Sound Transit Link Light Rail Operating Systems Resiliency Assessment

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Abbreviations

5S	sort, set, shine, standardize, and sustain
AC	alternating current
AFTC	Audio Frequency Track Circuit
ATO	Asset Transition Office
ATP	automatic train protection
BMS	building management system
CM	corrective maintenance
CP	cross passage
CRAC	Computer Room Air Conditioner
CTA	Chicago Transit Authority
DC	direct current
DCAM	distribution control automation and monitoring
DSTT	Downtown Seattle Transit Tunnel
EAMS	enterprise asset management system
EHU	electronic hydraulic units
EIC	employee in charge
ELSL	East Link Starter Line
EMI	electromagnetic interference
HHR	heat release rate
HVAC	heating, ventilation, and air conditioning
IDS	International District/Chinatown Station
IGA	intergovernmental agreements
IJ	insulated joints
IP	Internet protocol
IT	Information Technology
KCM	King County Metro
King County Metro	King County Metro Transit Department
kVac	kilo-volts alternating current
LACTC	Los Angeles County Transportation Commission
LCC	Link Control Center
LLE	Lynnwood Link Extension
LRV	light rail vehicle
MBTA	Massachusetts Bay Transportation Authority
MDBTD	Mean Distance Between Train Delays
mph	miles per hour
MPLS	multi-protocol label switching
MTA	New York Metropolitan Transportation Authority
MTM	main-tie-main
MVSS	Medium Voltage Switchgear Systems

MW	megawatts
NFPA	National Fire Protection Association
NOC	Network Operations Center
NTD	Notice to Designers
OCS	overhead contact systems
OMF	operations and maintenance facilities
OOS	out of service
PLC	programmable logic controller
PM	preventative maintenance
R2G	rail-to-ground
RACI	Responsible, Accountable, Consulted, and Informed
RAMS	Reliability, Availability, Maintainability, and Safety
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SCADA	supervisory control and data acquisition
SCL	Seattle City Light
SCRTD	Southern California Rapid Transit District
SEPTA	Southeastern Pennsylvania Transportation Authority
SIG	signals
SIT	system integration tests
SLP	Systematic Layout Planning
SME	subject matter experts
SMP	standard maintenance procedures
SODO	South of Downtown
SOP	standard operating procedures
ST	Sound Transit
ST1	Sound Transit 1
ST2	Sound Transit 2
ST3	Sound Transit 3
TCN	Train Control Network
TES	Traction Power
TP	Traction Power
TPSS	traction power substation
UPS	uninterruptible power supply
UW	University of Washington
Vdc	Volts Direct Current
VHLC	Vital Harmon Logic Controller
VPLS	Virtual Private Lan Service
WA	warranty repairs
WO	work order

Article 1. Executive Summary

Sound Transit has commissioned a study to evaluate portions of its Link light rail system. The study's purpose is to evaluate recent incidents that have impacted operations and determine potential root causes of these incidents as well as the underlying engineering assumptions for the design of the system. Regarding recent incidents, a companion review of data cites 177 reported incidents in 2024 (January through late November), totaling approximately 432 hours of service disruption. Traction power was the most common cause, representing 55% of total disruption hours (239 hours), followed by signal equipment at 22% (94 hours). These disruptions frequently required single-track or bus bridge operations, which significantly impacted passengers.

As the agency continues its expansion program, it is concurrently transitioning into a mature operating agency and is experiencing rising maintenance costs, mounting operational complexity, and increasing pressure from the public to maintain high service quality. These emerging circumstances demand methods for absorbing lessons learned, refining maintenance protocols, introducing asset management strategies, and streamlining internal procedures so Sound Transit can advance into a more reliable and sustainable period of operation.

There are many areas of efficient and solid performance by the agency and its employees, partners, and contractors, and this report may not reflect solutions that Sound Transit has put or is currently putting in place; however, this report purposely highlights potential areas of improvement. For example, companion data provided by Sound Transit show that over half of the 2024 disruption hours stem from root causes beyond simple equipment failure, many of them related to new extension integration, utility power loss, or personnel who are insufficiently trained on new traction power equipment. This data aligns closely with the broader themes discussed in this report, such as the need for robust commissioning, improved training, and proactive asset management. This report highlights key findings and recommendations for Sound Transit's governance, operations, maintenance, technical infrastructure, systems, and asset management. Taken together, the study's findings underscore the need for enhanced operational flexibility, updated infrastructure, advanced control systems, and stronger governance and organizational learning to build system reliability, resilience, and long-term sustainability.

1.1 Findings and Recommendations

Key findings and recommendations broadly fall into the following major themes:

Operating Partnership and Organizational Changes

Current intergovernmental agreements (IGA) with King County Metro limit Sound Transit's ability to enforce performance standards and streamline operations. To address these limitations, a transition toward enforceable, performance-based agreements is recommended. This recommendation includes assigning clear responsibilities by using Responsible, Accountable, Consulted, and Informed (RACI) matrices, establishing robust escalation processes for non-compliance, and strengthening accountability through external audits. Simplifying governance and potentially introducing a dedicated project turnover team would ensure that maintenance, documentation, and training obligations are consistently met. Longer-duration, role-based training programs and better-defined roles will help embed continuous improvement, capture lessons learned, and reduce siloed decision-making.

Standards and Procedures

Inconsistent or outdated operating procedures often prolong disruptions. A renewed focus on defining and implementing standards, including standardized interface cabinets for traction power substations and a streamlined alarm management policy, would help operators address critical alerts more effectively and will help embed continuous improvement by capturing lessons learned and reducing siloed decision making. Adopting Reliability, Availability, Maintainability, and Safety (RAMS) to develop design assumptions that match operating needs would ensure the highest levels of safety, reliability, and efficiency throughout the system's entire lifecycle. Additionally, simplifying processes to obtain track access, improving traction power system tests, and revisiting design requirements to achieve more frequent headways would strengthen overall readiness. Longer, more rigorous training programs covering maintenance, dispatch, and operations are vital to ensuring that Sound Transit and King County Metro staff can quickly adapt to new technologies, procedures, and system expansions. Recurring assessments and multi-week courses would elevate overall competency and support Sound Transit's goal of delivering safe, reliable service for a growing ridership.

Projects in Construction

Projects entering the commissioning stage, such as new segment expansions, need a consistent approach for producing as-built documentation and training materials that reflect final field conditions. Integrating robust testing protocols, including testing under degraded conditions, reduces transfer-trip issues and provides opportunities for training during handoffs to maintenance staff. Moreover, higher standards for contractor-led training, with multi-day certifications, would ensure that new infrastructure is delivered with minimal knowledge gaps.

Asset Management

Data fragmentation has hampered proactive maintenance. By expanding the use of enterprise asset management systems (EAMS) and linking digital documentation, spare parts lists, operating manuals, and as-built drawings to each asset, Sound Transit can move from reactive to data-driven, proactive maintenance. Retiring obsolete programmable logic controllers (PLCs), standardizing uninterruptible power supply (UPS) sizes for signal houses, and introducing rolling asset replacement schedules will reduce the risk of sudden equipment failures. Stronger knowledge transfer, continuous audits, and scenario-based training exercises would further reinforce a culture of preventive maintenance.

Long Range Planning

Limited track crossovers and limitations of existing utility feeds create single points of failure. Adding strategically located crossovers, exploring main-tie-main configurations for power in the Downtown Seattle Transit Tunnel (DSTT), and planning for additional redundancy with separate utility buses would improve resiliency against service disruptions. Comprehensive climate hazard assessments should also be undertaken to guide future expansions, ensuring tunnels and elevated segments stand up to evolving environmental changes.

Network

Aging network technologies impede rapid troubleshooting. Migrating from Multi-Protocol Label Switching (MPLS) train control to scalable, internet protocol (IP)-based solutions will facilitate dynamic load balancing and reduce downtime caused by network outages. Establishing a dedicated Network Operations Center (NOC), with remote configuration tools would enable faster event response and would improve flexibility during outages or special events.

1.2 Evaluation of Findings and Prioritization of Recommendations

The study's findings were evaluated against a qualitative rating system that takes into account four categories—Impact to the Public, Safety, Operational Risk, and Complexity. Each finding was rated from 1 (low impact) to 4 (critical impact) in each category. After the findings were evaluated, a set of recommendations were then developed to improve the resiliency of the system. The recommendations were also qualitatively rated to determine the magnitude of the effort to implement and the expected benefit. The Benefit-to-Effort rating scale can be used to prioritize recommendations into:

- Short-term improvements offering significant benefits with minimal effort (quick wins)
- High priority projects requiring considerable but still manageable effort and high benefit
- Major initiatives or transformational projects requiring extensive resources and multi-year timelines, or
- Low priority projects to potentially defer because the expected effort outweighs the benefit.

Article 2. Approach

The team's approach to the study began with a comprehensive review of relevant agency documents that covered design requirements, as-built records, maintenance procedures, operation disruption data, operating protocols, and past assessments. This document review established a baseline understanding of existing standards and practices; it also highlighted initial gaps and opportunities for improvement. After documentation review, the team undertook selected stakeholder interviews and engaged in selected field visits. The interviews, conducted with key personnel from both Sound Transit and King County Metro, validated findings from the documentation, clarified technical and operational questions, and incorporated operational insights that were not fully captured in written materials. The field visits provided a firsthand understanding of the systems in action and critical context for how operators and maintenance crews interacted with the infrastructure.

By focusing on previous incidents during the information-gathering process, the analysis was able to identify vulnerabilities, single-point failure risks, and areas where operational resiliency could be enhanced. From a comprehensive list of findings, a prioritized set of recommendations was developed. Each recommendation was then evaluated against a matrix of "operational benefit" to "effort required to implement it" as described in Section 2.4.

Ultimately, each recommendation was assigned to one of the following broad priorities:

- Short-term improvements offering significant benefits with minimal effort (quick wins)
- High priority projects requiring considerable, but still manageable, effort and high benefit
- Major initiatives or transformational projects requiring extensive resources and multi-year timelines
- Low priority projects to potentially defer because the expected effort outweighs the benefit.

Throughout the process, the team maintained regular communication with Sound Transit leadership, providing updates, presentations, and interim findings.

2.1 Document Review

Sound Transit supplied a vast array of technical documents, including design drawings, standard operating procedures (SOP), and standard maintenance procedures (SMP). The team began by categorizing and analyzing this information to establish a baseline understanding of Sound Transit's existing standards, practices, and infrastructure. However, the most critical insights came from internal documentation detailing specific incidents and the responses and analyses of those incidents. These internal records provided a firsthand look at how Sound Transit managed real-world challenges, revealing the practical application of its policies and procedures. The incident reports and response analyses highlighted issues, areas for process improvement, and patterns of reactive (versus proactive) decision-making. Findings from this internal documentation review allowed the team to tailor subsequent interviews and in-depth analyses. In particular, the following documents provided a wealth of information for understanding the challenges with Sound Transit's system:

- Light Rail Vehicle (LRV) Overhead Contact Systems (OCS) Damage Traction Power (TP) Timeline Memorandum (dated September 17, 2024)

- Matrix of Power Issues Memorandum (dated September 30, 2024)
- 2024 Summary of Sound Transit Systems Memorandum (dated September 18, 2024)
- Supervisory Control and Data Acquisition (SCADA) and Building Management System (BMS) Assessment (dated February 28, 2023)
- Sound Transit Review and Recommendations on Wheel/Rail Interface Management (dated January 26, 2024)

The LRV OCS Damage TP Timeline Memorandum is representative of how documentation reveals the issues that Sound Transit faces. The timeline shows a well-documented approach to managing the OCS damage incident, including consistent communication and updates through the Link Control Center (LCC), power crews, and leadership teams. However, there are notable areas for potential improvement in response coordination, including the following:

- Repeated attempts to troubleshoot and move the damaged train resulted in additional OCS damage.
- The fragmented timeline of updates suggests reactive rather than proactive decision-making, particularly identifying the root cause early and isolating the problem area.
- The decision to repeatedly move the damaged train (T7) without a clear assessment of the pantograph's condition prolonged the outage and exacerbated OCS damage.
- Insufficient inventory of specific replacement parts (e.g., insulators) delayed the repair process.
- The root cause analysis in the specific report points to a pantograph failure in the University of Washington (UW) interlocking that led to extensive OCS damage. However, the exact failure mode (e.g., pantograph misalignment, fatigue, or manufacturing defect) remains under-explored as of the date of the LRV OCS Damage TP Timeline Memorandum.
- Passenger management during the disruption appears reactive, particularly with concerns raised about confusion caused by moving empty trains through stations.
- There was no mention of any recent inspection records of either the pantograph or the OCS.
- Subsequent to the report, a discussion with Sound Transit staff revealed their belief that the OCS was under-tensioned, causing the pantograph to hang up on the contact wire; however, at the time of this report, King County Metro has yet to support that conclusion.

The document review of the LRV OCS Damage TP Timeline Memorandum was invaluable in understanding existing response patterns, standards, and practices as well as uncovering distinct opportunities for improvements. Other documents provided similar insights and helped guide the second phase of the assessment, interviews.

2.2 Interviews

2.2.1 Preliminary Online Surveys

Prior to conducting in-person interviews, a targeted anonymous online survey was developed to gather additional information. The survey gathered responses from key Sound Transit and King

County Metro stakeholders who represented diverse areas, including traction power systems, train control, communications, SCADA, and operations. Sound Transit provided the team with a list of stakeholders, and respondents were given one week to respond, with a 75% response rate.

The survey was a mixed-methods questionnaire blending both quantitative and qualitative question formats, with certain questions inviting respondents to elaborate on their responses. It aimed to collect information about operational continuity with a focus on identifying primary risks to reliability (e.g., power outages, vehicle failures, and communications breakdowns), preparedness for unexpected system failures, types of disruptions, barriers to maintaining assets in a state of good repair, and suggestions for improvements.

2.2.2 Themes Identified from the Online Survey

Interview responses provided insights into the risks, challenges, and priorities for improving the resiliency of the Link light rail system. The results indicate concerns related to aging infrastructure, maintenance backlogs, and gaps in operational procedures, as well as suggestions around opportunities for system-wide improvements.

One of the most pressing concerns identified was the vulnerability of aging infrastructure that is approaching the end of its lifecycle—including traction power systems, track components, and outdated signal processors (e.g., Vital Harmon Logic Controller [VHLC] units).Respondents identified that deferred maintenance on these assets, coupled with limited availability of replacement parts, has placed key systems at a high risk of reliability failure. Many respondents also noted significant physical infrastructure limitations, such as the lack of crossovers and pocket tracks, which reduces operational flexibility and adaptive capacity and limits the ability to single track effectively during disruptions or maintenance activities.

Power outages, TPSS reliability issues, and communication system failures were consistently identified as major threats to operational continuity. Several respondents indicated that these threats are compounded by the complexity of integrating new systems and technologies with legacy infrastructure, which can introduce service and maintenance delays as well as compatibility issues. Maintenance challenges were also a recurring theme, with respondents citing backlogs, unplanned breakdowns, and insufficient time during non-revenue hours to conduct necessary repairs. Additionally, the lack of coordination between departments and limited maintenance resources further hindered timely repairs and proactive upkeep.

Another significant theme was the need for improvement in emergency response protocols and staff training. Respondents noted gaps in emergency planning, particularly during peak travel times or large-scale events, where respondents perceived operational procedures as reactive rather than proactive. Training programs for operations and maintenance staff were described as insufficient, with new personnel struggling to navigate the steep learning curve required to manage unexpected disruptions effectively. The need for enhanced communication and preparedness across all teams was emphasized as a key area for improvement.

Stakeholders also raised concerns about asset management practices, which were viewed as ineffective in tracking assets' lifecycles, repair needs, and replacement timelines. A lack of granular tracking exists for critical assets such as track components and OCS, which impedes the ability to prioritize repairs and schedule replacements. The absence of predictive maintenance tools and systematic reporting further limits the organization's ability to transition from reactive to proactive maintenance.

