g., siding length, typical track circuit length in signaled territories, etc.) were based on typical subdivisions selected by participant railroads and approved by the AG, per the following:

- Signaled single track: Red Rock subdivision (BNSF)
- Signaled double-track: Mendota subdivision (BNSF)
- Signaled triple-track: Kearney subdivision (UP)
- Non-signaled territory: Red Rock subdivision (BNSF) used as reference for the geometry

Signaled Single-track Scenario Configuration

Using BNSF's Red Rock subdivision as the baseline to model the geometric characteristics of this scenario, the team analyzed the following sections of this subdivision:

- From milepost (MP) 411.3 to 517 (at this point, there is a change in MP enumeration to 417)
- From MP 417 to 387.4 (skipped from MP 387.4 to 380.6 as this is double-track configuration)

- From MP 380.6 to 312

Grades and curves were configured to characterize significant variations. Based on the sizes identified in the tracks analyzed, track circuit sizes were configured based on the average size. Table C2 shows the details of the configuration for the signaled single track model.

Table C2. Signaled Single Track Configuration Parameters

Length (miles)	204
Number of sidings	21
Length of sidings (min., max., avg. miles)	1.1, 2.1, 1.738
Spacing between sidings (min., max., avg. miles)	4.4, 11.5, 7.614
Sidings type	Controlled
Track circuit length (min., max., avg. miles)	1.85, 2.55, 2.147
Number of permissive signals	58
Number of absolute signals	42
Elevation (min., max. feet)	720, 1210
Degree of curvature (min., max. degrees)	0, 6.05
Switch type	Dual controlled
Frog number of the switches	20
Type of train control	CTC
Maximum speed (passenger, freight mph)	79, 60

The configuration of the trains included in the model was based on the information provided by the participant railroads and reviewed with the AG. The number and type of trains for the signaled single track scenario were 17 daily trains in total, and these trains had the following distribution: four passenger, three loaded grains, two empty grains, two high priority merchandise, two UPS freight, two merchandise, one unit (other than coal or grain), and one intermodal stack. Sixty-five percent of the trains depart from one end of the track, and 35 percent from the other end.

The train consist was based on typical parameters obtained from an analysis of the configuration of trains that currently run in actual subdivisions. Table C3 shows the train schedule and consist configuration of the signaled single track model.

Table C3. Signaled Single Track Train Schedule

Train ID	Type	Depart Time	Entry Point	# of Cars	Locomotive Type	No. of Locomotives	Total Weight (tons)	Total Length (feet)	P/W Ratio
Amtrak-01	Passenger	7:30 AM	East	8	F59PH	2	300	676	20.2
Amtrak-02	Passenger	7:40 AM	West	8	P40-HEP	2	608	818	8.4
LoadedGrain-01	Loaded Grain	8:55 AM	East	100	SD40-2	3	11,000	5706	0.7
Merchandise-01	Merchandise	9:05 AM	West	90	C44-9	2	7,650	5996	1.1
EmptyGrain-01	Empty Grain	10:20 AM	East	100	SD40-2	3	3,500	5706	2.2
LoadedGrain-02	Loaded Grain	10:30 AM	West	100	SD40-2	3	11,000	5706	0.7
UPS-01	Freight	11:45 AM	East	50	SD70MAC	2	4,400	3298	1.5
HPM-01	High Priority Merchandise	11:55 AM	West	70	SD70MAC	2	5,110	4558	1.3
Amtrak-03	Passenger	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Merchandise-02	Merchandise	1:10 PM	East	80	SD70MAC	2	6,800	5348	1
Amtrak-04	Passenger	2:20 PM	East	8	F59PH	2	300	676	20.2
IS-01	Intermodal Stack	2:25 PM	West	70	SD70MAC	3	6,300	5122	1.6
EmptyGrain-02	Empty Grain	3:50 PM	West	100	SD40-2	3	3,500	5706	2.2
Unit-01	Unit (other than coal or grain)	5:20 PM	West	110	SD70MAC	2	10,450	6748	0.6
LoadedGrain-03	Loaded Grain	6:40 PM	West	100	SD40-2	3	11,000	5706	0.7
HPM-02	High Priority Merchandise	8:05 PM	West	70	SD70MAC	2	5,110	4558	1.3
UPS-02	Freight	9:30 PM	West	50	SD70MAC	2	4,400	3298	1.5

Signaled Double-track Scenario Configuration

Using BNSF's Mendota subdivision as the baseline to model the geometric characteristics of this scenario, researchers analyzed 125 miles of this subdivision (from MP 165 to 40).

Researchers prepared a 204-mile-long model using the track configuration identified in the Mendota subdivision. The team applied the same track altitude and curvature configuration defined for the single track scenario. All track circuits between two control points were assumed to have the same length.

Track circuit sizes were configured based on average size, based on the sizes identified in the tracks analyzed. Table C4 shows the details of the configuration for the signaled double-track model.

Table C4. Signaled Double-Track Configuration Parameters

Signaled Double-Track Summary Configuration	
Length (miles)	204
Number of Crossovers	24
Length of Sidings (min., max., avg. miles)	N/A
Spacing between Crossovers (min., max., avg. miles)	3.9, 15.8, 8.01
Crossover types	Single and double
Track circuit length (min., max., avg. miles)	1.3, 2.14, 1.689
Number of permissive signals	188
Number of absolute signals	96
Elevation (min., max. feet)	728.5, 1180
Degree of curvature (min., max. degrees)	0, 6.05
Switch type	Dual controlled
Frog number of the switches	20
Type of train control	C.T.C.
Maximum speed (passenger, freight mph)	79, 60

The double-track model was configured with a total of 84 trains per day, with the following distribution: 4 passengers, 39 loaded grains, 4 empty grains, 17 high priority merchandise, 2 UPS freight, and 18 merchandise. Fifty-one percent of the trains depart from one end of the track, and 49 percent from the other end. Table C5 shows the train schedule and consist configuration of the signaled double-track model.

Table C5. Signaled Double-Track Train Schedule

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-01	Loaded Grain	12:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-02	Merchandise	12:15 AM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-03	High Priority Merchandise	12:30 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-04	Loaded Grain	12:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-05	Freight (High Prt Merch)	1:15 AM	West	50	SD70MAC	2	4,400	3,298	1.5
Dbl-06	Loaded Grain	1:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-07	Loaded Grain	1:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-08	Loaded Grain	2:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-09	Loaded Grain	2:15 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-10	Merchandise	2:30 AM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-11	Loaded Grain	2:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-12	Loaded Grain	3:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-13	Merchandise	3:15 AM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-14	Loaded Grain	3:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-15	Merchandise	3:45 AM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-16	Loaded Grain	4:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-17	High Priority Merchandise	4:15 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-18	Merchandise	4:30 AM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-19	Loaded Grain	4:45 AM	West	100	SD40-2	3	11,000	5,706	0.7

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-20	Merchandise	5:00 AM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-21	High Priority Merchandise	5:15 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-22	High Priority Merchandise	5:45 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-23	High Priority Merchandise	6:00 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-24	Passenger	6:15 AM	West	8	P40-HEP	2	608	818	8.4
Dbl-25	High Priority Merchandise	6:30 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-26	Loaded Grain	6:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-27	Loaded Grain	7:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-28	High Priority Merchandise	7:15 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-29	Passenger	7:30 AM	East	8	F59PH	2	300	676	20.2
Dbl-30	Empty Grain	7:45 AM	West	100	SD40-2	3	3,500	5,706	2.2
Dbl-31	Loaded Grain	8:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-32	Loaded Grain	8:15 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-33	Loaded Grain	8:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-34	Loaded Grain	8:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-35	Loaded Grain	9:00 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-36	Loaded Grain	9:15 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-37	Loaded Grain	9:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-38	Empty Grain	9:45 AM	West	100	SD40-2	3	3,500	5,706	2.2
Dbl-39	Empty Grain	10:00 AM	East	100	SD40-2	3	3,500	5,706	2.2

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-40	Loaded Grain	10:15 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-41	Loaded Grain	10:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-42	Loaded Grain	10:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-43	Loaded Grain	11:15 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-44	Loaded Grain	11:30 AM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-45	Loaded Grain	11:45 AM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-46	Loaded Grain	12:00 PM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-47	Loaded Grain	12:15 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-48	Loaded Grain	12:30 PM	East	100	SD40-2	3	11,000	5,,706	0.7
Dbl-49	High Priority Merchandise	12:45 PM	West	70	SD70MAC	2	5,110	4558	1.3
Dbl-50	Loaded Grain	1:00 PM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-51	Loaded Grain	1:15 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-52	High Priority Merchandise	1:30 PM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-53	Merchandise	1:45 PM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-54	Loaded Grain	2:00 PM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-55	Merchandise	2:15 PM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-56	Loaded Grain	2:30 PM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-57	Merchandise	2:45 PM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-58	Loaded Grain	3:00 PM	East	100	SD40-2	3	11,000	5,706	0.7
Dbl-59	Passenger	3:15 PM	West	8	P40-HEP	2	608	818	8.4

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-60	Merchandise	3:30 PM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-61	Loaded Grain	3:45 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-62	Merchandise	4:00 PM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-63	Loaded Grain	4:15 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-64	Merchandise	4:30 PM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-65	Freight (High Prt Merch)	5:00 PM	East	50	SD70MAC	2	4400	3,298	1.5
Dbl-66	Merchandise	5:15 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-67	High Priority Merchandise	5:30 PM	East	70	SD70MAC	2	5110	4,,558	1.3
Dbl-68	Merchandise	5:45 PM	West	90	C44-9	2	7650	5996	1.1
Dbl-69	Merchandise	6:00 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-70	Passenger	6:15 PM	East	8	F59PH	2	300	676	20.2
Dbl-71	High Priority Merchandise	6:15 PM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-72	Merchandise	6:45 PM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-73	Merchandise	7:00 PM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-74	Loaded Grain	7:15 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-75	Empty Grain	7:30 PM	East	100	SD40-2	3	3,500	5,706	2.2
Dbl-76	Loaded Grain	7:45 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-77	High Priority Merchandise	8:00 PM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-78	High Priority Merchandise	8:15 PM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-79	High Priority Merchandise	8:45 PM	West	70	SD70MAC	2	5,110	4,558	1.3

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-80	High Priority Merchandise	9:00 PM	East	70	SD70MAC	2	5,110	4,558	1.3
Dbl-81	Merchandise	9:15 PM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-82	High Priority Merchandise	9:45 PM	West	70	SD70MAC	2	5,110	4,558	1.3
Dbl-83	Merchandise	10:00 PM	East	80	SD70MAC	2	6,800	5,348	1
Dbl-84	Loaded Grain	10:15 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-85	Loaded Grain	10:45 PM	West	100	SD40-2	3	11,000	5,706	0.7
Dbl-86	High Priority Merchandise	11:00 PM	East	70	SD70MAC	2	5,110	4,558	1.3

Signaled Triple-Track Scenario Configuration

Using UP's Kearney subdivision as the reference to build the signaled triple-track model, the research team analyzed 109 miles of track (from MP 284.0 to 175.0) to determine the configuration parameters for the model.

The altitude and curvature of the model tracks were based on the same characteristics as the signaled single-track model tracks. The length of track circuits between two control points were configured based on an average track circuit length.

Table C6 shows the details of the configuration for the signaled triple-track model.

Table C6. Signaled Triple-Track Configuration Parameters

Length (miles)	109
Number of Crossovers	16
Length of Sidings (min., max., avg. miles)	N/A
Spacing between Crossovers (min., max., avg. miles)	2.2, 10.6, 6.188
Crossovers Type	Single and double
Track circuit length (min., max., avg. miles)	1.067, 1.5, 1.252
Number of permissive signals	207
Number of absolute signals	96
Elevation (min., max. feet)	953, 1150
Degree of curvature (min., max. degrees)	0, 4.0
Switch type	Dual controlled
Frog number of the switches	20
Type of train control	C.T.C.
Maximum Speed (passenger, freight mph)	79, 60

The model was configured with 110 daily trains, distributed as follows: 75 passenger, 5 loaded grains, 1 empty grain, 8 loaded coal, 4 high priority merchandise, 4 intermodal, 4 intermodal stack, 2 UPS freight, 4 merchandise, 1 empty coal, 1 vehicle, and 1 unit (other than coal or grain). From these trains, 52 percent depart from one end of the track, and 48 percent from the other end. Table C7 shows the train schedule and consist configuration of the signaled double-track model.

Table C7. Signaled Triple-Track Train Schedule

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-01	Freight	12:10 AM	East	50	SD70MAC	2	4,400	3,298	1.5
Tri-02	Intermodal	12:40 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-03	Freight	1:15 AM	West	50	SD70MAC	2	4,400	3,298	1.5
Tri-04	Intermodal	1:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-05	Intermodal	1:45 AM	West	70	SD70MAC	3	6,300	5,122	1.6
Tri-06	Intermodal Stack	2:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-07	Intermodal	2:45 AM	West	70	SD70MAC	3	6,300	5,122	1.6
Tri-08	Intermodal Stack	3:15 AM	West	70	SD70MAC	3	6,300	5,1,22	1.6
Tri-09	Intermodal Stack	3:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-11	High Priority Merchandise	4:00 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Tri-10	Intermodal Stack	4:00 AM	West	70	SD70MAC	3	6,300	5,122	1.6
Tri-12	Passenger	4:06 AM	West	8	P40-HEP	2	608	818	8.4
Tri-13	Passenger	4:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-14	High Priority Merchandise	4:40 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Tri-15	Passenger	4:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-16	High Priority Merchandise	5:00 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Tri-17	Passenger	5:15 AM	West	8	P40-HEP	2	608	818	8.4
Tri-18	Passenger	5:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-20	Passenger	5:45 AM	East	8	F59PH	2	300	676	20.2

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-19	Passenger	5:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-21	Passenger	5:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-22	Passenger	6:12 AM	West	8	P40-HEP	2	608	818	8.4
Tri-23	Passenger	6:32 AM	West	8	P40-HEP	2	608	818	8.4
Tri-24	Passenger	6:45 AM	East	8	F59PH	2	300	676	20.2
Tri-25	Passenger	6:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-26	Passenger	7:00 AM	East	8	F59PH	2	300	676	20.2
Tri-27	Passenger	7:12 AM	West	8	P40-HEP	2	608	818	8.4
Tri-28	Passenger	7:20 AM	East	8	F59PH	2	300	676	20.2
Tri-29	Passenger	7:25 AM	West	8	P40-HEP	2	608	818	8.4
Tri-31	Passenger	7:45 AM	East	8	F59PH	2	300	676	20.2
Tri-30	Passenger	7:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-33	Passenger	8:00 AM	East	8	F59PH	2	300	676	20.2
Tri-32	Passenger	8:00 AM	West	8	P40-HEP	2	608	818	8.4
Tri-34	Passenger	8:15 AM	West	8	P40-HEP	2	608	818	8.4
Tri-36	Passenger	8:30 AM	East	8	F59PH	2	300	676	20.2
Tri-35	Passenger	8:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-37	Passenger	8:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-38	Passenger	8:47 AM	East	8	F59PH	2	300	676	20.2
Tri-39	Passenger	9:00 AM	West	8	P40-HEP	2	608	818	8.4

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-40	Loaded Coal	9:00 AM	East	120	SD70MAC	2	17,160	6748	0.4
Tri-41	Passenger	9:02 AM	East	8	F59PH	2	300	676	20.2
Tri-42	Passenger	9:20 AM	West	8	P40-HEP	2	608	818	8.4
Tri-43	High Priority Merchandise	9:30 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Tri-44	Loaded Coal	9:30 AM	East	120	SD70MAC	2	17,160	6,748	0.4
Tri-45	Passenger	9:32 AM	East	8	F59PH	2	300	676	20.2
Tri-46	Passenger	9:40 AM	West	8	P40-HEP	2	608	818	8.4
Tri-47	Passenger	9:45 AM	East	8	F59PH	2	300	676	20.2
Tri-48	Passenger	10:00 AM	East	8	F59PH	2	300	676	20.2
Tri-49	Passenger	10:05 AM	West	8	P40-HEP	2	608	818	8.4
Tri-50	Passenger	10:20 AM	East	8	F59PH	2	300	676	20.2
Tri-51	Passenger	10:24 AM	West	8	P40-HEP	2	608	818	8.4
Tri-53	Loaded Coal	10:30 AM	East	120	SD70MAC	2	17,160	6,748	0.4
Tri-52	Loaded Coal	10:30 AM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-54	Passenger	10:40 AM	East	8	F59PH	2	300	676	20.2
Tri-55	Loaded Grain	10:45 AM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-56	Passenger	10:50 AM	West	8	P40-HEP	2	608	818	8.4
Tri-58	Passenger	11:00 AM	East	8	F59PH	2	300	676	20.2
Tri-57	Passenger	11:00 AM	West	8	P40-HEP	2	608	818	8.4
Tri-59	Loaded Coal	11:00 AM	West	120	SD70MAC	2	17,160	6,748	0.4

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-60	Passenger	11:20 AM	East	8	F59PH	2	300	676	20.2
Tri-61	Passenger	11:40 AM	East	8	F59PH	2	300	676	20.2
Tri-62	Passenger	12:20 PM	East	8	F59PH	2	300	676	20.2
Tri-63	Passenger	12:50 PM	East	8	F59PH	2	300	676	20.2
Tri-64	Passenger	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-65	Passenger	1:20 PM	East	8	F59PH	2	300	676	20.2
Tri-66	Passenger	2:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-67	Loaded Coal	2:10 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-68	Loaded Grain	2:10 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-69	Passenger	2:20 PM	East	8	F59PH	2	300	676	20.2
Tri-70	Passenger	2:30 PM	West	8	P40-HEP	2	608	818	8.4
Tri-71	Passenger	2:40 PM	East	8	F59PH	2	300	676	20.2
Tri-72	Passenger	3:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-73	Loaded Coal	3:10 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-74	Loaded Grain	3:10 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-75	Passenger	3:20 PM	East	8	F59PH	2	300	676	20.2
Tri-76	Loaded Grain	3:45 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-77	Passenger	3:50 PM	East	8	F59PH	2	300	676	20.2
Tri-78	Loaded Coal	3:50 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-79	Passenger	4:00 PM	West	8	P40-HEP	2	608	818	8.4

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-80	Passenger	4:05 PM	East	8	F59PH	2	300	676	20.2
Tri-81	Passenger	4:20 PM	East	8	F59PH	2	300	676	20.2
Tri-82	Passenger	4:38 PM	East	8	F59PH	2	300	676	20.2
Tri-84	Passenger	5:00 PM	East	8	F59PH	2	300	676	20.2
Tri-83	Passenger	5:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-85	Passenger	5:15 PM	East	8	F59PH	2	300	676	20.2
Tri-86	Passenger	5:25 PM	East	8	F59PH	2	300	676	20.2
Tri-87	Passenger	5:45 PM	East	8	F59PH	2	300	676	20.2
Tri-88	Loaded Grain	5:55 PM	East	100	SD40-2	3	11,000	57,06	0.7
Tri-89	Unit (other than coal or grain)	5:55 PM	West	110	SD70MAC	2	10,450	6,748	0.6
Tri-90	Passenger	6:10 PM	East	8	F59PH	2	300	676	20.2
Tri-91	Passenger	6:25 PM	West	8	P40-HEP	2	608	818	8.4
Tri-92	Vehicle	6:25 PM	East	60	SD70	3	7,200	5,322	1.4
Tri-93	Merchandise	6:35 PM	West	90	C44-9	2	7,650	5,996	1.1
Tri-94	Passenger	6:40 PM	East	8	F59PH	2	300	676	20.2
Tri-95	Merchandise	7:00 PM	East	80	SD70MAC	2	6,800	5,348	1
Tri-96	Passenger	7:10 PM	East	8	F59PH	2	300	676	20.2
Tri-97	Merchandise	7:30 PM	East	80	SD70MAC	2	6,800	5,348	1
Tri-98	Merchandise	7:35 PM	West	90	C44-9	2	7,650	5,996	1.1

Train ID	Type	Depart Time	Entry Point	No. of Cars	Locomotive Type	Qty.	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-99	Passenger	7:40 PM	East	8	F59PH	2	300	676	20.2
Tri-100	Passenger	7:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-101	Passenger	8:05 PM	East	8	F59PH	2	300	676	20.2
Tri-102	Empty Coal	8:10 PM	East	80	C44-AC	2	2800	4,546	3
Tri-103	Empty Grain	8:35 PM	West	100	SD40-2	3	3500	5,706	2.2
Tri-104	Passenger	8:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-105	Passenger	9:30 PM	East	8	F59PH	2	300	676	20.2
Tri-106	Passenger	9:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-107	Passenger	10:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-108	Passenger	11:00 PM	East	8	F59PH	2	300	676	20.2
Tri-109	Passenger	11:30 PM	East	8	F59PH	2	300	676	20.2
Tri-110	Passenger	11:50 PM	West	8	P40-HEP	2	608	818	8.4

Non-signaled Territory Scenario Configuration

The team configured the non-signaled territory model with the same geometric characteristics as the signaled single track model (i.e., the same number, length, and spacing of sidings; the elevation; and the curvature configuration). The main differences between the two models are the type of train control, types of sidings and switches, and the MAS.

Table C8 shows the details of the configuration for the non-signaled territory model.

Table C8. Non-signaled Territory Configuration Parameters

Length (miles)	204
Number of Sidings:	21
Length of Sidings (min., max., avg. miles)	1.1, 2.1, 1.738
Spacing between sidings (min., max., avg. miles)	4.4, 11.5, 7.614
Sidings type	Uncontrolled
Track circuit length (min., max., avg. miles)	N/A
Number of permissive signals:	N/A
Number of absolute signals:	N/A
Elevation (min., max. feet):	720, 1210
Degree of curvature (min., max. degrees)	0, 6.05
Switch type	Manual without any lock
Frog number of the switches	16
Type of train control	Track Warrant
Maximum Speed (passenger, freight mph)	60, 50

The model was configured with 22 daily trains, distributed as follows: 5 local, 4 passenger, 3 loaded grains, 2 merchandise, 2 empty grains, 2 high priority merchandise, 2 UPS freight, 1 foreign, and 1 intermodal stack. Sixty percent of the trains depart from one end of the track, and the rest depart from the other end of the track. Table C9 shows the train schedule and consist configuration of the non-signaled territory model.

Table C9. Signaled Triple-Track Train Schedule

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Amtrak-01	Amtrak	7:30 AM	East	8	F59PH	2	300	676	20.2
Local-01	Local	7:40 AM	East	60	SD40-2	6	5,400	4,313	2.8
Amtrak-02	Amtrak	7:40 AM	West	8	P40-HEP	2	608	818	8.4
LoadedGrain-01	Loaded Grain	8:55 AM	East	100	SD40-2	3	11,000	5,706	0.7
Merchandise-01	Merchandise	9:05 AM	West	90	C44-9	2	7,650	5,996	1.1
Local-02	Local	9:30 AM	West	60	SD40-2	6	5,400	4,313	2.8
EmptyGrain-01	Empty Grain	10:20 AM	East	100	SD40-2	3	3,500	5,706	2.2
LoadedGrain-02	Loaded Grain	10:30 AM	West	100	SD40-2	3	11,000	5,706	0.7
UPS-01	UPS Freight	11:45 AM	East	50	SD70MAC	2	4,400	3,298	1.5
HPM-01	High Priority Merchandise	11:55 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Local-03	Local	12:45 PM	East	60	SD40-2	6	5,400	4,313	2.8
Amtrak-03	Amtrak	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Merchandise-02	Merchandise	1:10 PM	East	80	SD70MAC	2	6,800	5,348	1
Amtrak-04	Amtrak	2:20 PM	East	8	F59PH	2	300	676	20.2
IS-01	Intermodal Stack	2:25 PM	West	70	SD70MAC	3	6,300	5,122	1.6
EmptyGrain-02	Empty Grain	3:50 PM	West	100	SD40-2	3	3,500	5,706	2.2
Foreign-01	Foreign	5:15 PM	West	90	C44-9	2	7,650	5,996	1.1
Local-04	Local	6:00 PM	West	60	SD40-2	6	5,400	4,313	2.8
LoadedGrain-01	Loaded Grain	6:40 PM	West	100	SD40-2	3	11,000	5,706	0.7

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Local-05	Local	7:25 PM	East	60	SD40-2	6	5,400	4,313	2.8
HPM-02	High Priority Merchandise	8:05 PM	West	70	SD70MAC	3	6,300	5,122	1.6
UPS-02	UPS Freight	9:30 PM	West	50	SD70MAC	2	4,400	3,298	1.5

Appendix D.
Detailed RAM Modeling Description

This section contains a detailed description of the RAM modeling design for three PTCIE examples for a single track configuration: En route Onboard Hardware Non-Recoverable with Enforcement, WIU HW Outage at Control Point, and Back Office Outage. The description includes an explanation of how train delays are modeled and how the RAM KPI TTDTM is calculated.

A similar modeling design was developed for every PTCIE in each type of operational scenario (i.e., signaled single, double- and triple-track, and non-signaled) and for the calculation of all other RAM KPIs.

GENERAL ASSUMPTIONS

For the signaled single track scenario, the following assumptions/considerations are made:

- Headway minimum (Hm) – Length of two track circuits plus average train length
- Headway average (Ha) – It is assumed that the average headway in one direction can be different than the average headway in the other direction. The headway in one direction is indicated as Ha, and the headway in the other direction is indicated as $Ha_{opposite\text{-}direction}$.

EXAMPLE 1: EN ROUTE ONBOARD HARDWARE NON-RECOVERABLE WITH ENFORCEMENT

Short description

An onboard HW failure that occurs when train is enroute, causing enforcement. The train resumes in fallback operation (Reduced Speed) for the remainder of the trip.

Assumptions

It is assumed that the failure occurs halfway through the trip, and the train will continue in fallback operation for the remainder of the trip.

Consequences to the railroad network operation

A failed train will impact trains in both directions. Depending on the headway between trains, trains behind will pass the failed train and additional meet-pass meetings with trains in reverse direction may also occur.

For passing trains, there are two possible scenarios:

1) Passing Scenario 1: Trains behind will be affected, as they will have to reduce their speed as they get closer to the failed train until a minimum separation distance is reached, and the failed train will stop to let the train behind pass, as shown in Figure D1.
2) Passing Scenario 2: Trains behind are not affected as the failed train stops before the train behind needs to slow down, as shown in Figure D2.

The model calculates the delay in train operations caused by the two scenarios and selects the model that causes less delay to overall train operation.

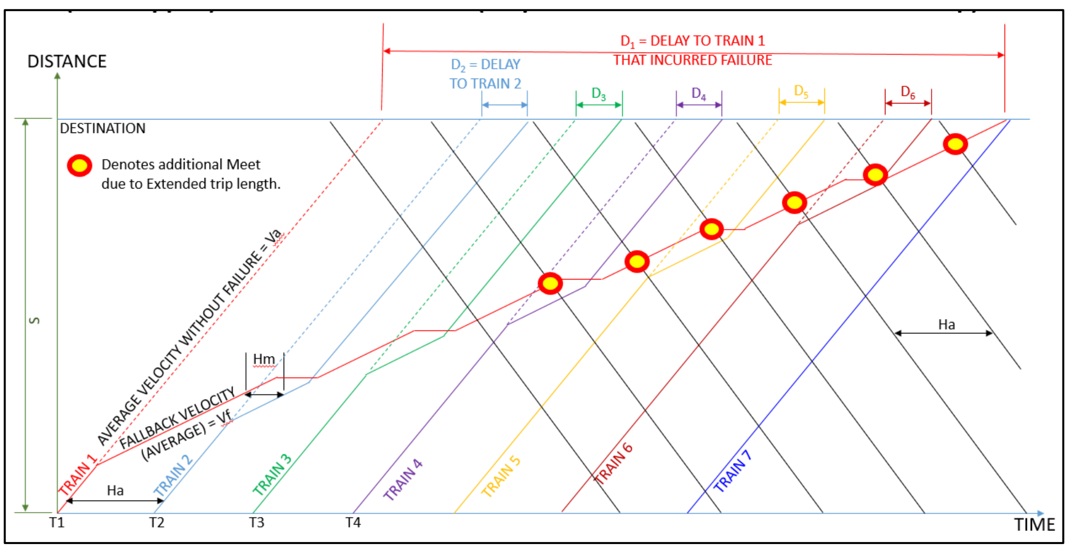

Figure D1. Illustration of Train Delay Impact due to Onboard HW Failure for Scenario 1 Where Passing Trains are Affected