Finally, several respondents expressed concerns about Sound Transit's ability to scale the system effectively, particularly because of the challenges of integrating old and new infrastructure, the lack of a robust asset management system, and effective handovers to operations and maintenance. Poor-quality handovers for documentation and training from contractors, unqualified oversight during construction, and limited collaboration with subject matter experts (SME) were identified as barriers to achieving a seamless expansion.

2.2.3 In-Person Interviews

The team conducted in-person interviews over two days, with follow-up meetings as necessary, to gather additional information. Interviews were conducted with multiple Sound Transit and King County Metro stakeholders who participated in the planning, engineering, operations, maintenance, and management of the transit system. These individuals included traction power engineers, directors of engineering, track managers, systems engineers, operations and maintenance personnel, and sustainability specialists. The roles of the interviewees ranged from front-line technical experts to senior leadership and discipline managers.

The interviews were semi-structured rather than strictly scripted. Each interview focused on the interviewee's area of expertise, current responsibilities, past involvement in system design or operation, and perspectives on technical challenges. The semi-structured format allowed the interviewers to guide the conversation around key topics (e.g., reliability, asset management, training, and organizational structure), while also giving the interviewee freedom to elaborate on issues they found most critical.

Interviewees were also assured that the information given in the interview would be anonymous in the sense that responses included within the report could not be traced back to a specific person. Statements, comments, and issues that were repeated in several interviews were included in this resiliency assessment. One-off statements that were not repeated were tested and validated to confirm accuracy before being considered for inclusion in the assessment report.

The interviews aimed to gather both technical details (e.g., specific engineering challenges, maintenance practices, and system design assumptions) and historical context (e.g., how certain design decisions were made, how systems evolved over time, and how responsibilities shifted between agencies).

Similar to the survey responses, many interviewees also referenced specific incidents, failures, or disruptions—such as cable faults in tunnels, rail-to-ground (R2G) voltage problems, wire burnouts, gear unit overhaul backlogs, and software integration challenges. These incidents served as anchor points, prompting the interviewees to go into more detail around root causes, response protocols, and lessons learned.

2.2.4 Themes Identified from the Interviews

During interviews, frequently mentioned topics were simulation results versus field observations, subsystem complexity, design requirements, difficulty obtaining access for maintenance, inadequate data and knowledge-sharing, and experiences during commissioning and early operational phases.

One recurring area of discussion was the discrepancy between initial simulation results, design requirements, and what actually occurred in the field. For example, several people discussed how simulations predicted low R2G voltages, yet actual measurements far exceeded those predictions. As of the date of this report, it is not clear why the voltages are spiking, whether from transient conditions that previous load flow studies did not capture, impedance bond failures, operators accelerating or braking across the Electromagnetic Interference (EMI) barrier, or other yet-to-be-determined conditions. This example underscores a persistent modeling and calibration gap that compromises system reliability.

Another recurring theme was that certain subsystems—TPSSs, communication networks, and control systems—were more complex than necessary. Over-design without corresponding simplifications or modularity increased difficulty in troubleshooting, maintaining, and securing the systems.

The need for effective knowledge and data-sharing protocols was another central idea repeated throughout interviews. Knowledge sharing of both power and R2G data from monitoring systems suffers because personnel are not able to efficiently access monitoring data. Several Sound Transit engineers were not able to validate design assumptions or respond proactively to emerging issues because they had limited visibility into real-time data and third-party monitoring results.

Persistent communication challenges among engineering, operations, and maintenance teams, as well as between Sound Transit and King County Metro was also a topic of concern the interview process identified. There were references to unclear roles, no single point of ownership, and an absence of enforceable accountability. Also noted, augmenting staff and providing training for new extensions is not happening in a timely manner. These challenges often result in slow responses to failures and difficulty implementing after-action recommendations.

Finally, interviewees frequently noted that preventive maintenance and asset management practices were insufficient. Specific to these two topics, inadequate lifecycle planning, outdated or missing as-built documentation, difficulty in securing maintenance windows due to service priorities, and reliance on reactive repairs were all mentioned during interviews.

2.3 Site Visits

2.3.1 Site Selection

Over the course of two days (and escorted by King County Metro maintenance staff), the team conducted focused, in-person visits to strategically selected locations within Sound Transit's Link light rail network. The choice of these locations which included TPSSs, signal houses, control rooms, and communications facilities was informed by the comprehensive document review and interview responses, during which specific areas had surfaced as potentially problematic because of limited access windows, and aging and obsolete equipment. Sites were also selected based on direct referrals from maintenance managers, operations personnel, and other key stakeholders who pointed to locations that exhibited persistent issues, such as short maintenance windows, long setup times for maintenance, unreliable equipment, and outdated as-built documentation.

The choice of sites was also informed by the desire to cover a representative cross section of the system. A diverse range of facilities included Seattle City Light (SCL) rooms at the UW Station, various TPSS and Medium Voltage Switchgear Systems (MVSS) rooms, substations at the International District/Chinatown Station (IDS) and Tukwila Station, the Northgate TPSS, the LCC, and signal houses at both the Operations and Maintenance Facility (OMF) Central and UW. These facilities presented different vintages of equipment, unique environmental conditions, and a range of geographic contexts. The team also focused on areas with complex operational environments, where power distribution, signaling, communications, security systems, and heating, ventilation, and air conditioning (HVAC) overlap.

2.3.2 Themes Identified from the Site Visits

During the site visits, the team spoke with maintenance and operations staff to gain insights into their daily work, the practical challenges they face, and the limitations imposed by short maintenance windows. Signal maintenance personnel described maintenance windows as too brief, with single-track operations limited to emergencies only. They noted difficulties maintaining switch heaters in cold, wet weather and not being included in the final testing phases before new lines entered revenue service. Maintenance staff also emphasized the complications arising from aging equipment—such as VHLC units needing immediate replacement because they are approaching the end of their useful life—and Distribution Control Automation Monitoring (DCAM) systems that never operated as intended. Additionally, the cable installation in the tunnels is difficult to maintain due to access limitations.

In addition to these conversations, visual inspections of equipment and facilities were conducted to verify reported issues. Inspections revealed evidence of aging infrastructure, poorly arranged gear that limited adequate access for maintenance, and overheated equipment caused by inadequate HVAC systems. At the UW's SCL room, maintenance activity has declined, housekeeping responsibilities are unclear, and gear that had once been routinely checked is no longer receiving attention. At communications rooms and the LCC headend, the site visits uncovered Computer Room Air Conditioning (CRAC) unit failures (leading to elevated temperatures) and overwhelming alarm conditions that have been hindering rapid problem identification.

By visiting multiple TPSS locations (IDS, Tukwila, and Northgate) and various signal rooms and houses (UW and OMF), the team also observed differences in installation quality, maintenance practices, and equipment standardization. While Northgate TPSS demonstrated more modern features—such as remote meter sockets and Wi-Fi-enabled data collection—older facilities (such as the IDS and Tukwila TPSSs) lacked uniformity in cable labeling and equipment layouts. Signal houses lacked remote access capabilities, which significantly complicates after-hours troubleshooting. Inconsistent wiring, difficult to operate environmental controls, and cramped uninterruptible power supply (UPS) setups were also observed.

2.4 Rubric for Prioritization

The team's approach included devising a rubric to help prioritize the recommendations in this assessment report. In consultation with Sound Transit staff, the following rubric was developed so recommendations could be qualitatively evaluated based on their Benefit to Operational Resiliency and the Effort (in terms of time, resources, and complexity) required to implement them. This framework ensures that all proposed recommendations are compared consistently, and it provides a tool for Sound Transit to focus first on those actions that most effectively improve system reliability and overall performance relative to the effort involved.

Under this methodology, each recommendation is qualitatively assigned a 1 to 5 rating for Benefit, (1 signifies the lowest benefit), and a 1 to 5 rating for Effort (1 is minimal effort and 5 is extremely resource-intensive). Refer to Table 1 for rating details.

Table 1. Benefit and Effort Rating Scale

Rating	Benefit to Operational Resiliency	Effort
1 (Low)	Minimal benefit; addresses minor or very specific, localized issues	Minimal resources needed; straightforward to implement; no major coordination or cost hurdles
2	Some benefit; addresses moderate operational gaps or modest vulnerabilities	Some resources needed; moderate complexity but manageable changes without high disruptions
3	Meaningful benefit; addresses a moderately severe vulnerability	Significant resources needed and cross-department coordination; moderate disruptions to operations
4	High benefit; addresses a major vulnerability or critical resiliency	Major investment and organizational effort; significant operational changes and service interruptions possible
5 (High)	Transformational benefit; addresses one of the most severe vulnerabilities	Extremely resource-intensive, requiring multi-year timeline, large scale redesign, or major capital expenditures

Plotting these two factors (Benefit and Effort) on a matrix yields four general prioritization categories:

- **High Benefit, Low Effort**. Top Priority/Worth Pursuing or “Quick Wins” that can be tackled immediately.
- **High Benefit, High Effort**. “Major Initiatives” that require long-term planning and substantial resources.
- **Low Benefit, Low Effort**. “Low-Priority Tactics” that may be addressed if time and resources permit.
- **Low Benefit, High Effort**. “Potential Defers” that may be postponed unless circumstances change.

Table 2. Benefit and Effort: Prioritization Categories Matrix

	Low Benefit	High Benefit
Low Effort	"Low Priority Tactics"	Top Priority / "Quick Win"
High Effort	"Potential Defer"	"Major Initiative" or "High Priority"

This approach also accommodates rapid gains, such as basic training enhancements or improved documentation, so they are not overlooked in favor of large-scale but lengthy initiatives. Figure 1 illustrates the main priority types that were identified and assigned to each of the report's recommendations, based on the Benefit to Effort matrix.

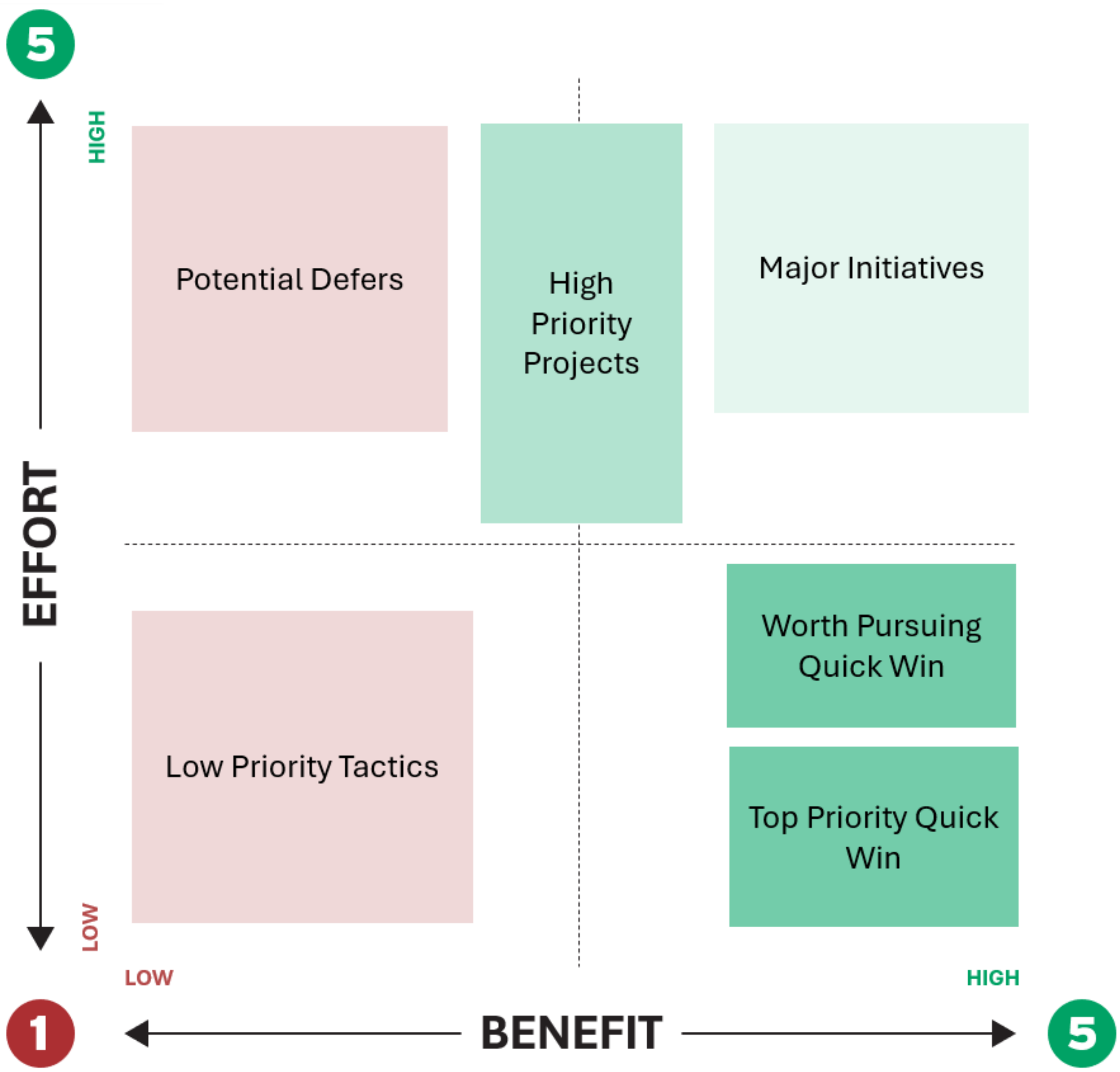


Figure 1. Benefit to Effort: Prioritization Matrix and Priority Types

Article 3. Findings and Recommendations

3.1 Governance and Organizational Strategy

3.1.1 Overview

Sound Transit's governance and organizational strategy reflect a regionally focused model designed to address the complexities of modern transit systems. The agency's Board of Directors, composed of locally elected officials and representatives from various jurisdictions, establishes high-level policies, approves budgets, and guides strategic directions. This board-led structure seeks to incorporate input from a diverse range of regional stakeholders, thereby reflecting a collective mandate that balances growth, environmental stewardship, and public service responsibilities. In practice, the governance framework relies heavily on intergovernmental agreements (IGA) and other collaborative arrangements with public entities.

The most significant partnership is that of Sound Transit and King County Metro, where King County Metro manages the daily operations and maintenance of the Link light rail system. However, the IGA between Sound Transit and King County is structured more as an agreement than a legally binding contract with enforceable provisions. Such a framework can limit Sound Transit's capacity to support compliance with performance benchmarks and to secure timely interventions when problems arise. Without formal accountability mechanisms in place, disagreements on priorities can emerge, maintenance efforts may be delayed, and coordination when recovering from service disruptions can become challenging. This framework is unusual in the United States; most light rail transit agencies do not operate under a similar bifurcated governance structure.

Beyond partnering with King County Metro to provide operations and maintenance, Sound Transit also engages with other partner agencies, municipalities, and external experts —such as personnel at UW for EMI data collection. These collaborations, intended for knowledge sharing and specialized support, sometimes suffer from limited data visibility and communication barriers. For example, Sound Transit staff do not have ready access to the EMI monitoring data, although having this data would allow Sound Transit to review whether the EMI system is needed. As another example, constraining direct access to monitoring or troubleshooting data between Sound Transit and King County Metro can slow decision-making between engineering and operations and lead to a more reactive rather than proactive problem-solving stance. As Sound Transit moves beyond its construction-focused origin to overseeing a full-fledged operating system, the complexity of integrating large-scale expansion projects will likely intensify governance and collaboration challenges.

Overall, the governance model and associated cooperative arrangements were established to unify the region's transit planning, operations, and development. However, the current frameworks fall short in providing clarity of roles and responsibilities and in their capacity to enforce compliance or accountability. Strengthening the mechanisms that enhance interagency coordination and improving data transparency would not only reinforce accountability but also promote service reliability and bolster the organization's long-term resilience.

3.1.2 Findings

3.1.2.(1) Enforcement mechanisms within intergovernmental agreements

No formal enforcement mechanisms exist that hold King County Metro (the primary operations partner) accountable for operational performance standards. This conclusion emerged from reviewing the 2019 IGA between Sound Transit and King County for the Operations and Maintenance of the Link light rail System (King County 2019), as well as King County's First (2020) and Second (2021) Amendments (King County 2020, 2021).