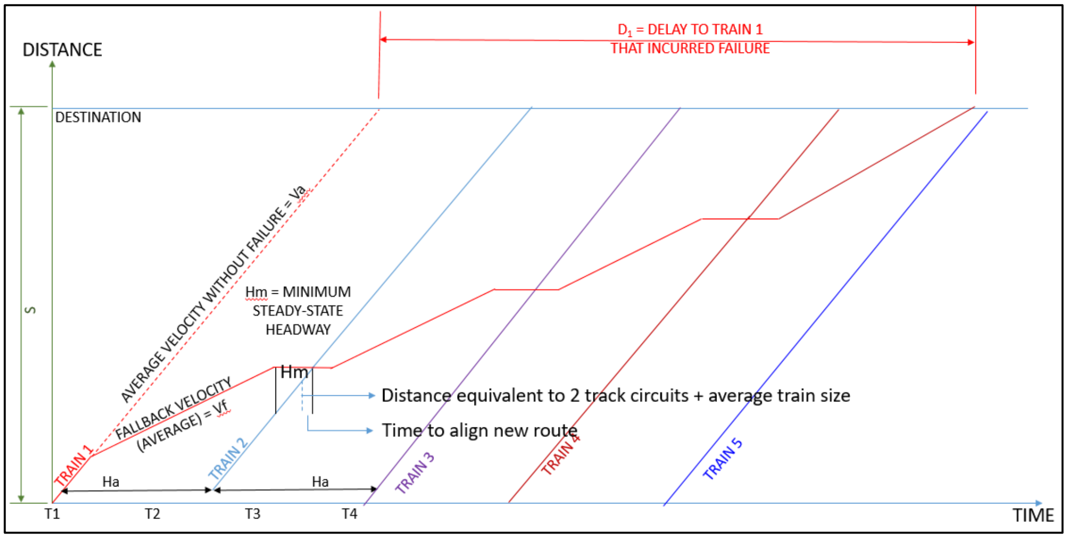

Figure D2. Illustration of Train Delay Impact due to Onboard HW Failure for Scenario 2 Where Passing Trains are not Affected

Train delay calculation

1) <u>Direct Train delay</u>

Direct train delay is calculated by first calculating the delay of the failed train alone ($DD_{failed\text{-}train}$), as illustrated in Figure D3. Note that this calculation does not include the additional delay that can be caused by a passing train in the same direction.

$$DD_{failed\text{-}train} = (\delta t2 - \delta t1) + \delta t3 + (\delta t5 - \delta t4) + (\delta t7 - \delta t6) \qquad (1)$$

Where:

(δt2-δt1) = time lost by failed train to stop, which is the difference between the time spent by the failed train to come to a stop and the time the train would have taken to travel the same distance at MAS

δt3 = time spent for failed train to cutout PTC

(δt5-δt4) = time lost by failed train to accelerate from stop to Reduced Speed (fallback), which is the difference between the time spent by the failed train to accelerate from 0 to Reduced Speed and the time the train would have taken to travel the same distance at MAS

(δt7-δt6) = time lost by train to operate at Reduced speed until destination, which is the difference between the time spent by the failed train to travel to destination at Reduced Speed (fallback) and the time the train would have taken to travel the same distance at MAS

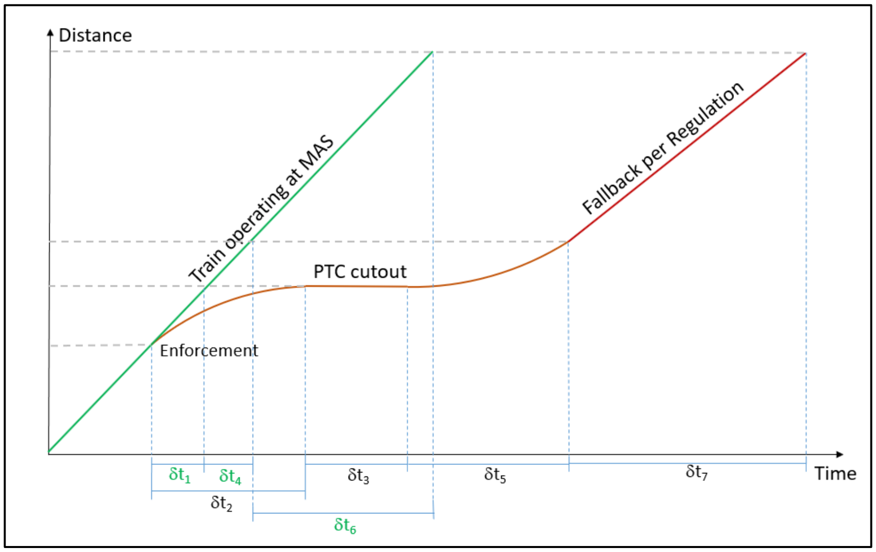

Figure D3. Illustration of Delay Caused to Failed Train Without Including the Effect Caused to Trains Behind

2) <u>Indirect Train Delay to a Train Behind the Failed Train</u>

The second step is to add the indirect delay caused to trains behind the failed train. This delay will differ depending on the passing scenario (Scenario 1 or Scenario 2).

For Passing Scenario 1, the total delay is the sum of the delay caused to the failed train to stop for the passing train and the delay caused to passing trains due to the reduction in the fallback speed, as illustrated in Figure D4.

Delay caused to a train behind passing the failed train in Scenario 1

It is assumed that the passing train will travel half of the average distance between sidings at an average fallback speed. It is also assumed that the route for the passing train will be automatically requested by the Dispatching System (memorized route) as soon as the failed train clears the switch, i.e., the only additional delay would be the time for the switch to return to normal position and be locked. However, as the failed train will release the switch much earlier than the time when the passing train reaches the approaching block of the switch, it is assumed that the switch will be locked already, i.e., there is no additional delay caused by the alignment of the switch nor the route request. Once the head of the train reaches the switch, the train will accelerate again to MAS.

$$(D_{\text{Pass-Follow}}) = (\delta t2 - \delta t1) + (\delta t4 - \delta t3) + (\delta t6 - \delta t5) \qquad (2)$$

Where:

$(\delta t2-\delta t1)$ = time lost for a passing train to decelerate from MAS to Reduced Speed, which is the difference between the time spent by the following train to reduce from MAS to Reduced Speed and the time the train would have taken to travel the same distance at MAS

$(\delta t4-\delta t3)$ = time lost by the following train to operate at Reduced speed for half the distance between sidings, which is the difference between the time spent by the following train to travel this distance at Reduced Speed and the time the train would have taken to travel the same distance at MAS (δt6-δt5) = time lost by the failed train to resume the MAS, which is the difference between the time spent by the failed train to accelerate from Reduced Speed to MAS and the time the train would have taken to travel the same distance at MAS.

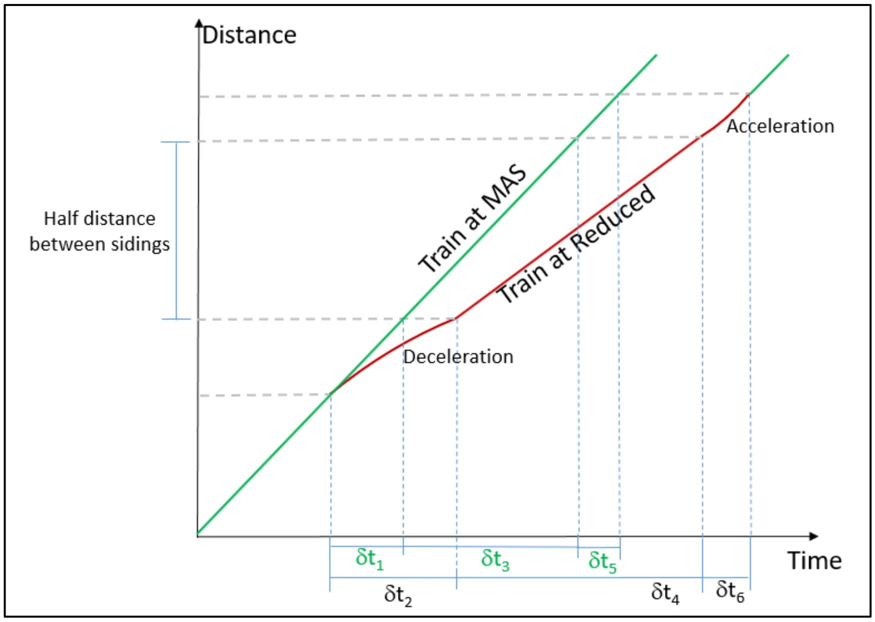

Figure D4. Illustration of Delay Caused to Passing Train due to Reduced-Speed Operation Behind Failed Train

Delay caused to the failed train in Scenario 1

The delay caused the failed train to stop for the passing train and includes the time that it takes for the passing train to arrive at the siding, cross it, and clear the next track circuit beyond the siding. In addition, the delay also includes the time lost for the failed train to accelerate from stop to Reduced Speed.

Per the assumptions for this scenario, included in Equation #2, the passing train will travel the distance that separates both trains (half distance between sidings) at Reduced Speed, while the failed train stops at the siding.

The calculation includes the following delay components, as illustrated in Figure D5:

- The time lost by the failed train to stop at a siding until the passing train reaches the siding, which is expressed as the time that it takes for the passing train to travel the minimum headway (Hm) at Reduced speed (δt1) minus the time that it would take for the failed train to travel the distance that it would take for the failed train to reduce speed and stop at the siding (δt2)
- The time that it takes for the train to travel the length of the siding (δt3), assuming the passing train will accelerate to MAS
- The time that it takes for the passing train to travel and clear the next track circuit after the siding (δt4), that will allow the CP signal to turn to flashing yellow
- The time that it will take for the switch to align to reverse and be locked (δt5)
- The time lost by the failed train to accelerate from stop to Reduced Speed (δt6)

Combining all the delay components:

$$D_{Pass\text{-}Failed1} = (\delta t1 - \delta t2) + \delta t3 + \delta t4 + \delta t5 + \delta t6 \qquad (3)$$

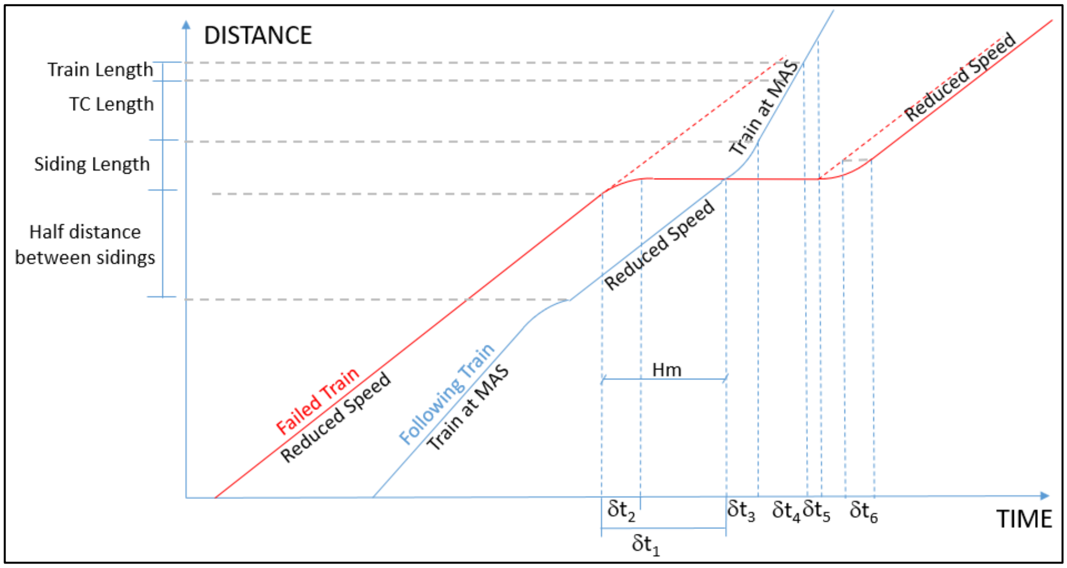

Figure D5. Delay Caused to Failed Train in Scenario 2

Delay caused to failed train in Scenario 2

For Passing Scenario 2, only the failed train is affected, as passing trains will not have to reduce their speed. The assumption is that passing trains do not have to reduce their speed if they are separated by at least two track circuits plus the average train length from the failed train plus the time that it takes for a switch to return to the normal position after the failed train clears it. This would allow the passing train to operate on clear signal indications and not have to reduce speed. Figure D6 illustrates the details of the operation.

The calculation includes the following delay components, as illustrated in Figure D6:

- The time that it takes for the passing train to travel the train separation distance (time it takes to travel two track circuit lengths and the average train length (δt1)
- The time that it takes for the switch to reverse to normal (δt3) minus the time that it would take for the failed train to travel the distance that it would take for the failed train to reduce speed and stop at the siding (δt2)
- The time that it takes for the passing train to travel the length of the siding at MAS (dt4)
- The time that it takes for the passing train to travel the length of the next track circuit at MAS (dt5)
- The time that it takes for the passing train to travel and clear the next track circuit after the siding (δt5), which will allow the CP signal to turn to flashing yellow
- The time that it will take for the switch to align to reverse and be locked (δt6)
- The time lost by the failed train to accelerate from stop to Reduced Speed (δt7)

Combining all the delay components:

$$D_{Pass\text{-}Failed2} = (\delta t1 - \delta t2) + \delta t3 + \delta t4 + \delta t5 + \delta t6 + \delta t7 \qquad (4)$$

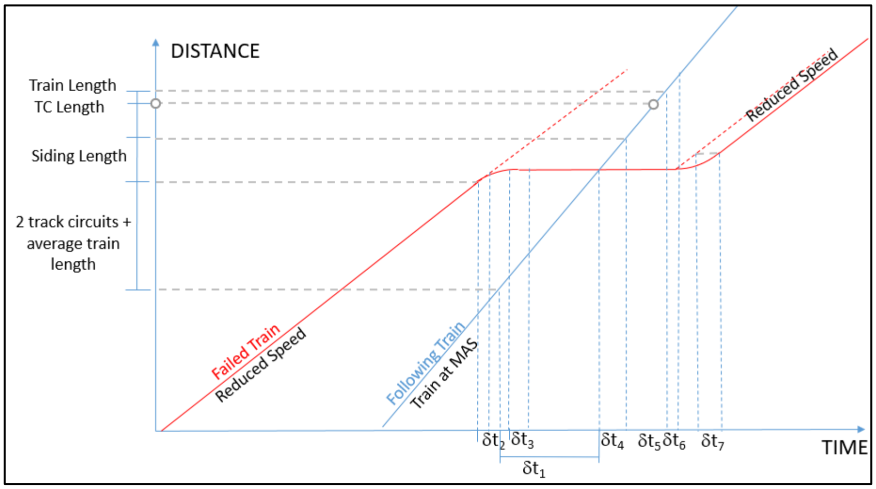

Figure D6. Illustration of Caused to Failed Train for Scenario 2, where Passing Trains are not Affected

The total delay of the failed train is calculated by the direct delay of the failed train ($DD_{failed\text{-}train}$) added to the additional delay caused by stops to allow following trains to pass, which is calculated per the following:

$$TD_{failed\text{-}train} = DD_{failed\text{-}train} (1) / (1 - D_{Pass\text{-}Failed} / Ha) \qquad (5)$$

Where:

$D_{Pass\text{-}Failed}$ will come from Equation #2 or #3, whichever is smaller

Combining the total direct and indirect delay for the trains in the same direction as the failed train, from Equation #1, #4, and #5:

$$TD_{same\text{-}direction} = TD_{failed\text{-}train} * (1 + D_{Pass\text{-}Follow} / Ha) \qquad (6)$$

Note that for Scenario 2, as $TD_{same\text{-}direction}$ is null, i.e., $TD_{same\text{-}direction} = TD_{failed\text{-}train}$.