Both parties expressed dissatisfaction during interviews, underscoring that the IGA is, in essence, an agreement rather than a traditional contract. Therefore, Sound Transit cannot strictly enforce performance standards or hold King County Metro fully accountable for operational deficiencies. Also, while performance standards and corrective action plans are specified, no direct financial penalties or other punitive measures exist for non-compliance. Without clearly defined accountability, differences in priorities persist, and King County Metro will not face consequences if they do not allocate resources or respond with the urgency required by evolving operational issues. Furthermore, King County Metro is unable to assume certain responsibilities related to asset management when the assets are owned by Sound Transit. Dispute resolution relies on escalation and mediation rather than on direct enforcement. Termination provisions for the IGA exist but are weakly linked to underperformance. Thus, the structure relies heavily on mutual oversight, audits, and joint meetings, resulting in a less robust accountability environment.

3.1.2.(2) Roles and responsibilities

More clarity is needed in delineating roles and responsibilities for operating and maintaining the Link light rail system. Lack of clarity stems from Sound Transit's evolution from capital project development to an operations and maintenance model that outpaced the organization's ability to transition. Review of the IGAs and associated documents, along with stakeholder interviews, reveals confusion and fragmentation among personnel. Although the IGA states that Sound Transit holds "policy decisions" and strategic planning authority, while King County Metro manages operational details, certain interface areas like SCADA management, IT infrastructure responsibilities, and heavy repairs remain poorly defined (King County 2019). This ambiguity leads to delays, duplicated efforts, and siloed decision-making. Without precise boundaries, roles often overlap or leave gaps in responsibility.

3.1.2.(3) Information sharing and knowledge management systems

Key personnel have limited direct access to critical data and information. Sound Transit's engineering teams cannot readily access critical data and are unable to obtain near real-time data during incidents to proactively analyze events. Such restricted visibility hampers proactive and timely issue resolution, encourages reactive approaches, and restricts the ability to adopt data-driven strategies for maintenance or operational improvements.

3.1.2.(4) Decision-making

Siloed decision-making persists between King County Metro and Sound Transit departments. Engineering, Information Technology (IT), and operational teams at the two agencies often work in isolation, resulting in incomplete integration of perspectives. Decisions by both agencies may not fully incorporate engineering or operations input, while maintenance teams frequently receive unclear directives from both Sound Transit and King County Metro. For example, King County Metro staff cited crossing improvements, sectionalization, and power system designs being executed without sufficient front-end dialogue with operations teams until late in the design process. Operations involvement has been limited in early engineering decision-making, although it appears to be improving.

3.1.2.(5) Lessons learned database

Lessons learned have not been effectively integrated into projects as the light rail system continues to expand. Despite expanding infrastructure and experience gained, no formal processes or accountability frameworks are widely used to capture best practices so they can be systematically carried forward. Lessons-learned practices have varied across the agency. Some projects, programs, and teams have robust processes and accountability in place, while others informally pursue continuous improvement without structured or formal documentation because gaps exist in enforcing accountability and requiring urgency for follow-through to implementation.

3.1.3 **Recommendations**

3.1.3.(1) Strengthen accountability and enforcement.

Introduce financial incentives or penalties linked to performance metrics, and establish clear, tiered escalation steps for unresolved or systematic failures. Strengthen clauses within the IGA framework to empower Sound Transit to deploy specialized teams or contract third parties when critical performance targets or needs are not met. Conduct regular external audits through mandatory third-party reviews that will be jointly funded by Sound Transit and King County Metro. Independent oversight will enhance transparency, identify recurrent issues, and promote continuous improvement. After events occur, revisit SOPs and update if necessary.

3.1.3.(2) Clarify roles, responsibilities, and decision-making.

Develop a responsible, accountable, consulted, and informed (RACI) matrix to clearly delineate responsibilities for all operational areas. Assign specific decision-making authority, so each task is associated with a defined role. Then form cross-functional governance structures that include representatives from Sound Transit and King County Metro. Such structures provide a clear forum for discussing priorities, evaluating trade-offs, and resolving conflict.

Undertake a value stream mapping process for shared systems like SCADA, procurement, and configuration management by creating clear workflows. The value stream mapping process identifies inefficiencies, shortcomings, and overlaps in process, while producing a refined, actionable process to follow. Completing this process will reduce delays and inefficiencies associated with unclear lines of accountability.

While there are no exact parallels for the unique arrangement between Sound Transit and King County Metro, there are examples of how other agencies have approached delineating accountability for different operational areas when sharing resources.

Chicago Transit Authority (CTA) has run continuous improvement initiatives (sometimes referred to as “Lean Projects” or “Process Improvement Projects”) to streamline internal workflows, particularly in the areas of vehicle maintenance procedures and parts procurement. These process improvements have been discussed in the context of Lean strategies to reduce the turnaround time for bus and rail vehicle overhauls, reorganize storerooms and parts distribution, and clarify maintenance staff responsibilities (CTA, 2024).

Another transit agency that has undertaken a similar initiative is the New York Metropolitan Transportation Authority (MTA). After high-profile service disruptions and external reviews, MTA has repeatedly reorganized to delineate responsibilities among agencies (e.g., MTA Capital Construction, Metro-North, Long Island Railroad [LIRR)]). In those reorganizations, internal teams have used RACI-style frameworks to ensure clarity about who owns capital project decisions versus day-to-day operations. Although not always labeled "RACI," MTA transformation updates in board presentations do mention clarifying "who is accountable vs. who is consulted" for certain project scopes (MTA, 2022).

3.1.3.(3) Implement recurring training and communication.

Another way to support accountability is to invest in training and communication programs. Facilitate regular workshops with both Sound Transit and King County Metro staff and with any other stakeholders to understand their roles, responsibilities, and processes, thus minimizing confusion and accelerating response times, particularly during periods of transition or system expansion.

3.1.3.(4) Study alternate governance structures.

Study alternate governance structures that bring single point accountability for the capital expansion program, operations, and maintenance of the entire Sound Transit system, eliminating cross-governance structures and siloed decision-making.

As stated previously, there are no exact examples to illustrate how a unique arrangement such as the one Sound Transit and King County Metro currently have would implement a single point of accountability; however, precedents do exist where transit agencies have merged or absorbed other entities, and these precedents offer valuable insights.

One of the most relevant examples is the Los Angeles County Metropolitan Transportation Authority (commonly known as Metro), which was formed in 1993 through a merger mandated by the California State Legislation (Los Angeles Times, 1976). The two key agencies involved in this consolidation were Southern California Rapid Transit District (SCRTD) and Los Angeles County Transportation Commission (LACTC). SCRTD was created to develop and operate a rapid transit system for Los Angeles County and was responsible for most of the region's public buses and initial heavy rail segments. LACTC was established to oversee the planning, funding, and coordination of highway and public transit projects across Los Angeles County. LACTC also managed the distribution of sales tax revenue approved to finance transit programs. By merging SCRTD and LACTC, state lawmakers aimed to unify planning, funding, and operational responsibilities under one umbrella agency for the entire county.

This merger eliminated redundant administrative structures, reduced confusion about which agency controlled which projects, and created a single planning authority. This merger also allowed for an efficient use of funds from the LACTC tax revenue for direct bus and rail operations, also accelerating transit expansions and coordinated spending.

Challenges included merging two distinct agency cultures, where SCRTD was operationally focused on running a large fleet of buses and early segments of the Metro subway, while LACTC was planning- and funding-oriented, managing project development and overseeing local sales tax allocations. Leadership roles had to be reshaped, ensuring that the newly formed Transportation Authority could cover every aspect of planning, construction, operations, and maintenance. The new agency gained direct access to LACTC's dedicated transit sales tax revenues, as well as federal and state grants, while SCRTD brought existing obligations (including fleet overhauls and pension overhauls) as well as continuing construction costs for projects.

Another example is the absorption of Conrail commuter rail services in 1983 by the Southeastern Pennsylvania Transportation Authority (SEPTA), which integrated Conrail's services into a new SEPTA Regional Rail Division. Conrail, formed primarily to manage failing freight railroads, had inherited the region's commuter rail operations but was not intended to be a long-term passenger operator. By absorbing these lines, SEPTA unified commuter rail with its existing bus, trolley, and subway systems, securing the financial support and oversight needed to maintain and eventually modernize the suburban rail network. This transition allowed for more consistent funding, better service coordination, and a single brand identity, ensuring the continued viability and expansion of the commuter rail for Southeastern Pennsylvania.

3.2 Operations

3.2.1 Overview

Sound Transit's operations have evolved from an initial focus on constructing new segments to a more complex, heavily utilized network that anticipates even further growth (under Sound Transit 3 [ST3]). As the system expands, operational elements like the strategic placement and utilization of pocket tracks and crossovers, the scheduling and management of maintenance windows, the integration of extensions such as the Lynnwood Link Extension, and the handling of deadhead times will significantly influence service reliability and system resilience. Historically, early design choices limited the frequent use of mainline crossovers and pocket tracks to reduce routine maintenance. While this approach minimized ongoing upkeep, it also curtailed operational flexibility. Running more frequent headways becomes challenging when single-track operations are hindered by insufficient crossovers, especially in areas like the DSTT, where disruptions can significantly impact headways.

For example, in the DSTT, the base minimum headway is 21 minutes when single tracking, and a base minimum of 26 minutes was planned for in January 2024. However, since the ridership was significantly more than the capacity provided, the platforms were overwhelmed, dwells increased, and headways extended to 30 minutes or more when single tracking. Typically, most segments have a headway of approximately 15 minutes during single-tracking operations, but the Stadium Station to Westlake Station, Judkins Park Station to Westlake Station, and the UW Station to Northgate Station segments are 24 minutes or more when single tracking. Implementing retrofits to address these gaps is complex, capital intensive, and cannot be undertaken lightly.

Similarly, maintenance windows and scheduling constraints complicate operations. Tight overnight windows and limited manpower for configuring signal houses, plus safety rules that slow train speeds when maintenance is adjacent to active tracks, make maintaining the system in a proactive manner difficult. As a result, King County Metro has a more reactive maintenance posture. As ridership grows and headways tighten, the challenge of fitting necessary track, OCS, and power system work into already constrained maintenance windows intensifies.

Lynnwood Link Extension

The Lynnwood Link Extension highlights the tension between design requirements and operational needs. While the extension includes additional switches and sectionalized power zones for greater single-tracking flexibility, the terminal station's constrained environment could prove challenging for achieving desired 4-minute headways.

The terminus at Lynnwood will be the end point for the 1 and 2 Lines for 15 years or longer. The combined service will result in trains turning every 4 minutes. The configuration at Lynnwood City Center Station is different than those utilized at every previous terminus, except Westlake Station, because the crossover is behind the station as opposed to in front. In this configuration, every train uses the same arriving platform. The trains then enter one of the two tail tracks and then return to the departing platform. When the crossover is in front of the station, the trains are able to turn at the platform, with each train alternating which platform they use. Having the crossovers behind the station allows for more trains to be at the Lynnwood terminus simultaneously, but this capacity comes at the expense of the resiliency of the operations.

The integration of new segments requires careful coordination to avoid adding future bottlenecks. Deadhead time management similarly affects operations as lines extend and interline. Trains traveling without passengers to reach revenue service start points consume capacity, further compress maintenance windows, and add complexity.

3.2.2 Findings

3.2.2.(1) Lynnwood Link Extension terminus

Operation at the Lynnwood terminus is critical to the overall operations of the system. The current infrastructure has multiple single points of failure. With a single platform used for arriving trains, a passenger incident that requires a longer-than-planned station dwell can result in cascading delays to the following trains. The disruption data provided by Sound Transit indicated that the new segments, including the Lynnwood Link, tended to experience higher failure rates in 2024. The terminus design and track layouts become even more critical to limiting service delays. The need to move the train through the tail tracks also reduces the amount of schedule recovery time available to overcome operating variability. The tail tracks are not available to store out-of-service or gap trains, as is possible when the crossovers are in front of the station. While placing a crossover behind the station is generally beneficial for high-capacity service, this design inherently reduces operational flexibility (due to having only one arrival and departure platform). Conversely, a crossover located in front would not sufficiently support existing operations. The lack of a crossover near the station exit limits the robustness of the terminus. Cost-saving decisions led to, among other factors, using a smaller sized crossover behind the station that slows the train's turnback time. Meanwhile, the crossover between Lynnwood and Mountlake Terrace is located approximately 8,000 feet away, with limited use for turn-backs at the terminal.

3.2.2.(2) Crossovers and pocket tracks

The limited placement of crossovers and pocket tracks restricts operational flexibility and makes single-track operations more challenging in the event of equipment failures or planned maintenance. Of the recent disruptions, almost a third required single tracking or a bus bridge, which were exacerbated by inadequate or distant crossover access. Central Link segments, including the DSTT in particular, are especially vulnerable if one segment is blocked or undergoing work.

3.2.2.(3) Design requirements and operational needs for new segments

Integrating new segments, such as the Lynnwood Link Extension, exposes tensions between design requirements and operational needs, with terminal stations presenting especially tight constraints for maintaining planned headways. Half of the incidents in 2024 that required single tracking or bus bridges occurred in newly opened or recently commissioned sections.

3.2.2.(4) Deadhead times

Extended deadhead times resulting from insufficient infrastructure and complex line interlining add operational complexity and diminish the availability of the right-of-way for revenue service, further compressing maintenance windows.

3.2.3 Recommendations

3.2.3.(1) Add crossovers to existing segments.

Evaluate the feasibility of adding additional crossovers or pocket tracks in strategic locations to enhance operational flexibility and reduce the impact of disruptions on headways. The DSTT in particular offers a significant opportunity to improve operational flexibility and adaptive capacity. At Lynnwood City Center Station, install a crossover as close to the south end of the station as possible; adding a crossing would provide resiliency during disruptions at the terminus and support operations during off-peak hours (tail tracks could be used to store out-of-service trains).

3.2.3.(2) Develop specific standard operating procedures.

Develop, model, and practice site-specific SOPs for certain vulnerable points in the system (such as at Lynnwood City Center Station, which would benefit from an SOP detailing the method of operation during service disruptions). Given that most of the disruptions in 2024 were in areas related to new extension integration or incomplete training, SOPs tailored to those areas will speed response and reduce confusion during abnormal conditions.

3.2.3.(3) Revisit design requirements for operational requirements.

Carefully align design requirements with operational requirements for all future extensions. For the Lynnwood City Center Station and beyond, build infrastructure that supports the desired service frequencies and make sure that operational staff input is integrated early in the design processes. For future projects, develop screening criteria for improving operational resiliency of the system. For example, uncoordinated traction power breaker settings on newly opened corridors caused multiple nuisance power trips.

3.2.3.(4) Implement strategies to minimize deadhead times.

Develop strategies to minimize deadhead times, such as possibly adding more strategically placed storage tracks, improving yard access, or adjusting operational schedules to reduce unnecessary non-revenue moves. Recent data from Sound Transit showed that deadhead times inflate whenever traction power or signal failures require trains to be moved out of service from extended segments.

3.2.3.(5) Build and maintain a lessons learned library.

Apply lessons learned from Sound Transit 2 (ST2) expansions to future projects, incorporating resiliency features—such as improved OCS segmentation and standardized asset management practices—to enable quick recovery and efficient long-term operations.

3.3 Maintenance

3.3.1 Overview

The relationship between Sound Transit and King County Metro for maintaining the Link light rail system is guided by an IGA that needs strengthening. As the asset owner of the Link light rail system, Sound Transit establishes standards, funds capital projects, and defines system requirements, while King County Metro provides day-to-day operations and maintenance services. However, as previously mentioned, the agreement is not performance based, so it offers Sound Transit little leverage when King County Metro does not meet certain operational expectations.

This arrangement creates a difficult environment where accountability, verification of work orders, and integration of engineering recommendations into maintenance schedules are often unclear. Culturally, Sound Transit's focus on capital expansion and adherence to strict reliability targets contrasts with King County Metro's historical approach of managing service to a headway rather than a rigid schedule. Without well-defined performance metrics or a "customer-supplier" dynamic, King County Metro's motivation to adjust staffing, prioritize preventive maintenance, or refine operational processes remains limited. The result is unreliable maintenance outcomes, slow resolution of long-term maintenance issues, and a backlog of unaddressed problems. In the past, Sound Transit has often found it necessary to deploy its own staff or escalate concerns to higher-level committees to encourage necessary action. Data from Sound Transit shows a growing backlog of maintenance work, especially within traction power, which has a backlog equating to over three months of work.

3.3.2 Findings

3.3.2.(1) Resource allocation and staffing needs

King County Metro must manage a workforce with varied skill sets (e.g., traction power and train control). Training crews on specialized rail equipment and maintenance protocols is time-consuming and resource intensive. While some training is being delivered, it is often insufficient and lacks formal certification or assessments to ensure competency. Additionally, aligning staffing schedules with the limited overnight maintenance windows or weekend outages (when the system is less busy) can be difficult. Without enforceable performance metrics or incentives, it can be challenging for King County Metro to prioritize maintenance activities that do not yield immediate operational benefits, especially in the face of competing demands across the broader transit network. According to data provided by Sound Transit, traction power crews in particular devoted only 11% of their recorded hours to corrective maintenance repairs, versus 53% to preventative maintenance tasks, leading to a backlog of repairs remaining open for months.

3.3.2.(2) Data visibility and systems integration

Maintenance teams grapple with incomplete or fragmented information on asset conditions and engineering recommendations. They often rely on spreadsheets, paper records, or incomplete data streams rather than integrated asset management systems. This lack of a centralized, user-friendly data platform makes it harder to proactively identify trends, schedule preventive maintenance, and understand long-term equipment performance. Communication gaps further exacerbate this issue. King County Metro staff often rely on personal relationships with Sound Transit staff to obtain the technical information or implement fixes in a timely manner, and if technical guidance or design updates are not conveyed effectively, King County Metro may be ill-equipped to implement best practices or timely fixes.

3.3.2.(3) Accountability structure

When maintenance issues arise, it may not be clear who holds ultimate responsibility. King County Metro managers must navigate a landscape where Sound Transit, as the asset owner, sets high expectations for maintaining assets but cannot directly enforce compliance. This dynamic can leave King County Metro management in a position of having to respond to requests and recommendations without having adequate resources to complete the request (or clear consequences for non-performance), making it difficult for them to prioritize improvements or justify the internal allocation of funds and staff time.

3.3.2.(4) Maintenance window processes

Maintenance windows for track and facility work are notably brief, partially due to lengthy pre-approval protocols and safety-driven procedures on the actual night of work. While rigorous safety measures are critical, the current process for scheduling and securing track access can introduce inefficiencies that further reduce the already limited time available. These inefficiencies include complex coordination requirements between operations, dispatch, maintenance, and engineering teams, last-minute changes, and procedural steps (both administrative and on-site) that extend setup and teardown beyond what is strictly needed for safe operations. As a result, maintenance teams have less time to complete required tasks, which can delay essential work or lead to rushed activity, raising the risk of incomplete or suboptimal repairs. Data provided from Sound Transit validates this finding: nearly 70% of traction power repairs took multiple site visits to complete, compounding service disruptions because the crews could not finish repairs in a single shift.

3.3.2.(5) Adapting to rapid expansion

As Sound Transit rapidly expands the Link light rail system, new segments typically introduce different equipment types, systems, and vendor-specific components. King County Metro is then responsible for integrating these varying technologies into its maintenance regime. Without standardized equipment or consistent design practices across expansions, King County Metro must develop new procedures, stock a wide range of spare parts, and train staff on multiple systems. Many current preventative maintenance checklists are outdated or based on previously built segments, missing critical tasks such as OCS tension checks or track circuit measurements. This complexity can lead to inefficiencies, complicate troubleshooting, and dilute the technical expertise needed for rapid, effective maintenance responses.

3.3.2.(6) Reactive maintenance activities

Maintenance activities remain reactive because of narrow overnight windows, complex procedures, and insufficient data-driven planning, which results in difficulty scheduling proactive maintenance without negatively affecting revenue service. In its current configuration, the Enterprise Asset Management System (EAMS) is not an effective tool for planning maintenance.

3.3.2.(7) Engineering feedback in maintenance

Continuous improvement for maintenance protocols and planning processes is limited by insufficient integration of technical data and delayed feedback from engineering.

3.3.2.(8) Digital data management and preventative maintenance

Although Sound Transit invests significantly in annual inspections and data gathering such as track scans and LRV health checks, much of this information remains siloed or documented in static files. Day-to-day maintenance continues to rely on older or manual processes such as searching for open work orders or performing ad hoc checks, which limits the ability to detect emerging trends. Rail geometry surveys, OCS tension measurements, vehicle break-fault logs and noise/vibration "signatures" are often archived separately. While there is interest in a digital twin, implementation remains at the conceptual stage, creating a missed opportunity to do more predictive maintenance.

3.3.3 Recommendations

3.3.3.(1) Expand the capabilities with the Enterprise Asset Management System or implement a new system.

Move away from spreadsheets and manual recordkeeping toward a centralized, digital asset management platform. Explore the use of all the modules within the Sound Transit EAMS to track component lifecycles, condition assessments, preventive maintenance schedules, and spare parts inventory. With better data visibility, decision-makers can identify trends, anticipate failures, and prioritize maintenance work more effectively. All assets should be tracked within the system as well as all required preventative and condition-based maintenance tasks (and how long those tasks will take). From this data, a model can be built to show the staffing level needed and the amount of track time needed for maintenance activities.

3.3.3.(2) Adopt performance-based agreements and clear accountability.

Restructure the intergovernmental agreement with King County Metro, so that responsibilities, performance metrics, and consequences for non-compliance with maintenance-related tasks are clearly defined. Introducing enforceable standards and incentives will help ensure that scheduled maintenance tasks, response times, and equipment overhauls meet agreed-upon benchmarks.

3.3.3.(3) Enhance maintenance training programs.

Provide comprehensive, longer-duration training courses for maintenance staff to ensure full competency with complex rail systems. Incorporate certification tests and recurring skill assessments to confirm that technicians remain current on best practices, equipment upgrades, and safety protocols. Regular refresher courses and workshops can reinforce a culture of continuous improvement.

3.3.3.(4) Streamline maintenance access processes.

Undertake a comprehensive review of maintenance access processes to balance personnel safety and efficient maintenance execution. This effort should begin with an evaluation of current access procedures and approvals, with the intention to eliminate redundant steps, clarify requirements, and establish firm timelines for obtaining and confirming track access. Next, scrutinize "night of" operations, carefully analyzing safety verifications, briefings, and staging routines to determine which steps are essential for worker protection and which could be restructured or consolidated. Developing a structured, risk-based prioritization system would further ensure that limited maintenance windows are dedicated to high-impact repairs or safety-critical inspections, thereby reducing the risk of incomplete or deferred tasks. Finally, institute a process of continuous improvement that ensures regular assessments of scheduled access windows, completion rates, and emerging best practices.

3.3.3.(5) Allocate sufficient maintenance windows and resources.

Secure longer or more frequent maintenance windows to accommodate preventive and corrective tasks. If necessary, adjust operations or service patterns to create reliable, dedicated work periods. In parallel, ensure adequate staffing levels and spare part availability during these windows to maximize productivity.

3.3.3.(6) Enforce higher standards for contractor-led trainings.

Improve and enforce contracts requirements to specify minimum durations, curricula, and certification requirements for all training provided by contractors. Instead of one- or two-day sessions, provide more comprehensive training—spanning multiple days or weeks—and include hands-on practice to support classroom instruction. To ensure effectiveness, include assessments or practical exams to validate the trainees' competencies when training is complete.

3.3.3.(7) Establish clear documentation and as-built requirements in contracts.

When projects reach the commissioning stage, mandate timely, accurate, and fully verified as-built drawings, operating manuals, maintenance instructions, and spare parts lists. As-builts need to reflect the actual installed condition, including last-minute field changes and corrections. For high-reliability outcomes, enforce robust quality assurance processes before system acceptance, using third-party reviewers if needed. While as-builts are under review by Sound Transit, provide a preliminary copy to King County Metro.

3.3.3.(8) Integrate documentation with the enterprise asset management system.

Integrate all as-built documents, manuals, and parts inventories into the centralized asset management and document control systems. This integration allows maintenance personnel to quickly reference the latest, most accurate information. By linking digital drawings, schematics, and operation manuals to the relevant assets, maintenance personnel can streamline troubleshooting and ensure that any replacement parts meet the original specifications.

3.3.3.(9) Create accountability and ownership for turnover processes.

Designate a formal turnover manager or a dedicated turnover team responsible for verifying that all training and documentation requirements have been met for maintenance activities. This team can coordinate between engineering, contractors, and maintenance crews to conduct spot checks, audits, and final sign-offs. By having a single point of responsibility, communication gaps can be reduced, and the quality of turnover deliverables can be upheld consistently.

3.3.3.(10) Embrace a proactive maintenance scheduling system.

Move toward a more data-driven, proactive maintenance scheduling system. This scheduling system may involve adopting predictive maintenance technologies, increasing the use of condition-based assessments, and expanding maintenance windows through strategic timetable adjustments.

3.3.3.(11) Implement Reliability, Availability, Maintainability, and Safety (RAMS).

Make RAMS (Reliability, Availability, Maintainability, and Safety) analyses an integral part of improving existing Sound Transit Lines and planning for future projects to ensure the highest levels of safety, reliability, and efficiency throughout the system's entire lifecycle. Identifying potential risks and optimizing maintenance strategies will help to minimize downtime, reduce operational costs, and maximize the availability of critical systems. Implementing this proactive approach can contribute significantly to the long-term reliability of the system.

3.3.3.(12) Establish a unified data repository.

Require that critical inspection data, such as rail defect logs, LRV subsystem faults, and substation fault logs, are uploaded into a single asset management system as a "single source of truth." Concurrently pilot a digital twin model for a high-impact corridor (e.g., DSTT) that fuses track geometry, LRV wheel profile data, real-time brake performance, and overhead contact wear patterns. If successful, scale this approach to other corridors.

3.4 Traction Power, Traction Power Substations, and Rail to Ground

3.4.1 Overview

Sound Transit's traction power network is configured as a 1500 Volts-Direct Current (Vdc) overhead system using silicon rectifier-based TPSS and industry-standard OCS hardware. Unlike typical 750 Vdc systems used in North American light rail systems, operation at 1500 Vdc allows greater spacing between substations, reducing capital cost. Sound Transit design requirements (criteria) have always specified the ability to operate full revenue service with any one TPSS out of service, a requirement referred to as an "N-1" design (Sound Transit, 2024). Outlying substations are powered with a single feeder operating at 13.8 Kilo-Volts Alternating Current (kVac) or 26.4 kVac, depending on the serving utility. Tunnels are powered by a Sound Transit-owned 26.4 kVac network with multiple connections to utility power supplies.

Control of the traction power system is provided through circuit breakers at each substation with relay equipment to trip breakers in case of dangerous overcurrent or other conditions. Each substation is equipped with a local, centralized control panel to monitor and operate the station, provide transfer trip functionality, and provide remote monitoring; control is provided at the LCC via a fiber-optic-based SCADA system.

Like most modern direct current (DC)-powered rail systems, the running rails (track) provide the return path for traction power currents supplied to the vehicles by the OCS. To prevent electrolytic corrosion from occurring on adjacent structures and pipelines, the tracks are isolated from ground, which prevents stray current from leaving the track and returning to the substation via the earth. From a resiliency perspective, however, there are challenges of maintaining an ungrounded DC return system.

Because the tracks are not grounded, a R2G monitoring system is installed at each TPSS. Using various thresholds, this monitoring system can temporarily ground the rails to earth or shut down traction power in the area in case of a significant rail voltage increase. Primarily the R2G device activates when the rail potential exceeds a specified rail potential threshold that is considered unsafe for personnel. During design, the thresholds are considered through simulation in the traction power load flow studies. Cross bonds and sometime supplemental return cables are added to ensure rail potentials do not exceed specified thresholds under normal and emergency conditions. However, in construction and through the life of a rail system the assumptions used in the initial studies may vary and hence the rail-to-ground device can operate. Data provided by Sound Transit support these challenges: traction power issues accounted for approximately 55% of total disruption hours in 2024, making it by far the largest driver of extended service impacts.

Although this safety measure helps protect against passenger contact hazards or infrastructure corrosion, 2024 operations data confirm that R2G-related alarms or false positives contributed to at least 14 hours of disruption, especially near the EMI zone.

While the existing Sound Transit system employs R2G monitoring and devices at each substation, it is noted that there are many rail systems in operation that do not use this technology and operate in a safe manner. Rail systems that do not employ R2G devices include Massachusetts Bay Transportation Authority (MBTA), CTA, SEPTA.

3.4.2 Findings

3.4.2.(1) Single points of failure

Single points of failure in traction power design increase the risk of service disruptions, especially if storms or seismic events disrupt service from adjacent substations. Outages at passenger stations, which lead to loss of communications links, can also cause traction power outages. Examples include the following:

- Single Door Switch Sensor for Transfer Trip: In certain older substations, opening a rear panel or switchgear door will trigger a transfer trip to adjacent substations because of a single sensor integrated into the protective relay logic. During maintenance or troubleshooting, this design can inadvertently force a service disruption for a significant track section if the door sensor misfires or must be bypassed.
- Single Data/Communications Link for Critical Substation or SCADA equipment: In some installations, a single communications link supports all SCADA signals and controls to and from the traction power or tunnel power equipment. If a fiber cut or network hardware fault occurs in that link, operators lose remote visibility of substation status, which reduces the ability to isolate, troubleshoot, and quickly recover from power disturbances. A failure in this fiber connection can also render emergency trip and transfer trip functions inoperable.
- Manual Switching in Under-Functioning System: In tunnel segments where DCAM was designed to provide automatic switching between multiple utility sources, actual operations use manual switching because the DCAM system is not functional.
- Outlying Substations Connected to Single Overhead Utility Source: Many outlying TPSS rely on a single overhead feeder from the local utility. If a storm, accident, or equipment fault disrupts that feeder, the substation cannot draw power from an alternative source, putting the adjacent segment of track at risk of a service outage.

3.4.2.(2) Interfaces for substation control functions

Different generations of traction power control equipment have been installed over time, causing compatibility issues. The intent of Sound Transit's more recent requirements nominally calls for standard, open communication protocols; however, in practice older installations predate or deviate from these standards, leading to diagnostic difficulties and reliance on obsolete equipment. Sound Transit data show that new extension equipment often lacks backward compatibility with older relay or breaker settings on the existing alignment, generating nuisance trips or unplanned partial outages. This mismatch reduces reliability and complicates troubleshooting.

3.4.2.(3) Rail-to-ground

The R2G monitoring system produces unnecessary outages due to false positives and potential flaws, which increases the frequency and impact of disruptions. Some issues are linked to isolated traction power sections under the UW campus, but they occur elsewhere too. In 2024, R2G false alarms, particularly around the EMI zone, caused multiple disruptions. Sound Transit field inspections also revealed track drains clogged with debris in the DSTT, reducing track-to-earth isolation and creating "false positives." It is not clear at the time of this report if the false positives have been reduced.

3.4.2.(4) Testing and pre-revenue phases

Issues identified during testing and pre-revenue phases were not fully resolved before revenue service was started because the priority of meeting schedule milestone dates is paramount.

3.4.2.(5) Testing backup systems

Emergency and backup systems have not been tested thoroughly, causing readiness gaps. For example, a recent inability to connect a portable generator because of incompatible connectors led to a service interruption after a UPS battery discharge and traction power trip-outs.

3.4.3 Recommendations

3.4.3.(1) Perform a systemwide audit of utility sources and add redundancy measures.

Sound Transit requirements do allow for one single utility substation to power two TPSSs from different buses within the utility substation, which does represent a potential single point of failure. Perform a systemwide audit of utility sources to confirm if all substations are fed from "dedicated" buses (a dedicated bus is one that is not shared with other utility customers such as hospitals and businesses). This audit should identify the reliability of the incoming lines, the reliability of utility sources of power and lines powering each substation, whether the power source is a dedicated or non-dedicated source, and availability of suitable alternate utility power sources.