3) Opposite Trains Indirect Train Delay

For indirect delays caused to trains traveling in the opposite direction, it is assumed that trains traveling in the opposite direction will stop and not cause additional delays to the failed train nor to passing trains that may have been delayed (as in Scenario 1).

It is assumed that a meet-pass conflict will cause the train traveling in the opposite direction to stop and wait for the other train to travel half the distance between the sidings on average.

The calculation includes the following delay components, as illustrated in Figure D7:

- The time that it takes for the train traveling in the opposite direction to travel half the distance between sidings (at Reduced Speed, if the meet-pass is with the failed train, and at MAS, if the meet-pass is with a non-failed train) - (δt1)
- The time that it takes for the other train to clear the switch (δt2), which is the time that it takes for the other train to travel its average distance

- The time that it takes for the switch to turn to reverse (δt3)
- The time lost for the train traveling in the opposite direction to accelerate from stop to MAS (δt4)

Combining all the delay components:

$$D_{Meet\text{-}pass} = \delta t1 + \delta t2 + \delta t3 + \delta t4 \qquad (7)$$

The total meet-pass delay depends on how many additional meet-pass encounters will occur due to the delay caused to the failed trains and other trains behind the failed train. For Scenario 1, additional meet-pass may occur for both the failed train and passing trains. For Scenario 2, additional meet-pass may occur for the failed train only, as passing trains are not affected by the failed train.

The number of additional meet-pass due to delay caused by the failed train ($N_{meet\text{-}pass\text{-}failed\text{-}train}$) is calculated by dividing the total delay of the failed train ($TD_{failed\text{-}train}$) by the average train headway in the opposite direction ($Ha_{opposite\text{-}direction}$):

$$N_{meet\text{-}pass\text{-}failed\text{-}train} = TD_{failed\text{-}train}/Ha_{opposite\text{-}direction} \qquad (8)$$

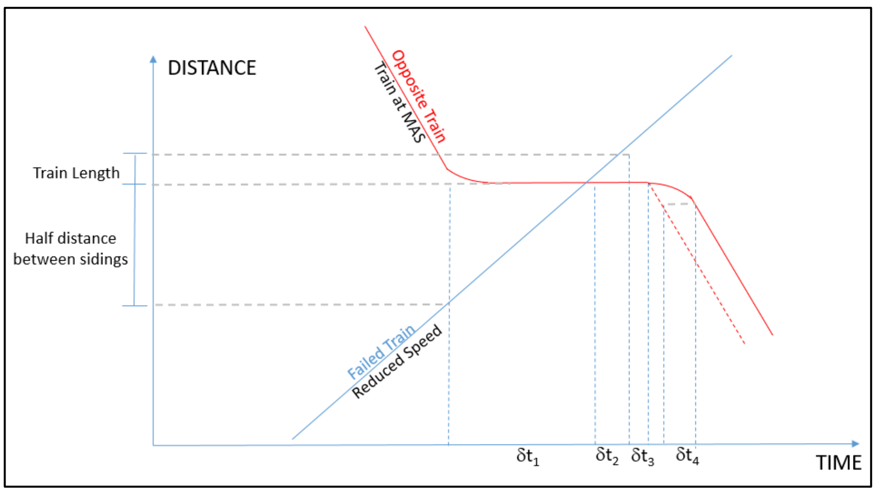

Figure D7. Illustration of Delay Caused to Opposite Train due to Meet-Pass Encounter

For Scenario 1, the additional meet-pass due to delay to passing trains is calculated per the following:

- Calculate how many passing trains are delayed by the failed train, which is the total delay of the failed train ($TD_{failed\text{-}train}$) divided by the average headway in the same direction of the failed train

$$N_{affected\text{-}passing\text{-}trains} = (TD_{failed\text{-}train} / Ha) \qquad (9)$$

- Calculate the total number of additional meet-pass encounters, which is calculated by multiplying the number of affected passing trains (Equation #9) by the number of passing trains ($D_{Pass\text{-}Follow}$) divided by the train headway in the opposite direction ($Ha_{opposite\text{-}direction}$)

$$N_{meet\text{-}pass\text{-}passing\text{-}trains} = N_{affected\text{-}passing\text{-}trains} \times D_{Pass\text{-}Follow} / Ha_{opposite\text{-}direction} \qquad (10)$$

Note that the number of meet-pass is not rounded to account for the fact that, in actual train operations, trains will not be uniformly separated, so the fractional number is a way to account for that.

Combining all the delay components, from Equations #7, #9, and #10:

$$TD_{meet\text{-}pass\text{-}encounters} = (N_{meet\text{-}pass\text{-}failed\text{-}train} + N_{meet\text{-}pass\text{-}passing\text{-}trains}) * D_{Meet\text{-}pass} \quad (11)$$

Note that for Scenario 2, $N_{meet\text{-}pass\text{-}passing\text{-}trains}$ will be null as passing trains are not affected.

The total train delay (TTD_{OHW}) calculation will be:

$$TTD_{OHW} = TD_{same\text{-}direction} + TD_{meet\text{-}pass\text{-}encounters} \quad (12)$$

TTDTM Calculation

TTDTM is determined by the total train delay divided by the total train miles operated by the trains during a certain period of time.

$$\text{TTDTM} = \frac{Total\ Train\ Delay}{Train_{miles}} \quad (13)$$

To calculate the operational impact caused by the onboard hardware failure, the number of defects per train-mile of operation ($ND_{OHW\text{-}train\text{-}mile}$) is calculated, which is the number of hours operated when the train travels one mile at average speed (i.e., 1/Average Speed) divided by the onboard MTBF. This is expressed by the formula:

$$ND_{OHW\text{-}train\text{-}mile} = \frac{\frac{1}{Average\ Speed}}{MTBF} \quad (14)$$

The total train delay per train-mile of operation ($TTD_{OHW\text{-}train\text{-}mile}$) is the total train delay (Equation #12) multiplied by the number of defects in one train-mile (Equation #14).

$$TTD_{OHW\text{-}train\text{-}mile} = TTD_{OHW} * ND_{OHW\text{-}train\text{-}mile} \quad (15)$$

The TTDTM of the Onboard Hardware Failure in the single track scenario ($TTDTM_{OHW\text{-}single\text{-}track}$), is the product of the total train delay per train mile of operation (Equation #15) and the total train miles that are actually operated in that operational scenario ($TTM_{single\text{-}track}$) over a certain period of time.

$$TTDTM_{OHW\text{-}train\text{-}mile} = TTD_{OHW\text{-}train\text{-}mile} * TTM_{single\text{-}track} \quad (16)$$

EXAMPLE 2: WIU HW OUTAGE AT CONTROL POINT

Short description

A failed WIU at a control point stops broadcasting WSMs, which will cause trains passing by that WIU to stop at the control point signal, contact the train dispatcher, and receive authorization to proceed at Restricted Speed through the next control circuit. A train resumes normal operation after the head of train reaches the next signal.

Assumptions

N/A

Consequences to the railroad network operation

When there is a failure to a WIU, trains in both directions will have to stop at the location of the control point, contact the dispatcher to obtain authorization to pass the next signal, and traverse the next signal at Restricted Speed. Trains that reach the control point location when the WIU is still failed will be directly affected, and the delay will cause them to fail as well. Trains that reach the control point after it is restored from failure may also be affected, depending on the headway separation, as the last train that has passed the signal at failure may still not have released the track circuit. Figure D8 illustrates the scenario. In this illustrative example, trains 4 and 5 are indirectly affected, because even though they reached the failed WIU after it was restored, train 3 had not yet released the track circuit.

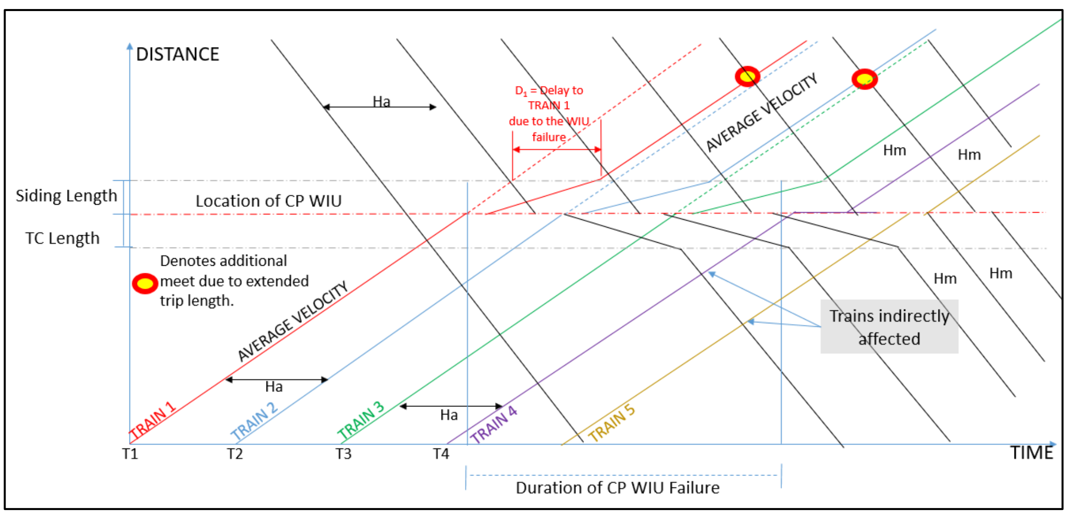

Figure 8. Illustration of Network Impact Caused by the Failure of a Control Point WIU

Train delay calculation

1) Direct Train delay

   The direct delay caused to trains that reach the control point when the WIU is failed ($D_{pass\text{-}failed\text{-}WIU}$) is the same for all trains and includes the time lost to stop the train plus the time that it takes for the train engineer to contact the dispatcher and obtain the authorization needed to pass the signal, plus 1) the time lost to accelerate from stop to Restricted Speed, 2) the time lost to travel the length of the next track circuit, and 3) the time lost to accelerate from Restricted Speed to Normal Speed. Figure D9 illustrates the direct train delay components for this scenario.

$$D_{pass\text{-}failed\text{-}WIU} = (\delta t2-\delta t1) + (\delta t4-\delta t3) + (\delta t6-\delta t5), \quad (17)$$

Where:

(δt2-δt1) = time lost for train to decelerate from MAS to stop, which is the difference between the time it takes the train to reduce from MAS to stop and the time the train would have taken to travel the same distance at MAS

δt4 = time lost to wait for authorization from dispatcher to pass the red signal

(δt6-δt3) = time lost by the train to accelerate from stop to Restricted Speed, which is the difference between the time spent by the train to accelerate from stop to Restricted Speed and the time the train would have taken to travel the same distance at MAS

(δt8-δt5) = time lost by the train to operate at Restricted Speed through the next track circuit, which is the difference between the time spent by the train to travel this distance at Restricted Speed and the time the train would have taken to travel the same distance at MAS

(δt9-δt7) = time lost by the failed train to resume to MAS, which is the difference between the time spent by the train to accelerate from Restricted Speed to MAS and the time the train would have taken to travel the same distance at MAS

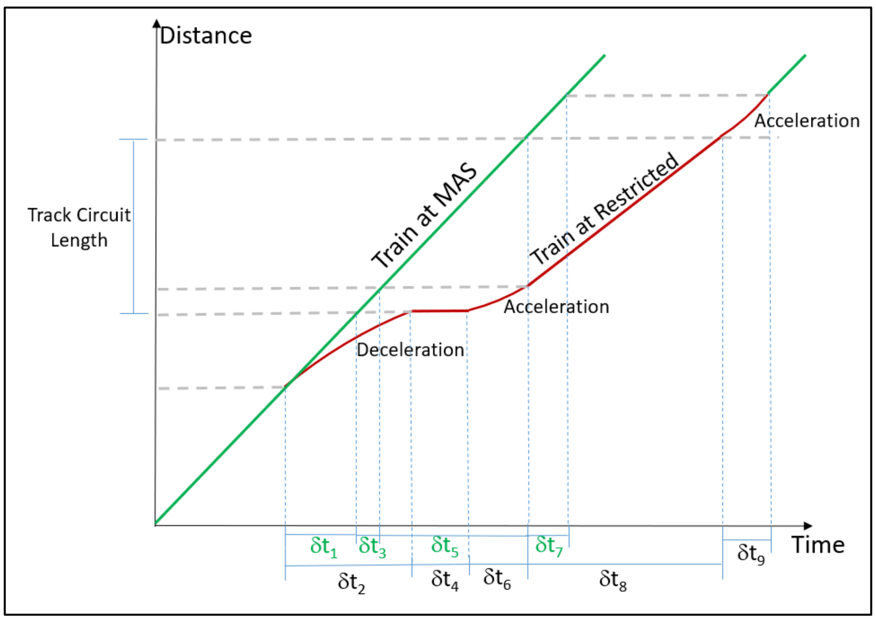

Figure D9. Illustration of Direct Train Delay Caused to a Train Passing a Failed CP WIU

The number of trains affected is the calculated by dividing the time that it takes to restore the WIU (MTTR) divided by the average headway. As the headway in each direction may be different, an average headway is used. As the failure affects trains in both directions, the total is multiplied by 2.

$$N_{trains\text{-}directly\text{-}affected} = INT\ (MTTR_{CP\text{-}WIU} / Avg\ (Ha, Ha_{opposite\text{-}direction})) * 2 \quad (18)$$

The duration of time that it takes to cross the track circuit after the control point varies if the train is entering a siding (length of siding) or if the train is leaving a siding (length of average track circuit between sidings). As the failure affects trains in both directions, an average track circuit length is used to approximate the results.