For locations where the power source is not dedicated, migrate to a dedicated bus or provide an additional redundancy option (such as mobile substations and generators) as a back-up or redundant power source. Where feasible, transition alternating current (AC) power for existing substations toward dedicated underground utility feeders. At tie stations, review viability of deploying substations to improve redundancy and overall system resilience. This recommendation directly responds to data provided by Sound Transit showing that overhead utility failures (often triggered by storm events) led to multi-hour outages in outlying segments. Some agencies have provided mobile generators and substations to be deployed in the event of an outage.

Consider approaches used by other agencies, such as the Massachusetts Bay Transportation Authority (MBTA) Green Line in Boston, Massachusetts, which require in their design criteria: "*A minimum of two independent supplies is required to provide for redundancy to cater for equipment failure or routine maintenance* (MBTA, 2022)." (Refer to Figure 2.)

Figure 2. Two Trailer Mobile TPSS with AC and DC Equipment for Massachusetts Bay Transportation Authority

3.4.3.(2) Establish a dedicated power control center.

Establish a dedicated power control center that works with the LCC and monitors power supply (wayside [DC] and utility side [AC]) throughout the entire system. A dedicated power control center allows LCC operators to focus on passenger services while specialized personnel concurrently manage power issues. This dedicated power control center could rapidly coordinate responses for large-scale events like the 2024 “bomb cyclone” storm, reducing downtime and preventing partial or system-wide shutdowns.

3.4.3.(3) Perform a new system-wide traction power load-flow study.

Engage an independent third party to perform a new traction power load-flow study of the entire Sound Transit system (both existing and planned light rail segments) to facilitate troubleshooting and planning of service-pattern changes, thereby reducing reliance on original equipment manufacturers. In particular, focus on identifying discrepancies between modeled results and field-tested results to identify root causes and solutions. A validated model can preempt further disruptions or nuisance trips from uncoordinated line protections when the next phase of expansions and technology upgrades come online.

3.4.3.(4) Standardize Substation Communication Interfaces

Evaluate and replace obsolete PLC and communications equipment at substations to maintain system reliability and simplify diagnostics. Instituting standard communications cabinets and local panels across all substations can reduce the learning curve for maintenance and mitigate downtime.

3.4.3.(5) Review requirements for high rail-to-ground voltage.

Study basic requirements for ensuring safety of the ungrounded traction power system to determine the necessity of the R2G system, its functionality, and alternative mitigations such as platform isolation. This study should include a detailed look at how peer agencies handle rail voltage and the technical, operational, regulatory, cost, and legal aspects of any proposed changes. As previously identified by Sound Transit, several peer agencies only ground the rail locally, without triggering wide-area transfer trips. As part of this study, review the practice of tripping traction power breakers on high R2G voltage. Undertake a thorough investigation of suspected accidental ground sources, with an emphasis on known items like impedance bonds. Perform a loop resistance test under single-point, grounded conditions to validate the simulation model.

3.4.3.(6) Establish a training protocol dedicated to traction power and signal maintenance.
Provide enhanced and recurring training for maintenance staff and establish dedicated engineering support for traction power maintenance. For example, the Denver Regional Transportation District requires its Maintenance of Way (MOW) Power and Train Control staff to undertake a 15-week training course on the power and train control elements; staff must pass an exam to demonstrate their understanding prior to allowing them to maintain the system

3.4.3.(7) Perform periodic emergency and backup function testing.
Verify that emergency and backup function testing occur both during commissioning and at a regular cadence thereafter. Confirm reliability in normal and degraded communication environments.

3.4.3.(8) Adopt a main-tie-main system for future expansions.
For future light rail expansions, adopt standard main-tie-main (MTM) AC power supply systems in tunnel environments, with redundancy and flexibility. An MTM configuration is a specific type of AC power distribution system designed to provide redundancy, flexibility, and resilience in critical infrastructure, including transit rail tunnel systems. It consists of two independent main power sources (feeders), connected by a tie breaker, which can be operated automatically or manually to ensure continuous power supply. MTM systems typically require additional breakers, cabling, and control systems but are inherently more reliable. Design substations with redundant utility connections and consider dedicated underground feeders to prevent outages caused by single drops such as a windstorm that can take out multiple overhead utility feeders.

3.4.3.(9) Avoid test exceptions and enforce quality requirements during testing phases.
Strengthen protocols for investigating alarm conditions during pre-revenue phases. Enhance engineering oversight of testing activities to prevent or eliminate test exceptions and enforce quality requirements over schedule pressures. Perform regression testing to confirm compatibility of new systems with existing segments.

3.4.3.(10) Remove or reduce reliance on rail-to-ground monitoring systems.
After investigating requirements for R2G voltage, as explained in recommendation 3.4.3 (5), consider removing rail-to-ground monitoring requirements for future light rail expansions. Instead, use electrically isolated platforms and hardware isolation so that the areas that passengers touch (touch zone) are isolated to maintain passenger and personnel safety.

3.4.3.(11) Mandate standardized interfaces regardless of contracting delivery methods.
Review design requirements to increase system standardization. Mandate standardized interfaces to simplify testing, troubleshooting, and maintenance. Provide a hard-wired interface terminal cabinet at each TPSS for communication isolation.

3.4.3.(12) Test system under degraded conditions.
Incorporate robust, fail-safe substation controls and thoroughly test reliability under normal and degraded conditions. This recommendation stems from 2024 Sound Transit data showing that

unplanned local power losses and partial communication outages repeatedly delayed substation fault isolation. This recommendation is geared toward testing for scenarios such as failed communications, internal substation failures, and other events to provide maintenance staff with experience in dealing with unusual situations (LCC and vehicle operators could be included as well).

3.5 Train Control and Signals System

3.5.1 Overview

The train control and signals system employed by Sound Transit operates within two main territorial categories: ATP territory and street-running territory. In ATP territory, most of the existing Link light rail system relies on an ATP/Cab signal system (a signal system that displays information in the locomotive's cab) that provides safe and efficient operations by preventing train-to-train collisions, train overspeed, and unauthorized route entries at turnouts or crossovers. In addition, automatic, grade-crossing warning systems, including gates and flashers, are installed at rail-street crossings, and the maximum train speed is 55 miles per hour (mph). These ATP-equipped segments use vital microprocessor-based controllers designed for high reliability and fail-safe performance, with redundant configurations that can automatically switch between normal and standby systems when failures occur. Battery backups and auxiliary power connectors are utilized for standby generators to provide continuity of operation even in adverse conditions.

In contrast, street-running territory involves train operations under line-of-sight rules without ATP/Cab signal functions or automatic crossing gates. The 1 Line Rainier Valley segment, for instance, is a 4.4-mile semi-exclusive right-of-way with city traffic signals governing intersections and granting trains conditional priority but still exposing them to delays caused by motor vehicles and pedestrians. The maximum train speed in this segment is 35 mph. The DSTT segment, a 1.3-mile underground route formerly shared by buses and trains until 2019 (which now is a trains-only segment), accommodates trains under line-of-sight rules, with various maximum train speeds between 20 and 30 mph.

Regardless of whether the territory is ATP or street running, fire safety standards require a ventilation zone signal at the entrance of each underground or tunnel ventilation zone to limit the number of trains allowed inside the tunnel simultaneously. These ventilation zone signals impact achievable headways and thereby influence operational flexibility.

3.5.2 Findings

3.5.2.(1) Signal system design headway and headways of vent zone signals

The *Sound Transit Requirements Manual* (Sound Transit 2024) mandates that in ATP territory where multiple lines join, the signal design headway be less than 90 seconds to support planned operations of three minutes or more. For branch alignments, the headway must be less than 150 seconds to support planned operations of five minutes or more. The minimum amount of time that must pass after a train leaves a tunnel section controlled by a particular ventilation system and before another train is allowed to enter that same section varies by Link light rail segment. Refer to Table 3.

Table 3. Tunnel Segments and Signal Design Headways

Tunnel Segment	Alignment Type	Signal Design Headway Requirement	Actual Vent Zone Signal Clear Time	Headway Impact
1 Line North Tunnel (Northgate to Westlake)	Joined (multiple lines converge)	< 90 seconds (to support planned 3-minutes service headway)	> 90 seconds (exceeds threshold)	Does not impede current service but may constrain future tighter headways (3 min)
2 Line East Link Mt. Baker and Mercer Island Tunnels	Branch alignment	< 150 seconds (to support planned 5-minutes service headway)	< 150 seconds	No headway restrictions; meets requirement for branch operation
2 Line East Link Downtown Bellevue Tunnel	Branch alignment (current)	< 150 seconds (to support planned 5-minutes service headway)	< 120 seconds	Currently acceptable for branch operation but becomes a constraint if converted to joined alignment
1 Line DSTT Segment and Beacon Hill Tunnel	Joined (DSTT) or Branch (Beacon)	< 90 seconds (joined) or < 150 seconds (branch)	Below respective thresholds	Vent zone clear times do not limit headways in these segments

Data provided by Sound Transit confirm that ventilation zones in tunnel segments enforce single-train occupancy, limiting actual achievable headways during disruptions. This restriction compounded service impacts during several events in 2024, where a single signal or interlocking malfunction triggered multiple zone closures.

3.5.2.(2) Signal system and headways in the Rainier Valley

The street-running Rainier Valley segment, operating without ATP and depending on city traffic signals, can experience priority overrides by vehicular and pedestrian traffic after extended delays. The risk of collision and track interference creates a major operational bottleneck. As a result, headways cannot realistically be reduced to below five minutes in this corridor. When issues occur, such as false occupancy events, they become more disruptive because the Rainier Valley street-running design complicates single-track or alternative routing.

3.5.2.(3) Signal system limitations in the Downtown Seattle Transit Tunnel segment

The DSTT, as a street-running underground segment, uses ventilation zone signals to separate trains, allowing only one train per ventilation zone. While this system manages occupancy, it does not provide ATP-level protection against collisions or overspeed, which limits overall operational safety and efficiency.

3.5.2.(4) Signal system equipment obsolescence

Certain components within the signal system, notably the VHLC (slated for discontinuation by the end of 2024) and the analog Audio Frequency Track Circuit (AFTC) (scheduled for retirement in 2025 or 2026), are approaching obsolescence. This situation calls for proactive lifecycle management and replacement planning. Sound Transit reported instances in the East Link Starter Line area where new digital signal cards did not interface properly with the older VHLC or track circuits, causing disruptions and downtime.

3.5.2.(5) Signal system equipment reliability

Analysis of supplied November 2024 malfunction data from Sound Transit (disregarding single-event occurrences) indicates repeat disruptions at specific locations. Switch out-of-correspondence events at interlockings such as N12 (Northgate), C16 (OMF junction), S01 (Angle Lake), and E20 (Kirkland Junction) cause trains to stop unexpectedly. Also, track circuit false occupancy (which indicates a train is present on the tracks when a train is not present) at E10, and crossing gate or signal malfunctions at E22 (20th Street crossing) and E24 (130th and 132nd Street crossings) also trigger operational delays. These reliability issues result in an average disruption duration of 1.9 hours per event.

3.5.2.(6) Track switch snow melter installations

On the Link light rail 1 and 2 Lines, snow melters are provided for switches integral to normal operations and not sheltered from snowfall. For upcoming and future Link expansions, the 2024 *Sound Transit Requirements* (Sound Transit 2024) requires snow melters for all such exposed switches, reflecting lessons learned from current operational conditions.

3.5.2.(7) Signal house remote control

Existing signal houses do not have full LCC/SCADA remote control capability. When single-tracking setup is needed at these signal house locations, the current setup requires signal crews to physically visit signal houses and perform dial-downs, a process that cannot be done remotely.

3.5.2.(8) Signal house battery sizes

Some existing signal houses are susceptible to power outages. The backup UPS batteries in these signal houses are often only able to provide backup power for approximately an hour before failing, leaving the associated signaling segment in a "dark territory" state.

3.5.3 Recommendations

3.5.3.(1) Revise signal system design headway and vent zone limitations for existing systems.

Revise the *Sound Transit Requirements Manual* (Sound Transit 2024) to reduce overly long headways caused by ventilation-zone signals. Where vent-zone clear times exceed 90 seconds (joined alignments) or 150 seconds (branch alignments), launch an engineering and operational review that allows two-train occupancy whenever safety permits. Align signal hardware and ventilation equipment, so multiple trains can safely share the same zone and ensure that new tunnel designs demonstrate support for these reduced headway targets. If deviations are unavoidable, coordinate with operations and planning teams to sustain desired service levels. Recent operational data confirm that single-train occupancy in DSTT segments creates a disproportionate impact during equipment failures.

3.5.3.(2) Address Rainier Valley segment limitations.

Convert the Rainier Valley segment to ATP territory by adding ATP equipment, cab signal track circuits, automatic crossing gates, and traffic signal preemption at grade crossings and by extending ATP coverage to all crossover locations. At a minimum, revisit train run times and coordinate with municipal traffic authorities to optimize traffic signal timing and reduce delays.

3.5.3.(3) Address Downtown Seattle Transit Tunnel limitations.

Convert the DSTT to ATP territory to enhance safety, reduce the risk of collisions and overspeed, and potentially increase allowable train speeds. Note that operational bottlenecks such as the lack of crossovers will limit the effectiveness of this recommendation.

3.5.3.(4) Implement and manage planned signal system obsolescence for existing systems.

Implement an asset management program to identify, track, and manage each piece of the signal equipment's lifecycle. Concurrently, evaluate the feasibility of transitioning the existing system to newer technologies in conjunction with planned expansions. Proactively maintain communication with equipment manufacturers to anticipate product life cycles and plan replacements in advance. Work closely with both Sound Transit procurement and King County Metro to develop an adequate spare parts inventory during transition periods.

3.5.3.(5) Review equipment lifecycle considerations during initial operations planning.

Review design requirements and specifications to guarantee that equipment lifecycle considerations are integrated into initial planning, thus enabling a full asset replacement lifecycle approach. Restrict new installations to the latest approved equipment models to maintain system standardization and longevity.

3.5.3.(6) Enhance signal system reliability.

Strengthen preventive maintenance programs, targeting signal system equipment known to be more prone to malfunction.

3.5.3.(7) Revisit snow melter operations on existing systems.

Operations and engineering should jointly review the operational importance of each track interlocking system to determine the necessity of adding snow melters to existing systems, so that cold-weather operations remain reliable and consistent. There are no snow melters on emergency crossovers.

3.5.3.(8) Add remote control capability to signal houses.

Upgrade existing signal houses that do not have full LCC/SCADA remote control capability to provide full LCC/SCADA remote control capability.

3.5.3.(9) Enhance signal house uninterrupted power supply battery capacity.

Coordinate with King County Metro maintenance to determine if the current UPS battery capacity is adequate or needs to be changed. Once the minimum battery capacity is determined, investigate the battery sizes on all signal houses and upgrade the battery sizes if needed.

3.6 Emergency Ventilation and Fire Alarm

3.6.1 Overview

Sound Transit's tunnels and enclosed stations employ emergency ventilation and fire alarm systems which are designed to maintain a safe tenable environment under both normal and emergency operations. The DSTT, originally built for joint bus and future light rail use, includes a fan plant with a set of axial fans arranged into relatively large ventilation zones that remove vehicle exhaust and can be activated for smoke control. Because the DSTT was designed to older standards, some control logic and emergency equipment configurations may not align fully with current standards or industry practices. Portions of its fire alarm system have been upgraded incrementally over time.

By contrast, University Link tunnels were built specifically for light rail and follow more recent National Fire Protection Association (NFPA) 130 guidelines, with modern smoke control strategies, smaller ventilation zones, and PLC-based fan control supporting scenario-specific ventilation modes. While the University Link tunnel's systems reflect newer, dedicated rail-based solutions, the DSTT may need targeted upgrades to enhance the ventilation capacity, alarm integration, and overall resilience. The findings and recommendations that follow are largely based on the *Sound Transit Requirements Manual* (Sound Transit 2024) and the NFPA 130 *Standard for Fixed Guideway Transit and Passenger Rail System*s (NFPA 2023).