The total direct train delay ($TTD_{Pass\text{-}failed\text{-}WIU}$) is the product of the train delay caused to one train (Equation #16) and the number of trains directly affected (Equation #18).

$$TTD_{Pass\text{-}failed\text{-}WIU} = D_{pass\text{-}failed\text{-}WIU} * N_{trains\text{-}directly\text{-}affected} \quad (19)$$

2) Indirect Train delay

The indirect train delay calculation is composed of two groups. The first group is the trains that may be affected after the WIU has been restored (if the last train that passed the failed WIU has not released the track circuit yet), and the second group is the additional meet-pass encounters caused by the delays of direct train delays.

The number of trains that would be affected after the WIU is restored is determined by comparing the direct delay caused to a train (Equation #16) to the average headway in both directions (Avg-Ha). If Avg-Ha is greater than $D_{pass\text{-}failed\text{-}WIU}$ plus Hm (minimum headway), no additional trains are affected. Otherwise, it is assumed that the trains behind the last train that passed the failed control point WIU will stop at the control point until the trains become separated again by Hm, which is assumed to be the time that it takes for a train to travel the length of two track circuits plus the average train length at MAS. Figure D10 illustrates that operation.

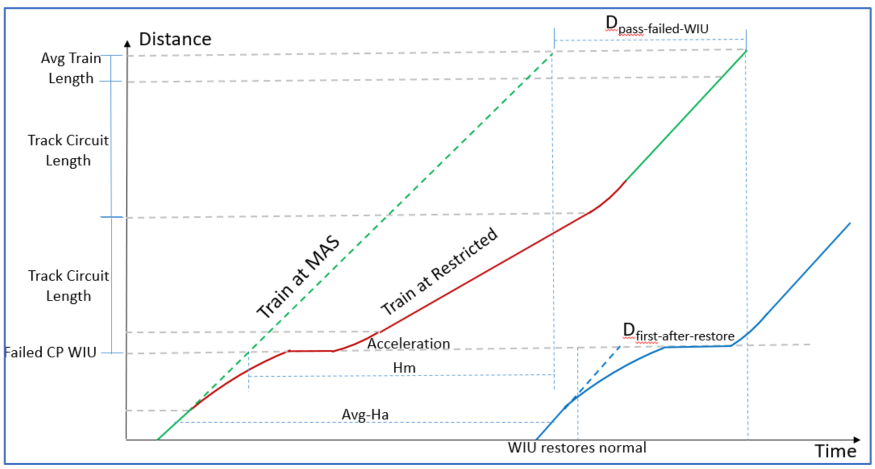

Figure D10. Illustration of Delay Caused to the First Train that Reaches the WIU at Control Point after it is Restored to Normal

$$D_{first\text{-}after\text{-}restore} = (D_{pass\text{-}failed\text{-}WIU} + Hm) - Avg\text{-}Ha, \text{ if } (D_{pass\text{-}failed\text{-}WIU} + Hm) \text{ is greater than } Avg\text{-}Ha, \text{ otherwise is } 0 \quad (20)$$

Other trains behind the first train can also potentially be affected, and the calculation is similar:

$$D_{second\text{-}after\text{-}restore} = (D_{first\text{-}after\text{-}restore} + Hm) - Avg\text{-}Ha, \text{ if } (D_{first\text{-}after\text{-}restore} + Hm) \text{ is greater than } Avg\text{-}Ha, \text{ otherwise is } 0 \quad (21)$$

The total delay of trains affected after the WIU is restored ($TTD_{after\text{-}WIU\text{-}restored}$) is the sum of all delays caused to each subsequent train, multiplied by 2 to account for the impact in both directions.

$$TTD_{after\text{-}WIU\text{-}restored} = Sum\ (D_{after\text{-}restore}) * 2 \quad (22)$$

The second group of indirect train delays is due to the additional meet-pass encounters created by the trains that were delayed by the failed WIU at CP, which is calculated as follows:

- Calculate the number of additional meet-pass encounters due to the number of trains directly delayed ($NMP_{trains\text{-}directly\text{-}affected}$) by dividing the duration of the failure ($MTTR_{CP\text{-}WIU}$) by the average headway (Avg-Ha) and multiplying the result by 2, as the additional meet-pass encounters will happen in both directions.

$$NMP_{trains\text{-}directly\text{-}affected} = 2 * (MTTR_{CP\text{-}WIU} / Avg\text{-}Ha) \quad (23)$$

- The total delay due to additional meet-pass caused by direct train delay (TTDmeet-pass-direct-delay) is the product of the number of trains directly affected (NMPtrains-directly-affected) and the number of additional meet-pass encounters that each directly affected train will have, which is calculated by dividing the direct train delay (Dpass-failed-WIU) by the average headway (Avg-Ha), multiplied by the delay caused by a meet-pass encounter, which is the same as calculated for the Onboard Hardware Failure (DMeet-pass).

$$TTD_{meet\text{-}pass\text{-}direct\text{-}delay} = NMP_{trains\text{-}directly\text{-}affected} * (D_{pass\text{-}failed\text{-}WIU} / Avg\text{-}Ha) * D_{Meet\text{-}pass} \quad (24)$$

- Calculate the total delay due to additional meet-pass caused by trains that are affected after the WIU is restored (TTDmeet-pass-after-restore), which is the sum of the train delay (Dafter-restore) divided by the average headway (Avg-Ha), multiplied by the delay caused by a meet-pass encounter (DMeet-pass) and multiplied by 2, as the additional meet-pass encounters will happen in both directions.

$$TTD_{meet\text{-}pass\text{-}after\text{-}restore} = 2 * Sum\ (D_{after\text{-}restore} / Avg\text{-}Ha) * D_{Meet\text{-}pass} \quad (25)$$

The total delay caused by additional meet-pass encounters ($TTD_{meet\text{-}pass}$) is the sum of the two partial calculations, i.e., Equation #24 and #25:

$$TTD_{meet\text{-}pass} = TTD_{meet\text{-}pass\text{-}direct\text{-}delay} + TTD_{meet\text{-}pass\text{-}after\text{-}restore} \quad (26)$$

The total train delay caused by the failure of a CP WIU ($TTD_{failure\text{-}WIU\text{-}CP}$) is the sum of all partial train delays, i.e., Equations #19, #22, and #26:

$$TTD_{failure\text{-}WIU\text{-}CP} = TTD_{Pass\text{-}failed\text{-}WIU} + TTD_{after\text{-}WIU\text{-}restored} + TTD_{meet\text{-}pass} \quad (27)$$

TTDTM Calculation

The calculation of TTDTM caused by the failure of a field component (such as a WIU) for an operational scenario considers that the field component is operating continuously. The calculation includes the following steps:

1. Determine the total train delay per year for all units ($TTD_{all\text{-}CP\text{-}WIUs\text{-}year}$) in the operational scenario, which is the total delay of a single WIU failure ($TTD_{failure\text{-}WIU\text{-}CP}$) multiplied by the number of CP WIUs in the operational scenario ($N_{CP\text{-}WIUs}$), multiplied by the number of hours in a year (365 * 24) and divided by the MTBF, in hours, of the WIU CP ($MTBF_{CP\text{-}WIU}$)

$$TTD_{all\text{-}CP\text{-}WIUs\text{-}year} = TTD_{failure\text{-}WIU\text{-}CP} * N_{CP\text{-}WIUs} * 365 * 24 / MTBF_{CP\text{-}WIU} \quad (28)$$

2. Calculate the total train delay per one mile of train operation ($TTD_{WIU\text{-}CP\text{-}train\text{-}mile}$), which is the total train delay per year for all units (Equation #28), divided by total train miles operated in a year in the modeled scenario ($TTM_{single\text{-}track\text{-}model}$)

$$TTD_{WIU\text{-}CP\text{-}train\text{-}mile} = TOI_{all\text{-}CP\text{-}WIUs\text{-}year} / TTM_{single\text{-}track\text{-}model} \quad (29)$$

3. Multiply the total train delay per one mile of train operation (Equation #29) by the total train miles that are actually operated in that operational scenario ($TTM_{single\text{-}track\text{-}actual}$) over a certain period of time

$$TTDTM_{CP\text{-}WIU\text{-}single\text{-}track} = TTM_{single\text{-}track\text{-}actual} * TTD_{CP\text{-}WIU\text{-}train\text{-}mile} \quad (30)$$

EXAMPLE 3: BACK OFFICE OUTAGE

Short description

A Back Office Outage is the Back Office failure that causes trains to not communicate with the Back Office during a certain period of time. The lack of communication may cause the onboard system to disengage from the Active state. After the Back Office resumes normal operation, the communication with trains resumes, and trains resume normal operation. The impact is the same for both the hardware and software.

Assumptions

It is assumed that the failure affects the entire operational scenario during the outage time.

Consequences to the railroad network operation

The failure of the Back Office component will cause trains to not receive the Office Segment Poll message, which causes trains to disengage, after the disengagement timeout (configured as 6 minutes default). See Appendix F for details on the impact to train operations due to lack of Office Segment Poll messages.

Figure D11 illustrates the impact in train operations in the format of time x distance diagram. The outage of Back Office service causes delay in train operations and exposes trains to unprotected operation since trains may operate disengaged during the outage.

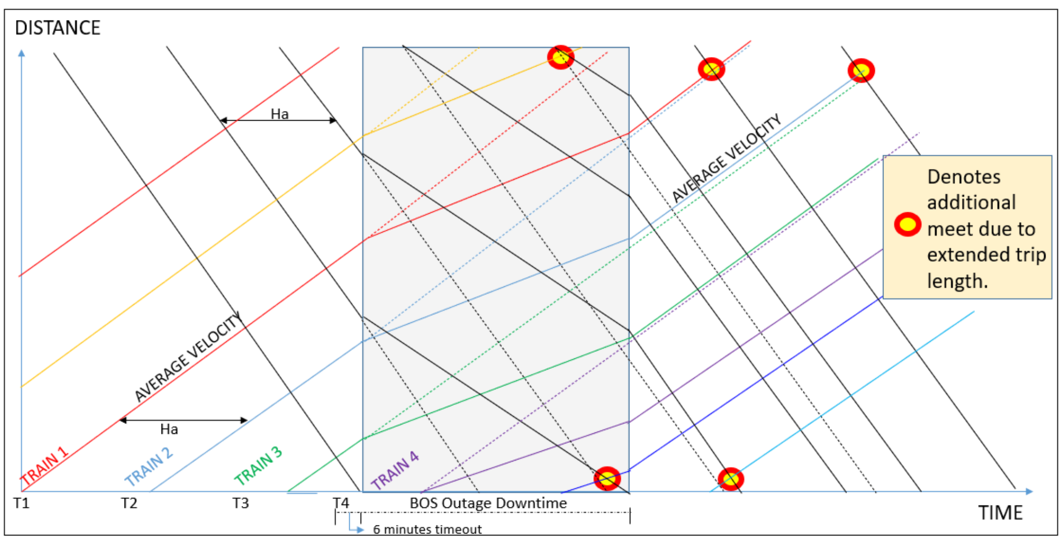

Figure D11. Illustration of Impact in Train Operations due to Back Office Outage

Train delay calculation

1) <u>Direct Train delay</u>

Three groups of train delays were included in the model:

- Group 1: Trains that left origin after the outage started, i.e., were partially affected during the outage
- Group 2: Trains that were fully affected during the outage, as they had departed before the outage started and did not arrive at destination before the outage ended

- Group 3: Trains that arrived at destination before the outage ended and were partially affected like Group 1

Figure D12 illustrates the three groups for one direction (the same groups exist for the other direction).

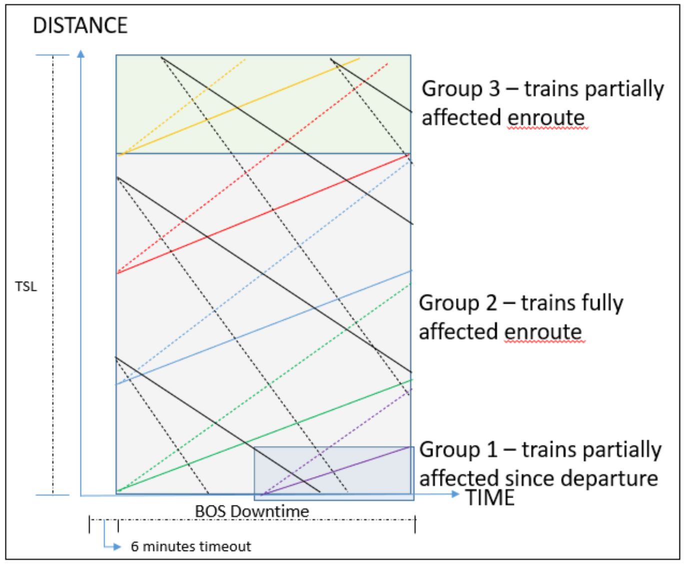

Figure D12. Illustration of Group of Trains Affected During Back Office Outage

The total number of trains affected en route in one direction is based on the total length of the scenario divided by the average separation between trains:

$$N_{trains\text{-}enr} = \text{Roundup}\ (TSL\ /\ (Avg_{Speed} * Ha)) \qquad (31)$$

Where:

TSL = total length of the scenario

AvgNormal = average normal speed of trains

Ha = Average headway separation

The number of trains fully affected en route (Group 2) is calculated by verifying how many trains would travel the entire outage time at Reduced Speed before arriving at destination and is expressed as:

$$N_{trains\text{-}f\text{-}enr} = \sum_{i=0}^{(N_{trains\text{-}enroute} - 1)} \left(\text{Integer}\left(\frac{TSL - i * Avg_{Normal} * Ha}{Avg_{Reduced} * Bos_{Outage}}\right)\right) \qquad (32)$$

Where:

$Avg_{Reduced}$ = average reduced speed of trains

BOS_{Outage} = duration of the Back Office outage, in minutes

The number of trains partially affected en route is the difference between Equations #31 and #32

$$N_{trains\text{-}p\text{-}enr} = N_{trains\text{-}enr} - N_{trains\text{-}f\text{-}enr} \qquad (33)$$