3.6.2 Findings

3.6.2.(1) Pine Street Ventilation Fans

The Pine Street ventilation fans' current and normal configurations are fed from the tunnel by non-dedicated SCL 26 kV cables running through the DSTT from IDS, with the redundant cables fed from the Capitol Hill Station (one of which has failed). Unlike other downtown stations that rely on SCL feeds, the Pine Street ventilation building does not have its own dedicated SCL service. The path for powering the fans is 1) the primary 26 kV from IDS; 2) the secondary 26 kV from IDS, and 3) the single cable remaining from the Capitol Hill Station. Any backup does require a manual confirmation of breakers rather than automatic switching.

3.6.2.(2) Single train per ventilation zone

Sound Transit requirements currently limit tunnel capacity to one train per fire zone (Sound Transit 2024). A special exception was approved in one tunnel segment allowing two trains in a vent zone based on special procedures that include the reversal of a trailing train, this restriction impacts operational headway.

3.6.2.(3) Design fire

Sound Transit requirements define the heat release rate (HRR) for a train fire as reaching 13.2 megawatts (MW) after 17 minutes and 42 seconds for all scenarios (stations and tunnels) (Sound Transit 2024). The peak HRR is used to size ventilation fans. Smoke control for fires with lower HHRs, are controlled by higher airflow rates. Lower smoke control schemes that rely on stratification are not considered.

3.6.2.(4) Tunnel fire ventilation procedures

In case of a fire on a train that is disabled in a tunnel, emergency ventilation procedures are initiated by standard operating procedures based on the location of the train and fire car location on the train. Tunnel Ventilation is operated with maximum capacity which leads to excessive airflow, depending on boundary conditions. The approach should be reviewed with the following considerations:

- For an undercar fire (or non-compartment fire) that disables a train in the tunnel, smoke will spread along the tunnel until the train comes to a stop then initially moves in the direction of travel due to the airflow induced by the piston effect and inertia. Until the ventilation system is activated, the smoke may spread a distance in the tunnel.

- Train operators manually report the fire event and train location then initiate train evacuation based on established emergency procedures and communication with LCC.
- Longitudinal ventilation is established immediately based on the fire scenario producing airflows inside the tunnel, which prevent smoke back-layering and push smoke over the fewest number of train cars, supporting a tenable path of egress for patrons.
- Emergency ventilation fan locations and automatic train control protections are established by design to coordinate the ventilation zones with train operations. Standard design approach limits a single train per vent zone to reduce risk of potential exposure of other non-incident trains to smoke. According to Sound Transit requirements, this is the reason no more than one train must be present in a ventilation section.

3.6.3 Recommendations

3.6.3.(1) Review and consider revising assumptions for tunnel ventilation and evacuation concepts.

Prepare a safety concept, engineering analysis and risk assessment that evaluates the feasibility of tunnel ventilation design schemes for fire scenarios in DSTT. The ventilation schemes should evaluate manual and automatic control for a disabled train in a tunnel. Safety and ventilation design schemes must address emergency evacuation, evaluate train traffic in the tunnel bores to prevent potential risk to evacuating patrons and non-incident trains. The following tasks are also outlined in support of this recommendation.

3.6.3.(2) Develop an overarching safety concept for tunnels.

An overarching safety concept for existing and future tunnel sections should be developed, prioritizing four layers of defense: 1) Prevention, 2) Mitigation, 3) Evacuation, and 4) Rescue. This 4-layered approach, fully compatible with NFPA 130 and Sound Transit requirements, should also enhance operational safety and determine acceptance criteria for two trains in the same ventilation zone, supporting increased tunnel throughput.

3.6.3.(3) Perform an engineering analysis.

An engineering analysis should evaluate the feasibility of both longitudinal critical velocity and moderate flow control velocity designs to determine the system limitations and capabilities to support smoke control and a tenable egress path. The analysis should consider both emergencies and congested modes. Passenger evacuation should be evaluated based on transient analysis considering smoke control direction, train location and proximity of exits.

3.6.3.(4) Perform quantitative risk assessments.

Based on existing data of railway tunnel hazards, a quantitative risk assessment methodology is recommended to support the safety concept. While the Federal Railroad Administration's report, *Evaluation of Risk Acceptance Criteria for Transporting Hazardous Materials* (USDOT 2020) provides a foundation, its risk thresholds should be critically evaluated for passenger transport applications. Developing a tailored methodology offers the following advantages:

- Quantifiable Safety: Moves beyond general conservative estimates, enabling more specific risk quantification.

- Targeted Mitigation: Allows for focused, effective mitigation strategies addressing specific risks.
- Informed Decision-Making: Provides both operators and authorities with data for informed risk acceptance, such as operating two trains in the same ventilation zone.

This approach provides a systematic approach to tunnel safety that evaluates ventilation, transparency and a Sound Transit data-driven understanding of safety considerations in tunnel operations.

3.7 Distribution Control Automation and Monitoring

3.7.1 Overview

The DCAM system was installed in phases from Central Link through Northgate Link extension. Its purpose is to provide utility power reliability to the stations, tunnel fans, and TPSSs in the area from the DSTT to Roosevelt Station. Since all those facilities are supplied by only five utility feeders, DCAM provides automatic switching to provide backup power (in the event of a utility, equipment, or cable failure) without overloading any of the sources. The system was deemed necessary because of the limited number of SCL utility sources available and maximum load restrictions on those sources imposed by SCL. The system is implemented on several local PLCs and tied together via Sound Transit's fiber optic communication system.

The 26 kV distribution system itself is configured with dual feeders along each tunnel section, with switchgear at each station. The 26 kV cables in the University Link and Northgate Link tunnels are installed in cable trenches in the tunnel inverts and grouted in place. Two of the five feeders were installed with the DSTT in 1990 and were tied into the new distribution system at Pine Street in 2016.

The DSTT DCAM system has complicated operational functionality and has never been fully implemented and tested. Options are limited by the number of SCL utility sources in the area and by load restrictions. Because the system was installed in three distinct phases, it was difficult to design and test all the complex failure response scenarios when University Link and Northgate Link light rail extensions were being completed. The DCAM system has proven to be difficult to troubleshoot and is not tolerant of internal faults. As a result switching is done manually by LCC operators during utility outages or other failure situations (Figure 3). This lack of functional automatic switching, relying on manual intervention for backup power, poses some risk in the event of a loss of power within the tunnel.

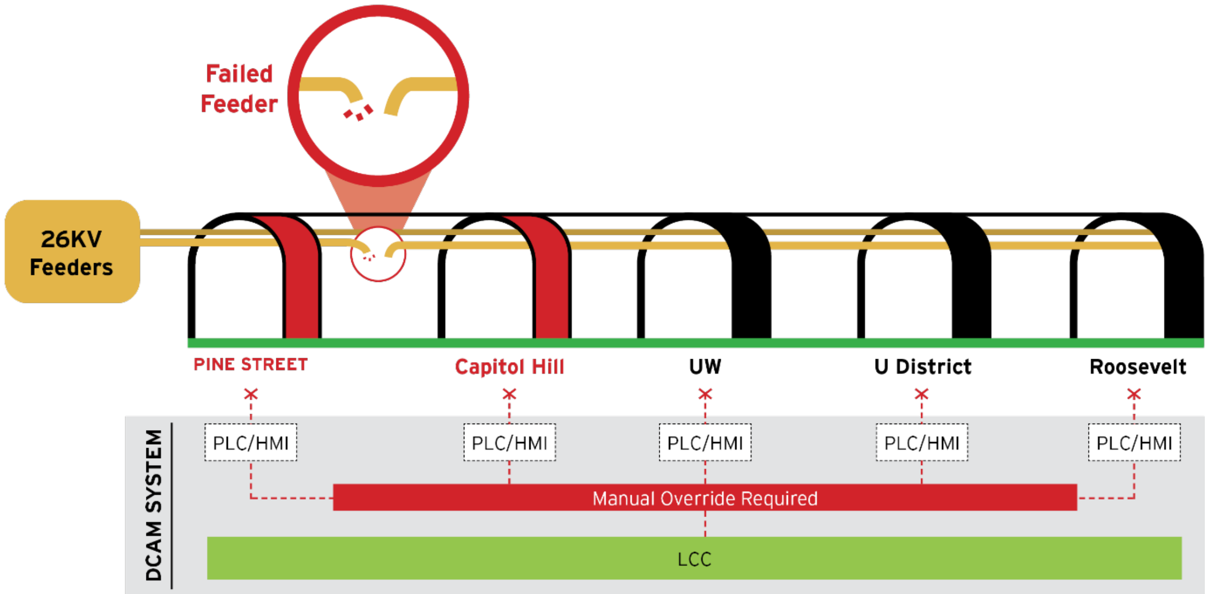


Figure 3. Outages or Other Failure Situations Require Manual Switching by LCC Operators

Part of the reason the DCAM system is not fully resilient is because of a failed 26 kV cable ("failed feeder," Figure 3) in the tunnel bore between Pine Street and the Capitol Hill Station. The installation method for these cables precludes easy replacement or testing because they are in the active tunnel area and covered by grout. Access to them is laborious and time-consuming; replacement cannot be completed during non-revenue hours and thus requires single tracking for extended periods.

Taken together, the reliance on difficult-to-maintain infrastructure and insufficient backup systems exacerbates associated risks when dealing with more than one failure at a time.

3.7.2 Findings

3.7.2.(1) Distribution Control Automation and Monitoring

The DCAM system's complexity and insufficient redundancy reduce resilience to multiple outages. With a limited number of utility sources and load restrictions from SCL, the system remains vulnerable, as it can only deal with one outage at a time.

3.7.2.(2) Failure Scenarios Testing

Because the DCAM system was implemented incrementally, testing all failure scenarios during commissioning proved difficult, and some failures were not identified and resolved before the in-service date. The system is now essentially inoperative in automatic mode, requiring manual switching by LCC operators.

3.7.2.(3) 26 kV Cable

The failed 26 kV cable between Pine Street and the Capitol Hill Station highlights the difficulties in maintaining entrenched infrastructure. Accessing and replacing these cables during non-revenue hours is not feasible, which necessitates long single-track periods.

3.7.3 Recommendations

3.7.3.(1) Within the DSTT, migrate DCAM system to a main-tie-main system.
Revisit limitations imposed by SCL and consider migrating from complex DCAM scenarios to a simpler, local MTM system. This simpler MTM system would choose whichever feeder is available during outages, increasing reliability.

3.7.3.(2) Establish a dedicated Power Control Center.
Establish a dedicated Power Control Center to ease LCC operator burdens during abnormal operations.

3.7.3.(3) Replace 26 kV cabling.
Replace failed 26 kV cables with more resilient infrastructure and consider alternative routing outside tunnels or in more accessible configurations within the tunnels. Whenever possible, route high-voltage circuits outside tunnels, minimizing reliance on buried high-voltage infrastructure. Figure 4 shows an example of cables installed in a more accessible configuration.

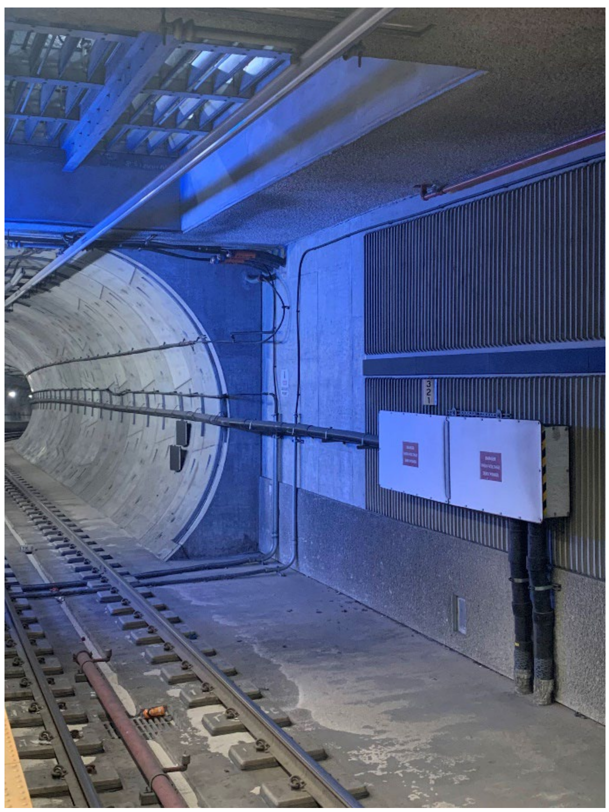


Figure 4. Los Angeles Metro 34.5 kV Trainway Feeder Installation at Little Tokyo Station Installed in 6-inch Fiberglass Resin Epoxy Conduit

3.7.3.(4) Conduct emergency and scenario-based training.
Develop robust emergency response protocols and regularly test them to prepare for cascading failures.

3.7.3.(5) Conduct regular testing and simulations.
Conduct periodic confidence testing and simulations to maintain system readiness.

3.7.3.(6) Evaluate future expansion design alternatives.

Evaluate using MTM configurations in place of the DCAM system to streamline design and improve resilience of future Link light rail expansions.

3.7.3.(7) Add sufficient redundancy and power source diversity in future tunnel designs.

Design future tunnel systems with sufficient redundancy and power source diversity.

3.7.3.(8) Include operational staff, including King County Metro staff, during design reviews.

Engage operations staff in comprehensive design reviews to leverage their hands-on knowledge and to preempt vulnerabilities.

3.8 Climate

3.8.1 Overview

Climate factors such as flooding, high winds, ice, and heat are significant considerations for Sound Transit, because the Sound Transit alignment traverses various terrains. The region is also susceptible to localized flooding, notably in low-lying areas or near rivers and creeks, such as those in the Redmond Extension around Marymoor Park. When heavy rains coincide with water tables that are already high, track segments and tunnel entrances could face inundation risks, potentially disrupting service if floodwaters encroach on trainways or sensitive electrical equipment. High winds can damage overhead contact systems by weakening support structures, breaking contact wires, or bringing down debris that may obstruct tracks. Although not a daily occurrence, windstorm events in the Seattle area have been known to topple trees and pose hazards for power lines and rail corridors. Meanwhile, ice and snow, though relatively infrequent, can quickly impact switch mechanisms, traction power hardware, and overhead wires if switch heaters or de-icing measures are insufficiently robust or if maintenance windows are too short for proactive inspections. Prolonged cold spells can also introduce rail fractures or lengthen braking distances.

3.8.2 Findings

3.8.2.(1) Risk to climate-related disruptions

Sound Transit currently lacks a comprehensive, data-driven understanding of how climate-related hazards such as flooding, heavy winds, heat, and ice events could disrupt its light rail operations and infrastructure. Although staff have performed an analysis that incorporated results into updated requirements and have observed the effects of weather extremes on assets like track components, switch heaters, and power systems, there is no formalized, system-wide analysis of climate vulnerabilities or thresholds that might trigger service disruptions. Existing climate-related responses tend to be ad hoc and reactive, rather than planned around documented risk scenarios or integrated into routine maintenance and expansion projects. This gap hinders Sound Transit’s ability to develop targeted resilience strategies, budget for necessary upgrades, or prioritize climate adaptation measures that could reduce long-term operational risks and costs.

3.8.2.(2) Climate guidance in Sound Transit Requirements Manual

The *Sound Transit Requirements Manual* (Sound Transit 2024) provides a structured approach to design, but it does not specifically outline a clear hierarchy or explicit guidance focused exclusively on mitigating risks. The manual addresses various environmental and sustainability needs under its “Set 803 – Sustainability” and mentions “Set 901 - Storm Drainage” for stormwater management practices. Additionally, “Set 700 series” (e.g., geotechnical, engineering, structures) indirectly includes relevant technical considerations for climate resilience through structural and site-specific design requirements. Environmental mitigation and drainage are handled per general sustainability and stormwater guidelines. *Sound Transit Requirements Manual* (Sound Transit 2024) mentions design lifespans for infrastructure, but they are not based on site-specific vulnerability to natural or man-made hazards.