The number of trains that were affected after the Back Office outage started is expressed as:

$$N_{trains\text{-}dpt} = \text{Integer}\,(Bos_{Outage} / Ha) \quad (34)$$

The total fully en route train delay is calculated by comparing the time that it would take for a train to travel the distance during the outage at both Average Normal and Average Reduced Speed and the time lost to decelerate from Normal to Reduced Speed and to accelerate again to Normal Speed after the outage ends, and is expressed as:

$$TD_{full\text{-}enr} = N_{trains\text{-}f\text{-}enr} * (\delta_{Operating\text{-}at\text{-}Reduced} * Bos_{Outage} + \delta_{Acc\text{-}Reduced\text{-}Normal} + \delta_{Dec\text{-}Normal\text{-}Reduced}) \quad (35)$$

Where:

$\delta_{Operating\text{-}at\text{-}Reduced}$ = the delay per minute of operation between Avg_{Normal} and $Avg_{Reduced}$ speeds

$\delta_{Acc\text{-}Reduced\text{-}Normal}$ = the delay in minutes for a train to accelerate from Reduced to Normal Speed

$\delta_{Dec\text{-}Normal\text{-}Reduced}$ = the delay in minutes for a train to decelerate from Normal to Reduced Speed

The delay caused to trains that arrived at destination before the outage ended (Group 3) varies, based on how soon those trains arrived at destination, and the delay is expressed as:

$$TD_{p\text{-}enr} = \sum_{i=0}^{(N_{trains\text{-}p\text{-}enr}-1)} (TSL - (N_{trains\text{-}f\text{-}enr} * Ha + i * Ha) * Avg_{Normal}) * \delta_{Operating\text{-}at\text{-}reduced} + \delta_{Dec\text{-}Normal\text{-}Reduced} * N_{trains\text{-}p\text{-}enr} \quad (36)$$

The delay caused to trains that left the origin after the outage had started also varies, based on how long after the outage these trains departed, and the delay is expressed as:

$$TD_{dpt} = \sum_{i=1}^{N_{trains\text{-}dpt}} (Bos_{Outage} - i * Ha) * \delta_{Operating\text{-}at\text{-}reduced} + \delta_{Acc\text{-}Reduced\text{-}Normal} * N_{trains\text{-}dpt} \quad (37)$$

The total direct train delay is the sum of delays calculated for the 3 groups, multiplied by 2 (to account for both directions), and is expressed as:

$$TDTD_{BOSOutage} = 2 * (TD_{full\text{-}enr} + TD_{p\text{-}enr} + TD_{dpt}) \quad (38)$$

2) <u>Indirect Train delay</u>

The indirect train delay is calculated in the same way as in Example 2.

TTDTM Calculation

The TTDTM RAM KPI is calculated the same way as in Example 2.

Appendix E.
Back-Office-to-Locomotive Link Availability

The PTC system has two prevalent message types sent by the office to the locomotive that can result in train delays and eventually in PTC protection reduction, if the messages are not received by the locomotive onboard in a timely manner:

- Office Segment Poll Messages: Messages sent by the back office to the train to provide information on the current set of mandatory directives and track data
- Wayside Status Relay Service (WSRS) Messages: WSMs sent by the Back Office WSRS server with the latest received status of monitored field devices received from WIUs

If a train does not receive the Office Segment Poll Message, the onboard system does not know if the information on mandatory directives and track data has become outdated. For this reason, after a pre-determined elapsed time since the last Office Segment Poll message was successfully received, the locomotive onboard determines that it can no longer rely on that information. The PTC onboard then prompts the crew with a request to acknowledge that it will disengage from PTC. If the crew does not respond within a certain time, the locomotive onboard will force the train to stop. For this study, it is assumed that the crew acknowledges the request, i.e., the locomotive onboard disengages in this situation. Office Segment Poll messages are sent periodically every 3 minutes, and the locomotive onboard will disengage if three consecutive messages are missed. In a worst-case scenario, if a coverage gap coincides with the location where the next Office Segment Poll is sent and persists for more than 6 minutes, the locomotive onboard will miss three consecutive messages, as illustrated in Figure E1. As a result, the PTC system will not protect the train operation if there is a loss of Back Office-to-Locomotive communications for a duration of between 6 and 9 minutes. The model assumes 6 minutes as the threshold for assuming that the locomotive onboard is disengaged.

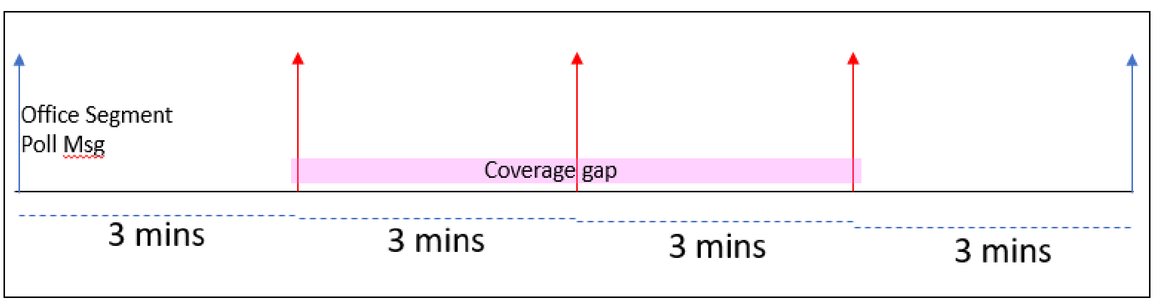

Figure E1. Coverage Gap Threshold for Office Segment Poll Messages

There is an impact on PTC protected time caused by WSRS messages only in territories where trains are dependent on WSRS to receive WSMs. The status of the monitored wayside signaling devices are constantly updated to WSRS servers. In territories where WIUs do not have their own 220 MHz radios or trains cannot reliably receive WSMs directly from WIU radios, the WSRS server relays WSMs to trains; thus, trains operating in these territories depend on the Back Office-to-Locomotive link to receive WSMs. In territories where WIUs have their own 220 MHz radios, the WIUs communicate the WSMs directly to the trains without depending on the Back Office-to-Locomotive link. The PTC onboard system is currently designed to assume the most restrictive state of a wayside device if it does not receive the status of that device for more than four 220 MHz radio superframe cycles, equating to 16 seconds.

Therefore, in territories where WIUs rely on WSRS for communication of WSMs, a loss of Back Office-to-Locomotive communications for a duration of 16 seconds when approaching a control point or dark territory switch will result in PTC unprotected time.

Locomotives can communicate with the Back Office through multiple communication paths, including Wi-Fi, cellular, and 220 MHz radios. Railroads have equipped or are equipping their locomotives with these three communication paths. The Wi-Fi infrastructure is typically available only at terminals/yards. For this reason, the analysis of the availability of the Back Office-to-Locomotive link in this study included only the cellular and 220 MHz radio communication paths.

Thus, the unavailability of the Back Office-to-Locomotive link is determined by the probability that both communication paths are simultaneously unavailable at a given moment.

The research team prepared a method to account for these conditions that is comprised of the following steps:

1. Determine the probability of a base station continuous coverage gap of > 6 minutes
2. Determine the probability of a cell continuous coverage gap of > 6 minutes
3. Determine the probability of cell service being down
4. Determine the probability of both (1) and (2) OR both (1) and (3)
5. Repeat (1) – (4) for coverage gaps of > 16 seconds for WSRS territory

The estimation of base station coverage gap sizes per operational scenario (item 1 from the list above) was prepared with the results of RF simulations along railroad tracks.

For the estimation of cell service (item 3 from the list above), the model used the cell service probability number configured by the user for a given operational scenario.

Base Station Communication Path Availability

An analysis of the impact of base station failures was performed for each operational scenario, as the redundancy of base station coverage is expected to differ for each operational scenario. Three aspects were included in the analysis:

- The impact on PTC protected time when a train cannot communicate with a base station
- The delay caused to train operation when trains operate with the PTC Onboard not in Active state
- How much redundant coverage is typically observed in each operational scenario

Train disengagement from an Active state will occur due to not receiving an Office Segment Poll message if there is a loss of Back Office-to-Locomotive communications for more than 6 minutes. In territories where trains depend on WSRS to obtain the status of WIUs, the onboard will assume the most conservative indication from the wayside signal if there is a loss of Back Office-to-Locomotive communications for more than 16 seconds. The minimum size of coverage gap that would impact PTC protection is dependent on the speed of the train (i.e., the slower a train operates, the longer it will remain in a coverage gap). Table E1 shows the coverage gap sizes that would impact PTC operation for territories that are WSRS-dependent for various train speeds.

Table E1. Coverage Gap Size Impacting PTC Protection due to Not Receiving WSM in WSRS Territory, as a Function of Train Speed

Train Speed (mph)	40	30	24.6	20
16-second Gap Size (feet)	939	704	577	469

Table E2 shows the coverage gap sizes that would impact PTC protection because of not receiving Office Segment Poll messages.

Table E2. Coverage Gap Size Impacting PTC Protection due to Not Receiving Office Segment Poll Messages, as a Function of Train Speed

Train Speed (mph)	40	30	24.6	20
6-minute gap Size (miles)	4.0	3.0	2.5	2.0

The coverage gap resulting from the failure of a base station depends on how much redundancy there is (i.e., how much coverage can be provided by other base stations in the vicinity of the failed base station). Researchers developed a method to determine the typical coverage gaps caused by a single base station failure for each of the operational scenarios. The steps of the method are as follows:

1. Simulate the failure of one base station at a time within a defined area (such as a dense urban area or a single subdivision) using an RF simulation tool (Planet) that will generate a list of points below coverage requirements (coverage gap results) along the track.
2. Export coverage gap results to an Excel file and visualize in Google Earth® to estimate the size of the coverage gap.
3. Process coverage gap sizes and tabulate for the area being analyzed.

Figures E2 and E3 provide a visualization of the coverage gap estimation process. The RF Network design for Dense Urban Areas [3] contain details of the method used to determine coverage gaps.

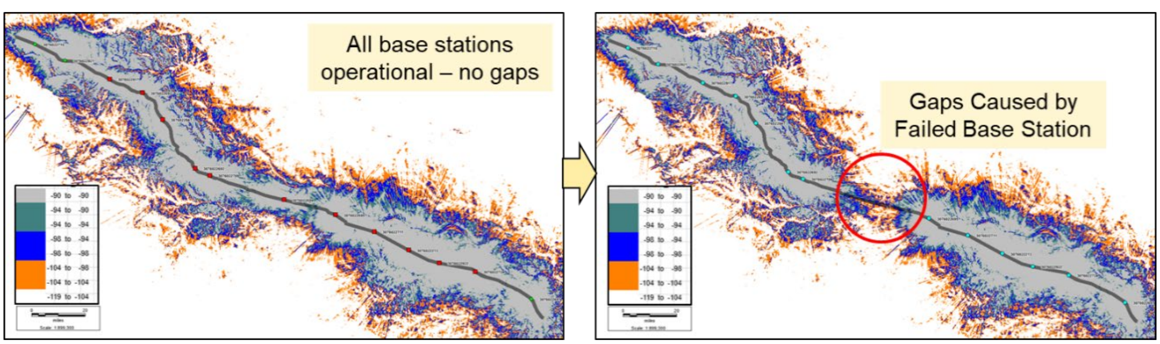

Figure E2. Illustration of Coverage Gaps Resulting from the Failure of a Base Station along the Tracks of a Railroad Subdivision

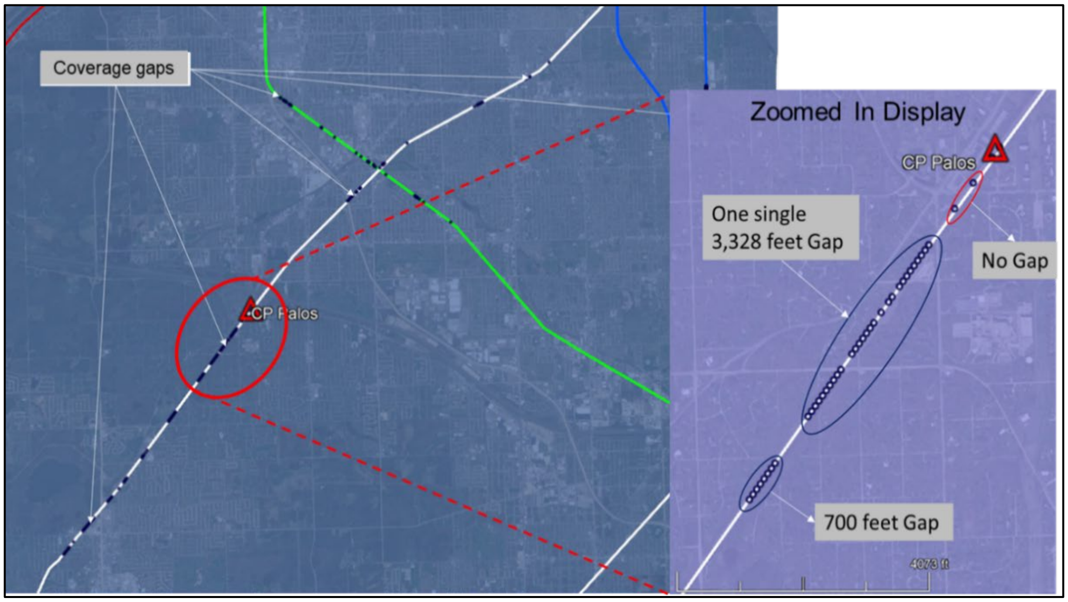

Figure E3. Illustration of Coverage Gap Size Estimation using Google Earth®

The team executed the method above for all operational scenarios using selected reference territories agreed to by the participating railroads (details in Appendix D) to generate the default coverage gap parameters included in RAMIA (see Appendix C). The selected reference territories include subdivisions from multiple railroads for the signaled single, double- and triple-track and dark territory scenarios.

The average unprotected times calculated for each operational scenario were included in the calculation of RAM KPIs for the Back Office-to-Locomotive link in conjunction with the probability that a train will reach a base station that has failed at a given time, and the probability that there is not cell service or coverage along the tracks.

Appendix F.
PTC Operating Zones and Message Loss Modeling

PTC Operation Zones and Transition to Restrictive States

PTC data radio performance requirements are driven by their system-level impact upon railroad operations. The highly reliable transmission of messages between base station, WIU, and locomotive radios is critical to prevent unnecessary operational impacts. These impacts can consist of false enforcement, false warning, or false display downgrade. These can be defined as follows:

- **False enforcement** occurs when a brake application is invoked by the PTC System, even when the actual external conditions are such that the train could continue to operate safely without an enforcement brake application.
- **False warning** occurs when the PTC onboard system displays an enforcement warning, even when the actual conditions could permit continued safe operation without it.
- **False display downgrade** refers to when the PTC system displays a restriction even when the actual conditions would permit continued safe movement without the display of the restriction.

Locomotive onboard systems start receiving WSMs from each PTC-monitored wayside device (such as a signal or switch) within a specified distance ahead of the train's current location, typically 5 miles minimum. The distance ahead of the wayside device accounts for the train braking distance and the locomotive onboard display horizon requirements.

Locomotives can be exposed to false enforcement, false warning, or false display downgrade for a WIU-attached device, depending on the proximity to the affected WIU. The area where a locomotive is exposed to false enforcement is named Zone 1, the area where a false warning can occur is Zone 2, and the area where a false display downgrade could be present is named Zone 3. The design of the ITC system allows for the locomotive radio multiple attempts to receive a WSM before it assumes a more restrictive condition, meaning that the train needs to start attempting to receive the WIU signal before the PTC Operating Zones start.

Using average train speeds and an assumed length of the ITC radio superframe size of 4 seconds, the distance ahead of the train to the WIU location for the ITC radio system needs to be extended by 0.19 miles (i.e., the end of Zone 3 becomes 5.19 miles). Additionally, for RF design purposes, an extra zone beyond Zone 3 can be defined, named Zone 4. This zone does not influence operations, but it can be used as an approaching zone where the onboard system can be programmed to start receiving WSMs. Figure F1 shows the location of Zones 1 to 3 with respect to the locomotive and the wayside signal location.

The reliability requirements for the WSMs are different in each operating zone. The coverage probability threshold and packet error rates for each zone are derived from the reliability requirements explained in previous paragraphs.

The details on the design and characteristics of the PTC 220 MHz radio system can be found in the RF Network Design for Dense Urban Areas report [3].

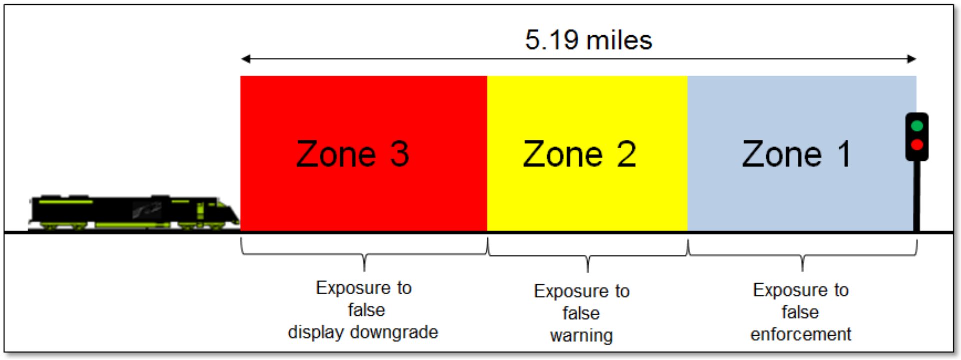

Figure F1. PTC Operating Zones

Message Loss Calculation

The modeling of impact in train operation caused by WSM message loss due to interference, fade, ducting and other external factors considered the following:

- The probability that WSM messages can be lost due to external factors
- The message retry mechanisms included in the design of the 220 MHz radio network (see the RF Network Design for Dense Urban Areas [3] for details)
- The probability that multiple WSM messages are lost when a train is operating in Zone 1

The PTC data radio performance requirements are driven by their system-level impact upon railroad operations (e.g., rate of false PTC enforcements). When a train is operating in Zone 1, WIU_Status report messages need to be received by the train with high reliability to avoid false enforcements.

The probability of false enforcement of a PTC train at any WIU monitored device is the probability that a data refresh timeout occurs while the false enforcement exposure for the WIU-monitored switch or signal exists. This is equal to the probability that four consecutive broadcasts from the WIU to be received by the PTC onboard system are not received while the train is within Zone 1.

The data refresh timeout tolerance interval broadcast is equal to four WIU broadcast intervals. When in Zone 1, a locomotive will issue Get_WIU_Status messages after operating 8 seconds without receiving a WIU_Status message. This is assumed to typically result in three additional transmissions of the WIU_Status message, over the Common Channel, totaling seven WSM messages (i.e., a train would have to miss seven WSM messages consecutively to be enforced).

Considering the average speed that a train operates and the size of Zone 1, it is possible to calculate the number of WSMs that a train will receive while operating in Zone 1. Assuming that a typical message success rate, the WSM broadcast rate, and the Zone 1 length is known, the probability of enforcement due to message loss in Zone 1 ($P_{Zone1\_WSM\_Loss}$) can be expressed as follows:

$$P_{Zone1\_WSM\_Loss} = (Z1_{Length}/Avg_{Speed} * 3600/SFrame_{Size}) * ((1 - Msg_{SuccessRate})^{\wedge}7)), \quad (1)$$

Where: $Z1_{Length}$ = Zone 1 length, in miles

- Avg_{Speed} = Train average speed, in mph
- $SFrame_{Size}$ = superframe size, in seconds (4 seconds for the 220 MHz radio)
- $Msg_{SuccessRate}$ = typical message success rate percentage

Appendix G. Track Utilization Level

Foundation Concepts

Track utilization level (TUL) defines the volume of traffic in a portion of territory compared to that territory's capacity to assess congestion levels.

The capacity of a rail corridor or subdivision is defined as the maximum volume or number of trains per day that the infrastructure can accommodate without compromising the safety or reliability of the flow of trains. The capacity of a rail line is affected by many factors including the number of tracks, the frequency and length of sidings, the capacity of the yards and terminals along a corridor to receive the traffic, the type of control systems, the terrain, the mix of train types, the power of the locomotives, the track speed, and the individual railroad operating practices.

The research team used the National Rail Freight Infrastructure Capacity and Investment (NRFICI) study [4] as a reference to determine railroad capacity and TUL. According to this study, rail capacity can take two forms: the *theoretical capacity* is the maximum number of trains assuming perfect conditions; the *practical capacity* considers factors such as possible disruptions, maintenance, human decisions, weather, possible equipment failures, supply and demand imbalances, and seasonal demand. Practical capacity is about 70 percent of the theoretical capacity and provides reliable service. The theoretical capacity is obtained based on the results of the simulation of the operational scenarios.

However, translating the definition of capacity to practical numbers is a subjective task because the perception of an impact on safety or on the reliability of the train flow may vary depending on the situation or the viewer. For practical purposes within this project, to have an objective threshold from which capacity could be defined, the capacity of a scenario was determined to be the number of trains per day that could run on the scenario to achieve the maximum number of train-miles per day.

The definition of the maximum number of train-miles per day as a threshold is based on the following reasoning: if the number of trains per day is increased in a scenario, then the number of train-miles per day will also increase, as will the delay due to the rise in the number of conflicts that need to be resolved. However, there will be a maximum number of train-miles per day that can be achieved. Beyond that point, the number of train-miles per day will start decreasing as the number of trains per day increases, since the delay effects will have surpassed the effects of the increase in number of trains.

Practical Capacity and TUL Calculation Methodology

The calculation of the practical capacity depends on two main parameters: 1) the characteristics of the territory (e.g., single or multiple track, signaled or non-signaled, number of tracks), and 2) the mix of train types (e.g., freight, passenger) that operate in the corridor.

The NRFICI study explains that the mix of trains is an important factor when determining the capacity of a rail line [4]. A corridor that serves a single type of train will usually accommodate more trains per day than a corridor that serves a mix of train types since trains of the single type can be operated at similar speeds and with more uniform spacing between the trains due to similar braking capabilities.

The NRFICI study also introduces a method to adjust for different mixes of trains. Each operational scenario is assigned a lower and an upper boundary for the maximum number of trains. The lower boundary is defined as the maximum number of trains per day assuming an equal mix of merchandise bulk, intermodal-auto, and passenger trains (one-third each). The upper boundary is defined as the maximum number of trains per day, assuming 100 percent one type and 0 percent of the other two types (i.e., complete homogeneity). To move between the lower and upper boundaries, the standard deviation of the train mix is used to scale the range between them. For a train mix of 33 percent for each of the three types, the standard deviation is zero; therefore, a zero adjustment is added to the lower boundary. A train mix of 100 percent, 0 percent, and 0 percent yields a standard deviation of 0.47. This standard deviation is scaled to produce a factor that, when added to the lower boundary, equals the upper boundary. A standard deviation falling between the minimum of zero and the maximum of 0.47 produces a capacity somewhere between the lower and upper boundaries.

The calculation of the practical capacity was done per the following steps:

1. For each operational scenario, the team developed RTC simulation runs with one type of train (High Priority Merchandise) and calculated the theoretical capacity of the scenario using the steps described below:

    a. The process begins by running a simulation with the initial number of trains configured to depart at evenly spaced intervals throughout the day, although their departing time is affected by a randomization process that may anticipate or delay the departure by up to 30 minutes. Fifty percent of the trains will start from one end of the track, and the rest of the trains will start from the opposite end. Once the simulation ends, the results are compiled and the number of train-miles per day is obtained after processing one of the simulator's output files.

    b. Next, the number of trains per day is increased, and the process is repeated until the maximum value of train-miles per day is determined. The number of trains per day that corresponds to the maximum value of train-miles per day stablishes the theoretical capacity of the scenario.

2. Based on the theoretical capacity, the team calculated the practical capacity (70 percent of theoretical capacity).

3. The practical capacity calculated for a single train type was converted to capacity values of cases with multiple types of trains, using the method described in the NRFICI study [4].

Table G1 shows the practical capacity figures per operational scenario, as calculated in the NRFICI study.

Table G1. Practical Capacity Values per Operational Scenario

Operational Scenario	Practical Capacity (Trains per Day)	
	Mixed Train Types	Single Train Type
Signaled Single-track	30	48
Signaled Double-track	75	100
Signaled Triple-track	133	163
Non-signaled	16	20

The following sections describe the practical capacity calculations for each operational scenario using RTC simulations and how they compare with the values from Appendix C, Table C3.

Practical Capacity of the Signaled Single-Track Operational Scenario

Researchers ran multiple RTC simulations with an increasing number of daily trains to identify when practical capacity was reached. The team used the total train-miles per day as the parameter to define the practical capacity of the scenario. The initial number of daily trains was established at 56. Table G2 shows the results of the simulations. Based on the number of train-miles per day, the theoretical capacity is reached with 68 trains per day as highlighted in green. The practical capacity results in a value of 48 trains per day (70 percent of 68) for a single train, which matches the number shown in Table G1 for the signaled single track operational scenario.

Table G2. Results of RTC Runs for the Signaled Single Track Theoretical Capacity Calculation

Theoretical Signaled Single Track Capacity Runs (RTC)			
Train count per day	**Headway (min)**	**Average Speed (mph)**	**Total Train-miles per day**
56	51	39.904	11,204.00
60	48	38.206	11,897.83
62	47	33.072	11,616.05
64	45	31.756	12,050.39
65	44	27.587	11,553.59
66	43	29.465	12,029.47
67	42	27.084	11,785.71
68	42	26.59	**12,072.65**
70	41	23.342	11,541.78
72	40	18.677	10,555.38

The mix of trains originally configured for the signaled single-track scenario is composed of four passenger trains (24 percent), five expedited trains (29 percent), and eight freight trains (47 percent), resulting in a standard deviation of 0.09998. Based on the standard deviation, the practical capacity for this mix of trains in the signaled single track results in 34 trains per day. Table G3 summarizes the calculations of practical capacity and TUL for this scenario.

Table G3. Practical Capacity Summary for the Signaled Single-Track Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	48	34	26	17	9

Practical Capacity of the Triple-Track Operational Scenario

To determine the practical capacity of the signaled triple-track scenario, the team used the same method used to determine the capacity of the signaled single-track scenario. The initial number of trains, 242, was gradually increased to 262 trains per day. RTC was unable to resolve the case with the higher number of trains due to the increasing number of conflicts that were generated during the simulations. The team made more than 40 attempts of simulation with 264 trains per day, each with different seed numbers for the randomization process, but RTC failed to complete the runs.

Researchers held conference calls with Berkeley Simulations to review the issues found and that the model had reached the maximum number of feasible daily trains that could be dispatched. This number, 262 trains per day, was considered the theoretical capacity for this scenario. Table G4 shows the results of the practical capacity simulation runs performed for this scenario.

Table 4. Results of RTC Runs for the Signaled Triple-Track Theoretical Capacity Calculation

Train count per day	Headway (min)	Average Speed (mph)	Total Train-miles per day
242	13:35	39.54	25,102.33
246	13:20	38.54	25,521.38
250	13:05	38.47	25,780.64
254	12:51	38.39	26,270.94
258	12:37	37.61	26,503.99
262	12:24	37.10	27,057.19

The practical capacity for the triple-track scenario for a single type of train resulted in 183 trains per day (70 percent of 262 trains). This number is slightly higher than what is shown in Table G1 (163 trains per day for signaled triple-track), but the difference between both numbers is acceptable as the results in the NRFICI study [4] represent the average numbers obtained from multiple lines.

The mix of trains originally configured for the signaled triple-track scenario is composed of 75 passenger trains (68 percent), 15 expedited trains (14 percent), and 20 freight trains (18 percent), resulting in a standard deviation of 0.24711. The practical capacity for this mix of trains in the signaled triple-track scenario results in 159 trains per day. Table G5 summarizes the calculations of practical capacity and TUL for this scenario.

Table G5. Practical Capacity Summary for the Signaled Triple-Track Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	**Practical Capacity (100 percent TUL)**	**Practical Capacity (100 percent TUL)**	**75 percent TUL**	**50 percent TUL**	**25 percent TUL**
Number of Trains per Day	183	159	120	80	40

Practical Capacity of the Signaled Double-Track and Non-Signaled Territory Operational Scenarios

The practical capacity results obtained from the RTC simulation runs for the signaled single track and triple-track operational scenarios showed results comparable to the NRFICI study [4] practical capacity values for the same operational scenarios. As the simulation runs are extremely time-consuming, and as the project was facing budget restrictions, the team did not perform RTC simulation runs for the signaled double-track and non-signaled territories, but rather used the practical capacity numbers as calculated in the NRFICI study.

The practical capacity for the signaled double-track scenario with a single type of train is calculated as 100 trains per day in the NRFICI study (Table G6).