3.8.3 Recommendations

3.8.3.(1) Conduct a comprehensive climate hazard and vulnerability assessment.
Undertake a system-wide process to identify and characterize both natural and human-induced hazards capable of disrupting light rail operations. This effort should not only map known vulnerabilities (such as documented flooding and seismic risks) but also examine emerging and less predictable scenarios, including unprecedented weather events or new operational hazards.

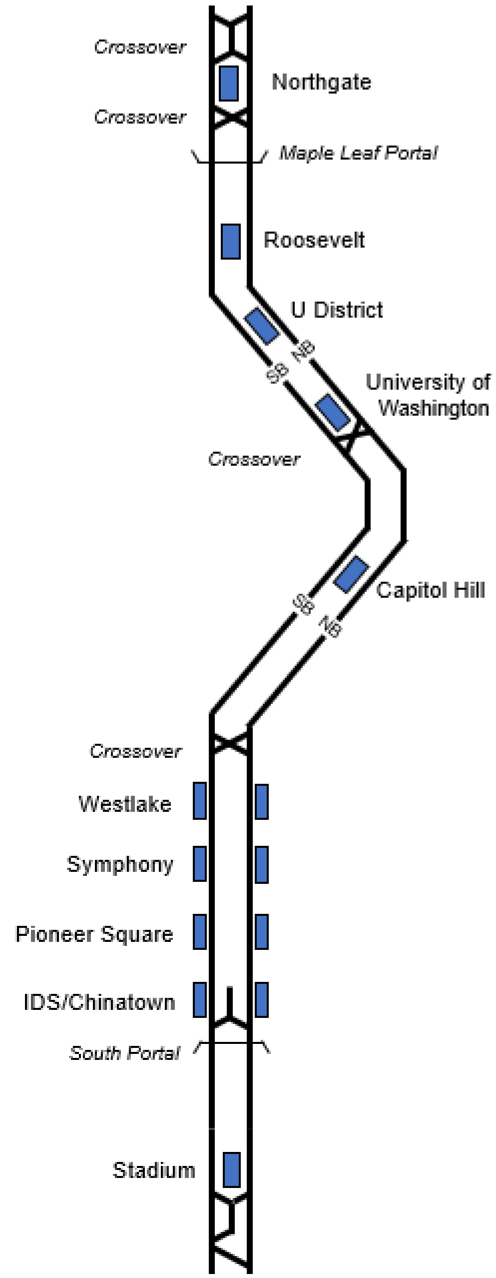
3.8.3.(2) Adopt a resiliency hierarchy.
Develop and implement a resiliency hierarchy within the design requirements for project and program specific requirements. These criteria are developed with respect to planned programs or projects to guide the development and evaluations of alternatives for resilience. Examples of projects or programs that incorporate resiliency hierarchies as part of the requirements include New Jersey Transit Raritan Bridge Replacement Project, MBTA Bus Maintenance Facility Modernization Program (MBTA 2020), and the LA Metro Bus Shelter Replacement Program.

3.8.3.(3) Research and develop design consideration tools.
Agencies or organizations that have exposure maps (and often have conducted vulnerability assessments) have developed internal or public tools to help inform where and what resilience considerations should apply based on asset exposure, criticality, and useful life. Examples include Maryland DOT Adaptation and Resiliency Toolbox and the Massachusetts Statewide Climate Resilience Design Standards and Guidelines (a tool free to the public with no specific assets linked).

3.9 Track Configuration and Structure

3.9.1 Overview

Sound Transit’s existing system features double-track alignments with maintenance crossovers generally spaced between 1 and 3 miles apart. Variation in spacing depends on track speed, geometry, and contract conditions over time. Three mid-line pocket tracks enable storage of gap or bad-order trains. While newer ST2 and ST3 segments generally have crossovers between every pair of stations, older segments—particularly those converted from existing infrastructure like the DSTT and the bored tunnels north of the UW—have fewer crossovers. This configuration creates long intervals without crossovers, complicating single-track operations and recovery from disruptions. Figure 5 illustrates the lack of crossovers between International District (IDS)/Chinatown Station and Westlake Station (i.e., one crossover between every three to five stations instead of every two stations), which makes single-tracking operations difficult. Data provided by Sound Transit indicate that limited crossovers notably contributed to longer headways or bus bridging in almost a third of service-disruption events.



Source: HNTB, 2024

Figure 5. Crossovers Between International District (IDS)/Chinatown and Northgate Stations

Sound Transit's existing track structure consists of a mix of at-grade ballasted track, at-grade embedded track, direct fixation track on aerial structure, direct fixation track in tunnels, and embedded track in the DSTT. Most of the system uses standard 115RE Tee rail, with high-strength rail in areas of accelerated rail wear per the design requirements; however, the DSTT uses girder rail. Using girder rail in the DSTT reflects the original design, which allowed a flush shared roadway for buses and required an internal flangeway for train wheels. This design has repercussions for everything from day-to-day maintenance practices to long-term asset management and lifecycle costs.

3.9.2 Findings

3.9.2.(1) Lack of crossovers in key segments

The long distances between crossovers in key segments limit the ability to single track efficiently. Reduced flexibility during incidents leads to extended headways and service disruptions, particularly in high-demand, central locations.

For example, the distances between crossovers through downtown Seattle not only create challenges for single-tracking operations but also result in some of the longest headway single-track sections. While the DSTT segment is only 2 miles between crossovers, there are five stations in this 2-mile section, and they are high-ridership, central business district stations. At 4 miles long, the segment between the UW and Northgate Stations is one of the longest distances between crossovers and includes three stations that are also high ridership stations serving university students and workforce commuters. In the *Emergency Assessment of Link Light Rail Service Reliability Report* (Appendix A) provided by Sound Transit, a lack of accessible crossovers was cited repeatedly as a reason service disruptions escalated, sometimes forcing extended single tracking that led to 20- to 30-minute headways or full bus bridges.

3.9.2.(2) Rail wear issues

Sound Transit has been experiencing issues with rail defects. In some places, rail defects develop more quickly than expected for normal rail wear, and in certain parts of the system, the defects tend to recur. The Link light rail segment between the SeaTac/Airport and Rainier Beach Stations has experienced rail head defects known as studs, which have appeared earlier than expected in the service life of the rail. Sound Transit has controlled these defects by rail milling, but the root causes are still poorly understood. Also, the section of the DSTT that uses girder rail has experienced more frequent rail breaks than other parts of the system, including one section that has broken more than once in a year. These issues present ongoing maintenance costs and potential operational issues if not remediated. A review of the *Sound Transit Review and Recommendations Report on Wheel/Rail Interface Management* (refer to Section 2.1) identified the most immediate cause of rail breaks as badly executed weld repairs, but it is unclear if the root reasons behind the uptick in breaks and wear include the following:

- Training or quality gaps in weld procedures
- Higher frequency of weld repairs driven by studs on very hard rails
- Aging and expansion of the network, leading to more wear and tear, more defects, and thus more weld fixes
- Lack of thorough data-driven interventions or incomplete use of objective grinding and welding specifications

3.9.2.(3) Rail defects in embedded and girder rail

Recent operational data from Sound Transit indicates that rail breaks in embedded or girder track tend to originate at welds or points where moisture and debris accumulate. In some DSTT segments, repeated breaks have emerged at or near weld beads. Field investigations indicate a combination of aging welds and hidden corrosion, aggravated by the fact that embedded track conceals small cracks until they become more extensive. Additionally, Sound Transit has observed “stud” formations on the rail. Studs are localized high-pressure contact points that create raised defects and can accelerate wear or create minor shock loads on train wheels.

3.9.3 Recommendations

The first three recommendations in this section describe three options for an overarching recommendation to add a crossover to the light rail system. Table 4 summarizes the advantages and disadvantages of each option.

3.9.3.(1) Add Crossover (Option 1) — Place a crossover in the platform at Symphony or Pioneer Square Station.

Perform operations modeling simulation using software to confirm the optimal placement of a crossover, and then conduct conceptual engineering of a crossover directly on the tangent track sections at either Symphony or Pioneer Square Station. This approach to adding a crossover capitalizes on existing horizontal and vertical tangents and does not require complex adjustments to the overall track geometry. Construction would primarily involve removing and replacing embedded track and invert concrete with special trackwork. Table 4 summarizes the advantages and disadvantages of this option.

3.9.3.(2) Add Crossover (Option 2) — Place a crossover using reverse curves at Symphony Station.

Perform operations modeling using software to confirm optimal placement of crossover, and then perform investigation, feasibility analysis, engineering, and construction to replace the existing horizontal reverse curves at both ends of Symphony Station with an intermediate track segment and #10 equilateral turnouts (a symmetrical track switch design where both diverging routes are balanced). This approach would effectively create a crossover through the station, avoiding direct platform encroachment by relocating the special trackwork away from the platform tangents. By situating the crossover outside the platform tangent, the dynamic envelope issues associated with diverging moves at the platform edge are mitigated (diverging moves refers to a train movement in which the train leaves its current track alignment onto a different route). This approach reduces the need for mechanical gap fillers or similar devices. Although single-track reverse running in one direction would still bypass this station, the geometric arrangement may simplify some operational scenarios compared to placing the crossover directly at the platform. Table 4 summarizes the advantages and disadvantages of this option.

3.9.3.(3) Add Crossover (Option 3) — Place a crossover between Symphony and Pioneer Square Stations (via shaft).

Perform operations modeling using software to confirm optimal placement of crossover, and then evaluate constructing a new underground shaft or cavern between Symphony and Pioneer Square Stations to create a crossover located entirely between the stations. This solution would not require modifying the stations themselves or constraining their use during single-track operations. Because the crossover would be placed between stations, both Symphony and Pioneer Square Stations could remain fully operational during single-track conditions. Passengers in both directions would continue to have normal access to both stations without platform service interruptions. The crossover could facilitate flexible single-track operations without compromising station stops, thereby improving overall service reliability during incidents or maintenance activities. Table 4 summarizes the advantages and disadvantages of this option.

Table 4. Crossover Options

Option	Advantages	Disadvantages
Crossover in platform at Symphony or Pioneer Square Stations	● Least cost ● No track geometry modifications	● Station out of service during single tracking ● Mechanical solution with associated operations and maintenance costs for platform edge conflict ● Safety consideration of flip-up edges
Crossover using reverse curves at Symphony Station	● No impact to platforms ● No safety issues at platforms	● Horizontal and vertical changes to track profile required in station entrances ● Station out of service during single tracking
Crossover between Symphony and Pioneer Square Stations (via shaft)	● All stations remain in service during single tracking ● No impact to platforms ● No safety issue at platforms ● No track geometry modifications	● Highest cost ● Construction challenges and risk of building new shaft and box structure around existing DSTT bored tunnels

3.9.3.(4) Perform a rail-wheel interface study.

Perform a system-wide rail-wheel interface study that systematically measures and evaluates the current state of rail and wheel profiles, track geometry, and operating conditions to identify abnormal wear or accelerated track degradation. By examining factors such as vehicle loads, train speeds, curve radii, lubrication practices, and maintenance intervals, the study could pinpoint the root causes of excessive wear and inform targeted solutions, including adjustments to wheel profiles, rail grinding schedules, and lubrication strategies. Recommendations derived from this data-driven approach can then be integrated into the agency's broader asset management program, enabling proactive interventions that extend track and vehicle life.

3.9.3.(5) Investigate unresolved rail wear issues.

While Section 3.9.3.(4) already recommends a wheel-rail interface study, additional emphasis is warranted for the tunnel track and for embedded, girder rail areas that were historically shared with buses. Sound Transit has been proactive in trying different strategies to mitigate the rail studs issue, including using different methods of detection and root cause investigation. In the DSTT, Sound Transit would benefit from investigating the root causes of rail breaks, which can often go undetected in embedded track because they may not cause track-circuit or ride-quality issues. However, rail breaks in embedded track can be indicative of subsurface issues, poor rail isolation, poor drainage, and other problems that can further damage infrastructure. Use sensor-based or ultrasonic methods (especially in the embedded track) to detect incipient fractures before they trigger track-circuit or ride-quality alarms. Investigating and correcting these issues will reduce service disruption and potential operational issues caused by track quality in this heavily used section of the 1 Line. Significant advances in embedded track structure materials have been made in the last 10 years that may provide longer lasting and more resilient track.

3.10 Communications Network

3.10.1 Overview

Sound Transit's communications network supports a variety of mission-critical functions, including train control, traction power, emergency ventilation systems, fire life safety, and other non-mission-critical elements such as station systems and administrative data. To accommodate the continual expansion of the Sound Transit system, the network architecture and fiber backbone topology have been updated during the last 5 years to improve resilience (multiple layers of redundancy) and to make the network more scalable. A three-tier topology for the TCN backbone has been implemented, with Layer 3 core routing for the TCN and a collapsed three-tier topology for the EFN (with the fiber distribution layer providing Layer 2/Layer 3 ethernet local). However, the existing legacy Central Link system operates as a flat Layer 2 architecture (meaning that all devices on the network, such as switches, stations, control units, and endpoints, are essentially part of the same broadcast domain with minimal [or no] segmentation at the network layer) . The C Link core switches are located in a single data room at OMF-C. These core switches are over 15 years old and prone to unpredictable reconvergence during network outages.

ST has also implemented a backup center at OMF-E to replace the IDS data center but it is still unclear if the new data center is fully equipped and commissioned to provide redundancy for all servers. If that is not the case, then a disruption at OMFC-C could bring down Central Link and potentially disrupt applications, communications, and databases systemwide.

Because the system lacks robust Layer 1 or Layer 2 documentation, staff frequently connect new devices (e.g., ticket machines or cameras) to available ports without comprehensive tracking and proper capacity planning. The combination of outdated hardware, minimal documentation, and a run-to-failure approach to maintenance hampers troubleshooting and reduces overall reliability.

The absence of a segmented enterprise/operations structure magnifies the risk, because any interruption to the core switches can affect both administrative users and live railroad operations. In 2024 at least three significant disruptions were directly tied to human error in updating or troubleshooting network and server configurations, thus confirming this risk. Collectively, these illustrate the need for a more resilient, layered, and well-documented communications infrastructure.

3.10.2 Findings

3.10.2.(1) Network architecture

Although designed with redundancy in mind, the system's legacy core switches and Layer 2 architecture in certain segments remain vulnerable to localized failures. In 2024, network reconvergence and uncoordinated updates caused at least three major service disruptions, including one lasting 15 hours when a single switch misconfiguration cascaded, severing remote visibility of key stations or TPSSs.

3.10.2.(2) Backup power equipment

In 2024, a UPS backup failure caused parts of the system to go offline, revealing that backup power for critical equipment is not maintained or tested adequately. The lack of a formal maintenance program for UPS units, coupled with insufficient SCADA failover processes (e.g., two instances, both labeled “SCADA1”), further undermined reliability during outages.

3.10.2.(3) Aging hardware

Core switches are over 15 years old and losing data packets, yet it is unclear if new Juniper switches purchased to resolve this issue can be configured with the VPLS protocol used by SCADA, further complicating planned network upgrades in the Sound Transit, mixed-vendor environment. This lack of clarity has led to a “run to fail” scenario, with the network going down intermittently, halting real-time communications and restricting operational visibility.

3.10.2.(4) Layer 1/Layer 2 documentation

Little to no mapping exists of existing fiber, port assignments, or internet protocol (IP) addresses. Staff often connect new devices (e.g., ticket vending machines or cameras) to any available port with minimal tracking or accountability. This approach impedes network troubleshooting, expansions, and segmentation. Incomplete or outdated documentation has resulted in manual, trial-and-error troubleshooting during outages. In 2024, at least two extended disruptions (8 hours total) were partly attributed to staff being unable to quickly isolate a faulty switch or fiber link, delaying service restoration.

3.10.2.(5) Separation between enterprise Information Technology and Operations Technology

It is consistently unclear if enterprise and operations data traffic ride the same flat network, which could create a situation where typical service outages could also disrupt live operational data flows for trains, station systems, and SCADA. When directly querying multiple stakeholders within Sound Transit, multiple different answers were given regarding whether the enterprise and operations networks were physically and logically isolated. At best, based on a review of documentation provided, the separation appears to be a Layer 3 separation. A review of data provided by Sound Transit also indicates that human error on the communications systems has caused disruptions impacting live revenue systems without formal isolation or enforced change control.