The mix of trains for the signaled double-track scenario is composed of four passenger trains (5 percent), 19 expedited trains (22 percent), and 63 freight trains (73 percent), resulting in a standard deviation of 0.29113. The practical capacity for this mix of trains in the signaled double-track scenario results in 81 trains per day. Table G6 summarizes the calculations of practical capacity and TUL for this scenario.

Table G6. Practical Capacity Summary for the Signaled Double-Track Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	100	81	61	41	21

The practical capacity for the non-signaled operational scenario with a single type of train is calculated as 20 trains per day in the NRFICI study [4], as shown in Appendix C, Table C3. The typical train mix for this scenario is 4 passenger trains (18 percent), 11 expedited trains (50 percent), and 7 freight trains (32 percent), resulting in a standard deviation of 0.13033. The practical capacity for this mix of trains in the non-signaled operational scenario results in 17 trains per day. Table G7 summarizes the calculations of practical capacity and TUL for this scenario.

Table G7. Practical Capacity Summary for the Non-signaled Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	20	17	13	9	5

Combined Results for all Operational Scenarios

Table G8 shows the combined results from all operational scenarios (Tables G5, G6, and G7) as well as the proportion of trains/day from all the operational scenarios compared to the single track operational scenario per TUL and the average proportion.

Table G8. Number of Trains per Day per Operational Scenario and Proportion to Single Track

TUL	Total Number of Trains/Day				Proportional to Single-track		
	Single-track	Double-track	Triple-track	Non-Signaled	Double-track	Triple-track	Non-Signaled
100	34	81	159	17	2.38	4.68	0.50
75	26	61	120	13	2.35	4.62	0.50
50	17	41	80	9	2.41	4.71	0.53
25	9	21	40	5	2.33	4.44	0.56
				Average	**2.37**	**4.61**	**0.52**

Train Traffic Volumes per TUL Extrapolation

The research team used the results of RTC simulations to associate train traffic volumes to four TULs, 25, 50, 75, and 100 percent. The traffic volumes are described in terms of average train headways and total train-miles operated in one year. Table G9 shows the results for the signaled single track configuration. Figure G1 shows the same results in a graphical format.

Table G9. Results of TUL per Average Train Headway and Total Train-miles/Year for Signaled Single Track Configuration

Signaled Single Track			
TUL	**Route Miles**	**Train miles per year**	**Average Headway (Hrs)**
25	204	613,050	5.83
50	204	1,226,099	2.92
75	204	1,839,149	1.94
100	204	2,452,198	1.46

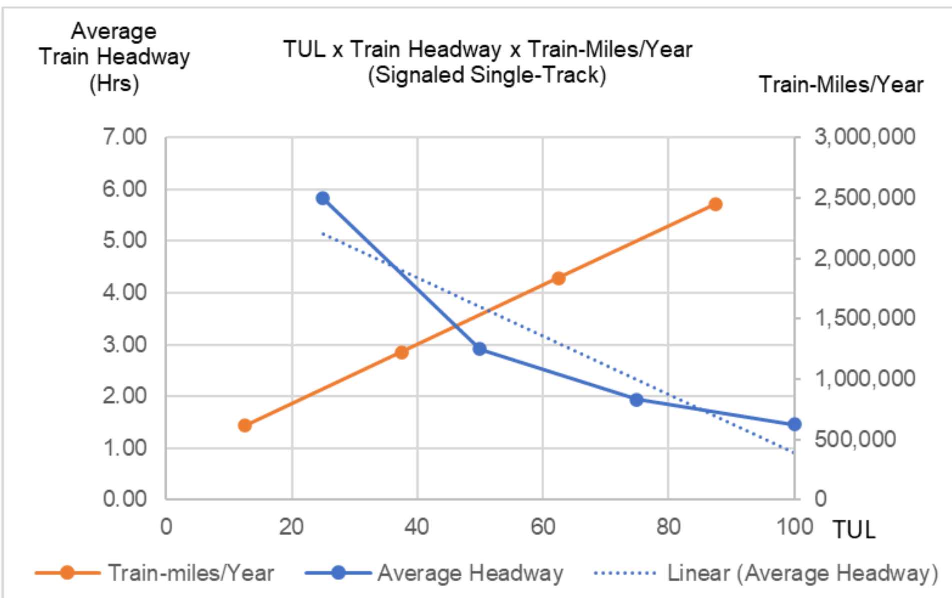

Figure G1. Graphical Representation of TUL per Average Train Headway and Total Train-miles/Year for Signaled Single Track Configuration

The team used the linear trend indicated in Figure G1 to associate average train headways to TUL for signaled single-track configurations.

The same process was developed for the other three track types. Table G10 and Figure G2 show the results for Signaled Double-Track, Table G11 and Figure G3 show the results for Signaled Triple-Track, and Table G12 and Figure G4 show the results for non-signaled tracks.

Table G10. Results of TUL per Average Train Headway and Total Train-miles/Year for Signaled Double-Track Configuration

Signaled Double-Track			
TUL	Route Miles	Train-miles/Year	Average Headway (Hrs)
25	204	1,527,385	2.34
50	204	3,054,769	1.17
75	204	4,582,154	0.78
100	204	6,109,538	0.59

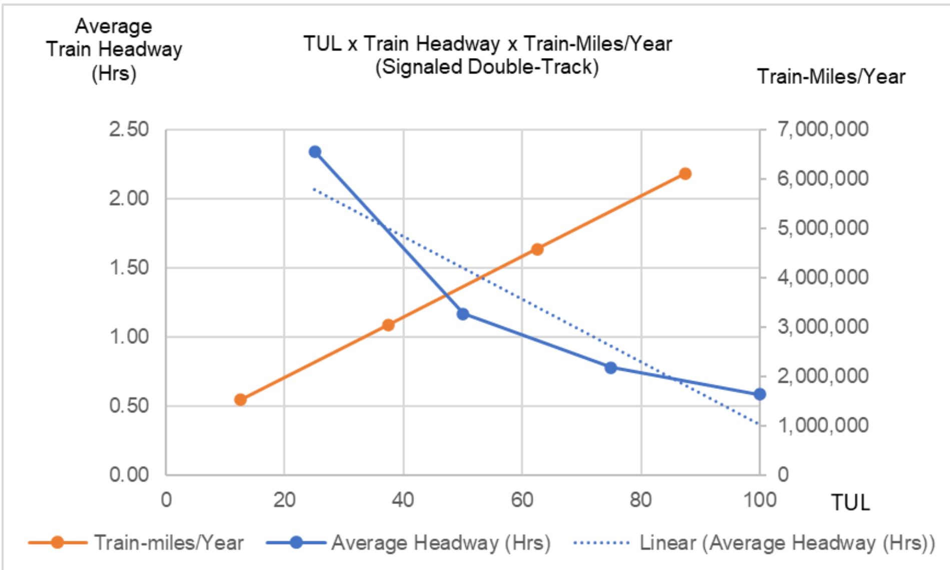

Figure G2. Graphical Representation of TUL per Average Train Headway and Total Train-miles/Year for Signaled Double-Track Configuration

Table G11. Results of TUL per Average Train Headway and Total Train-miles/Year for Signaled Triple-Track Configuration

Signaled Triple-Track			
TUL	Route Miles	Train-miles/Year	Average Headway (Hrs)
25	204	2,929,574	1.22
50	204	5,859,148	0.61
75	204	8,788,722	0.41
100	204	11,718,296	0.30

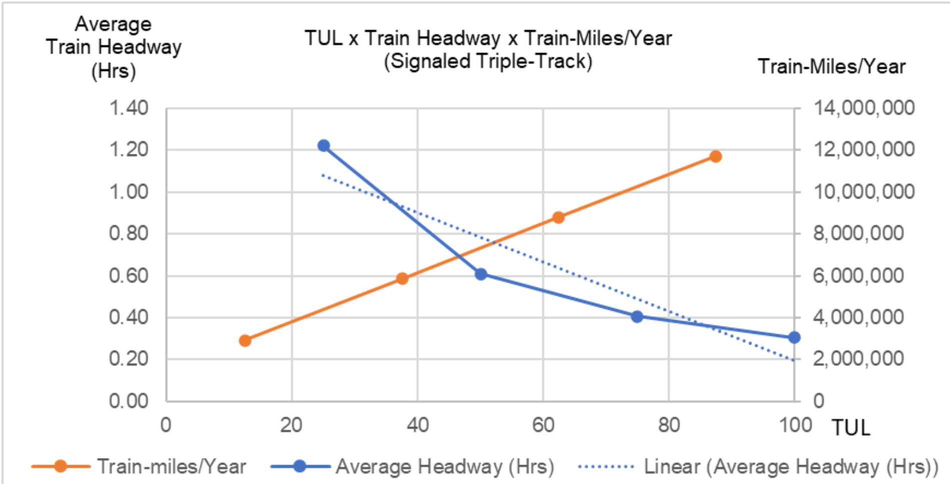

Figure G3. Graphical Representation of TUL per Average Train Headway and Total Train-miles/Year for Signaled Triple-Track Configuration

Table G12. Results of TUL per Average Train Headway and Total Train-miles/Year for Non-Signaled Track Configuration

Non-signaled Track			
TUL	Route Miles	Train-miles/Year	Average Headway (Hrs)
25	204	446,760	8.00
50	204	735,075	4.86
75	204	960,774	3.72
100	204	1,224,000	2.92

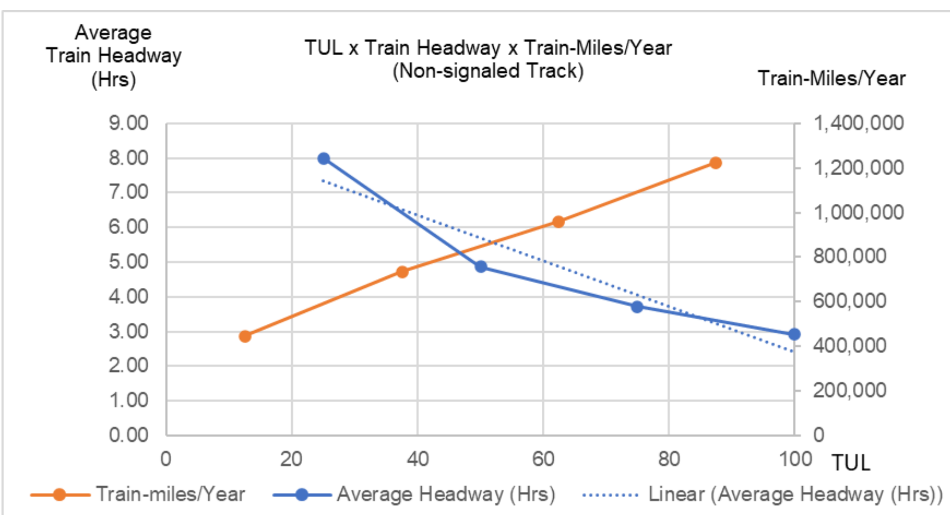

Figure G4. Graphical Representation of TUL per Average Train Headway and Total Train-miles/Year for Non-Signaled Track Configuration

Appendix H. Train Delay Calculation and PTCIE Simulation in RTC

The research team used RTC simulations to estimate the operational impacts caused in a railroad network due to the occurrence of PTCIEs. Researchers configured Operational Scenarios (OS) where those events were triggered during RTC simulation and measured the train delays.

The team used the train travel times from the RTC simulations as the core data to calculate the total train delay in each OS.

For a given OS, RTC simulation runs were executed and the total travel time (arrival time at destination minus departure time at origin) of all trains in the simulation was accumulated, generating the total travel time for the case, as expressed in Equation (1).

$$TravelTime(OS) = \sum_{i=1}^{N_{Trains}} ArrivalTrain(i) - DepartureTrain(i) \qquad (1)$$

Where:

N_{Trains} is the total number of trains in the simulation. The total delay for a given OS was calculated by comparing the total train travel time of that train control method with the baseline (no PTCIE) for the same case configuration parameters, as expressed in Equation (2).

$$TrainDelay(OS) = TravelTime(OS) - TravelTime(Baseline, OS) \qquad (2)$$

The total miles operated by all trains in the simulation was also accumulated, generating the total train miles operated for that case. The average delay per train mile was calculated by dividing the total train delay by the total train miles of that case, as expressed in Equation (3).

$$DelayperMile(OS) = \frac{TrainDelay(TC,Case)}{TotalMiles(Case)} \qquad (3)$$

Researchers ran RTC simulations separately for each type of PTCIE, configuring the occurrence of the event and the time for the recovery from the event, i.e., MTTR. The team ran multiple RTC runs for each PTCIE case, according to the following specifications:

- At five different locations in the operational scenario
- At six different times during the day
- With 20 different simulation seed numbers (that cause each run to have variable train departure times, based on the configuration of train departure variance)

The results of the 600 simulations were compiled and analyzed and average train delay results were calculated for each PTCIE and OS.

Appendix I.
RAM Phase 2 – High Level Program Plan

Abbreviations and Acronyms

ACRONYM	DEFINITION
AG	Advisory Group
BOS	Back Office Server
FRA	Federal Railroad Administration
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
Ha	Headway Average
Hm	Headway Minimum
HW	Hardware
KPI	Key Performance Indicators
LRU	Line Replacement Unit
MAS	Maximum Authorized Speed
MP	Milepost
MTBDE	Mean Time Between Downing Events
MTBDE	Mean Time Between Downing Events
MTBF	Mean Time Between Failure
MTTR	Mean Time To Restore
NRFICI	National Rail Freight Infrastructure Capacity and Investment
O-PTC	Overlay PTC
OS	Operational Scenarios
PTC	Positive Train Control
PTCFA	PTC Functional Availability
PTCIE	PTC Impact Event
RAM	Reliability, Availability, and Maintainability
RAMIA	RAM Impact Analysis
RBD	Reliability Block Diagram
RF	Radio Frequency
RSR	Restricted Speed Restriction
RTC™	Rail Traffic Controller

SW	Software
TTCI	Transportation Technology Center, Inc.
TTDTM	Total Train Delay per 100,000 Train-Miles
TTDTS	Terminal Train Delay per 1,000 Train Starts
TUL	Track Utilization Level
UPSTM	Unnecessary PTC-caused Stops per 1,000,000 Train Miles
VBA	Microsoft Visual Basic for Applications™
WIU	Wayside Interface Unit
WSM	Wayside Status Message
WSM	Wayside Status Message
WSRS	Wayside Status Relay Service