3.10.2.(6) Fallback procedures

When staff attempted to shift SCADA functions to a backup instance, they discovered both SCADA servers were labeled “SCADA1,” causing the system to revert repeatedly to the failed configuration.

3.10.2.(7) Application of Sound Transit IT architecture backbone topology to operational network

The Sound Transit enterprise IT network and the operational network share the same standardized fiber topology. Applying a standard IT backbone topology—designed primarily for an enterprise environment—to an operations communications network generally does not resolve fundamental issues related to merging these two environments. Even when using established enterprise network design approaches and applying them to the operational domain, the underlying differences in priorities, reliability requirements, and security postures remain significant.

3.10.2.(8) Network monitoring practices

The current monitoring protocols do not provide continuous oversight, which leaves infrastructure segments unwatched for intervals. As a result, potential failures or performance degradations can go unnoticed until they have a substantial impact on operations.

3.10.2.(9) SCADA and alarm management

Current alarm management methodologies often generate low-priority alerts. This makes it more difficult for operators to focus on and address the most pressing issues in a timely manner.

3.10.2.(10) Building Management System

Building management system (BMS) users without proper training in alarm management struggle to differentiate between issues requiring a response and routine signals, slowing the response times needed to maintain system integrity and service reliability.

3.10.2.(11) Cybersecurity

The network remains vulnerable because of insufficient security controls, particularly in virtualized SCADA environments that lack robust authentication measures. Without multi-factor authentication and proper segmentation, sensitive systems and operations can be disrupted.

3.10.2.(12) Equipment interoperability

Aging hardware, legacy infrastructure, and labor-intensive Multi-Protocol Label Switching (MPLS) Train Control Network (TCN) protocols limit the network's ability to scale effectively and adapt to newer technologies. This incompatibility hampers seamless integration of modern devices, applications, and services. Consequently, the system will struggle to meet evolving operational needs as the system expands..

3.10.2.(13) Fiber capacity

Existing fiber capacity and switching equipment for C-Link are insufficient to accommodate growing data demands as the Link light rail system expands. With limited bandwidth, the network cannot efficiently support additional services, higher-speed communications, or future applications. Such constraints ultimately hinder performance improvements, operational enhancements, and long-term scalability. Sound transit is currently upgrading this infrastructure, however there is a need to coordinate all projects touching this network infrastructure

3.10.2.(14) Redundancy testing

Redundancy and convergence testing are not performed regularly or thoroughly enough to confirm reliable failover during disruptions. Without routine confirmation that backup systems activate as intended, untested pathways may fail when needed most. This lack of consistent testing increases the likelihood of extended outages and delays in service restoration.

3.10.2.(15) Communications equipment asset management

Current asset management practices for communications equipment lack a systematic approach to lifecycle tracking, timely repairs, and planned replacements. Without a reliable strategy to identify aging or failing components, the organization cannot prevent performance degradation before it affects service. The absence of proactive asset management leads to inefficient maintenance cycles and unplanned downtime.

3.10.2.(16) Overall communications network preparedness for future expansions

The existing communications infrastructure is not equipped to scale easily or adapt to more complex service patterns, which will complicate and slow network growth as new projects come online. Limited resiliency, inadequate redundancy mechanisms, and insufficient capacity restrict its ability to handle future expansions like Tacoma Dome or West Seattle Link lines. Without strategic upgrades and planning, operational growth will be stunted, and service quality may deteriorate over time.

3.10.3 Recommendations

3.10.3.(1) Establish a centralized network operations center.

Consolidate all network monitoring, event management, and escalation protocols into a 24/7, fully staffed Network Operations Center (NOC). This center would incorporate real-time dashboards, automated alerting tools, and integrated communication links with field teams. The NOC should be equipped with direct access to SCADA, signaling, and BMS data so that issues can be quickly identified, triaged, and escalated to the appropriate technical teams. Implementing this recommendation would provide immediate visibility into network health and more efficient coordination with maintenance crews and control center operators, resulting in reduced outage durations.

3.10.3.(2) Develop specialized role-based training for building management system users.

In coordination with the IT and Operations departments, a specialized training curriculum targeting BMS operators could be developed to include simulation-based modules that reflect real-world alarm scenarios and cover critical decision-making frameworks. By emphasizing situational awareness, priority assessment, and structured escalation procedures, these trainings would enhance operators' confidence and efficiency in managing a wide range of operational events such as HVAC malfunctions, platform ventilation alerts, or equipment room environmental alarms.

3.10.3.(3) Streamline alarm management practices.

By adopting a multi-tiered alarm prioritization policy and setting clear escalation thresholds, Sound Transit can ensure that only the most important issues, such as critical TPSS faults or SCADA communication failures, reach the NOC or require field technician intervention. Regular audits of alarm logs would help identify and minimize nuisance alerts, allowing staff to focus their efforts on true operational challenges. Analytical tools can further refine alarm thresholds and quickly recognize repetitive, non-critical warnings, reducing clutter and downtime. With more meaningful alarms and improved dashboards, operators can respond faster and more effectively, leading to improved system reliability, reduced maintenance costs, and better service quality for passengers.

3.10.3.(4) Enhance cybersecurity measures.

By segmenting virtualized SCADA systems, Sound Transit can create protective barriers that prevent a single breach from spreading, thereby safeguarding critical operational functions. Strengthened authentication measures—such as multi-factor authentication and role-based access—ensure that only authorized individuals can access sensitive systems, significantly reducing the risk of service disruptions. Consistent penetration testing, vulnerability assessments, and adherence to well-established security guidelines (like the National Institute of Standards and Technology [NIST] SP 800-82 framework) bolster overall cyber resilience.

3.10.3.(5) Plan infrastructure upgrades for legacy systems.

By replacing aging switches, routers, and other legacy network hardware, Sound Transit can significantly enhance its communication infrastructure. Prioritizing replacement of the most outdated or least reliable devices will immediately improve bandwidth, reduce latency, and confirm compatibility with advanced digital signaling systems. Upgrading to standardized, high-capacity equipment that meets modern interoperability standards will not only streamline existing operations but also support seamless integration with future projects like ST3 corridors.

3.10.3.(6) Implement an ongoing EAMS configuration review.

By working with IT and ServiceNow teams to regularly review and optimize the EAMS, Sound Transit can verify that the system accurately reflects current field conditions and incorporates the latest equipment lifecycle data. This proactive approach of updating asset hierarchies, refining service request workflows, and adjusting lifecycle parameters for new technologies leads to more efficient preventive maintenance, better warranty oversight, and improved capital replacement planning.

3.10.3.(7) Separate operating and enterprise networks.

Physically, logically, and organizationally isolate SCADA, Train Control, and BMS networks (the operational network) from the corporate enterprise environment (enterprise IT). The current separation appears to be a Layer 3 separation. By placing operating networks under Operations control rather than enterprise IT, strict performance baselines, latency thresholds, and real-time operational priorities can be enforced. A dedicated operational network segment that utilizes firewalls and intrusion detection systems tuned for operational technology will reduce the risk of malware penetration so that mission-critical transit functions remain unaffected by corporate network activities such as office applications or remote file transfers.

3.10.3.(8) Transition from Multi-Protocol Label Switching Train Control Network to scalable technologies.

Adopting more flexible network paradigms and more efficient switching protocols would allow dynamic path selection, load balancing, and rapid rerouting in case of light rail system failures. Sound Transit could validate performance improvements by beginning with pilot installations on less critical lines or maintenance yards. As confidence builds, a phased migration plan can be implemented to gradually retire MPLS TCN protocols, enabling more adaptive traffic management and streamlined integration with next-generation, internet protocol (IP)-based train control systems.

3.10.3.(9) Implement ROADM/wavelength routing.

Integrating a reconfigurable optical add-drop multiplexer (ROADM) and Dense Wave Division Multiplexing (DWDM) technology into the backbone would give Sound Transit the ability to add, drop, or reconfigure optical signals remotely without manual fiber patching. This capability would facilitate quick recovery from fiber cuts, dynamically provision additional capacity for special events or ridership surges, and seamlessly segment critical control traffic from passenger Wi-Fi or closed-circuit television data streams. Over time, the ability to adjust optical paths would minimize service interruptions and support resilience goals for multi-line expansions.

3.10.3.(10) Future-proof communications systems design.

When deploying new communications systems for upcoming expansions (e.g., Tacoma Dome or West Seattle Link Extensions), adopt modular hardware designs and software-defined networking capabilities. Using standardized field device interfaces (e.g., open platform communications unified architecture for industrial data) and cloud-ready architecture will enable Sound Transit to scale, upgrade, and integrate new solutions rapidly as technology and rider demands evolve.

3.10.3.(11) Plan for proactive replacement of end-of-life equipment.

Create a rolling asset replacement program, aligned with the EAMS database, that targets hardware projected to reach end-of-life within 5 years. By coordinating procurement cycles, maintenance schedules, and manufacturer notifications, the agency can prevent unforeseen failures. Early identification of replacement candidates and testing alternative vendors will ensure that modernization efforts do not lag behind ridership growth and technological advancement.

3.10.3.(12) Develop regional network hubs.

Establishing regional aggregation points—such as localized network hubs in strategic geographic areas—would decentralize traffic load and shorten communication paths. This approach would allow Sound Transit to compartmentalize disruptions, so a failure in one region would not cascade system wide. Each hub could include redundant equipment, uninterruptible power supplies, and quick access for maintenance teams, improving uptime and simplifying troubleshooting.

3.10.3.(13) Implement geo-redundancy strategies.

By distributing critical servers, databases, and configuration files across multiple geographically separate data centers, Sound Transit can maintain operational continuity even if a primary facility is compromised. Geo-redundancy supports rapid failover during natural disasters, significant fiber cuts, or extended power outages. Periodic failover drills and integration with emergency response plans will reinforce the network's resilience and readiness.

3.11 Vehicles

3.11.1 Overview

Sound Transit issued an analysis of ST2 service disruptions caused by LRV failures in a memorandum titled Service Disruptions due to ST2 LRV Faults (dated December 13, 2024) (Appendix A). Sound Transit has been managing an active vehicle procurement program, with new vehicles entering revenue service since 2021. In 2023 and 2024, the program accepted LRVs at a rate of approximately three per month. According to the vehicle memorandum, service disruptions have been increasing due to a few primary causes, including communications systems and brake systems failures, lack of operator and dispatch troubleshooting training, limited maintenance facility storage, and limited electromechanics. The memorandum provides a status for each primary cause that includes varying amounts of detail, progression to resolution, and recommendations.

3.11.2 Findings

3.11.2.(1) Additional analysis is required

The analysis by Sound Transit provides an explanation of a few potential issues and status of their resolutions, but it does not uncover—quantitatively—the leading causes of service disruptions related to LRVs and how disruptions are being reduced. It is also challenging to interpret trends in the Monthly Availability Chart percentages due to the expanding fleet size. The Mean Distance Between Train Delays (MDBTD) only reflects faults resulting in delays greater than 5 minutes, leaving potential "invisible elements" unexamined. Current recommendations suggest strategies to address brake and communication faults, but these recommendations lack objective proof that the suggested interventions will quantitatively reduce service disruptions. The correlation between LRV reliability, faults, and overall service disruptions is not fully understood and goes beyond just the two known fleet defects identified within the Sound Transit memo (Appendix A).

3.11.2.(2) Facility capacity and workforce

The analysis states that facility capacity limitations and workforce shortages affect vehicle availability, but their direct impact on service disruptions is unclear.

3.11.2.(3) Vehicle system integration and wayside interfaces

Stakeholders are engaged in troubleshooting brake system issues, but vehicle system integration and vehicle-to-wayside interfaces should be evaluated. The communication system has been a major persistent source of service disruptions since 2022; more detail is needed, along with verification that it is not affecting the reliability of other systems. Field representatives from LRV suppliers are on-site to resolve multi-year issues with new vehicles, indicating ongoing, long-term reliability concerns.

3.11.2.(4) Brake system contamination vs. software logic

Sound Transit staff has indicated that some recurring disruptions, initially ascribed to “hydraulic fluid contamination,” involve complex software logic in new LRV brake units. The brake system fulfills dual roles for normal stopping and car leveling, and the valve assemblies have proven sensitive to minute debris or possible fluid pressure fluctuations when leveling cycles coincide with braking tasks. Multiple investigations by the LRV manufacturer and sub-suppliers suggest that while foreign particles can cause valves to stick, a portion of the problem derives from software parameters (e.g., pump timing or fault detections) that unnecessarily log or “latch” minor anomalies as major brake faults.

3.11.2.(5) On-board communications and software integration

Sound Transit staff also indicated that the repeated source of LRV disruptions stems from on-board communications systems, including camera modules and other sub-systems. Software patches delivered incrementally have resolved some issues; however, incomplete sub-supplier integration has slowed resolution.

3.11.3 Recommendations

3.11.3.(1) Perform supplemental analysis.

A supplemental report with analysis created from detailed fault and failure information is recommended to understand the interconnection between vehicle availability, faults, failures, and service disruptions, as well as to uncover leading causes of service disruptions. Sound Transit can use actual fleet quantities rather than percentages to provide clearer trend analyses, especially within data subsets (e.g., out-of-service, warranty repairs, and preventative maintenance). Pair vehicle availability data with vehicle failure data to identify correlations and trends that may provide insight into causes of service disruptions. Further verify whether vehicle failure data correlates with systems failure data to better understand the underlying issues. Additionally, investigate the “invisible elements” not captured by MDBTD (e.g., faults not causing delays over 5 minutes) to ensure a comprehensive view of reliability is conducted. Confirm that differing operational conditions (e.g., train configurations, operators, and environmental factors) are not contributing to increased fault rates. Collect data to prove that addressing these faults leads to fewer service interruptions to confirm which solutions actually work.

3.11.3.(2) Evaluate vehicle system integration and vehicle-to-wayside interface.

Evaluate vehicle system integration and the vehicle-to-wayside interface in consultation with Siemens and relevant systems stakeholders to ensure seamless operation. Provide more detailed information on the communication system failures and confirm whether these issues influence the reliability of other systems. Present more detailed outcomes from field trials and the conclusions drawn thus far to guide decision-making.

3.11.3.(3) Enhance training.
Enhance operator and dispatch training; improved troubleshooting approaches and skill levels may help reduce the frequency or duration of service disruptions.

3.12 Operations and Maintenance Facilities

3.12.1 Overview

Sound Transit's Link light rail maintenance facilities—referred to as OMFs—are located at several sites in the Puget Sound region. The primary sites currently in operation or under development include the following:

- OMF Central (Seattle): Located in the South of Downtown (SODO) district of Seattle, near the Duwamish River corridor.
- OMF East (Bellevue): Situated east of Lake Washington in the Bellevue-Redmond (BelRed) corridor.
- Future OMFs (e.g., OMF South): Planned in south King County (generally in Kent or Federal Way areas).

Sound Transit's OMF Central serves as the primary hub for storing, servicing, and preparing Link light rail vehicles before they enter daily service. Situated in Seattle's SODO district, the facility includes multiple storage tracks, allowing off-peak staging of LRVs. Inside the OMF are maintenance and repair bays where technicians carry out everything from routine preventive work, such as inspections and lubrication, to more complex tasks, such as brake repairs and electrical troubleshooting. Administrative offices and operations teams are also housed here, supporting overall coordination of train availability, scheduling, and daily operations. The facility also contains a substantial portion of Sound Transit's core network infrastructure, including critical servers and network switches for train control, SCADA systems, and station subsystems. Given the essential nature of these systems, any disruption at OMF Central has potential to ripple throughout the entire light rail system.

3.12.2 Findings

3.12.2.(1) Single point of failure within the OMF
Much of Sound Transit's core networking equipment (e.g., servers, switches, and SCADA hardware) is housed at OMF Central. A critical incident in this space, such as a fire or severe equipment failure, could disrupt connectivity for the light rail system.

3.12.2.(2) Maintenance culture
Existing workflows and resource limitations at the OMF sometimes lead to a run-to-failure or fix-on-failure maintenance approach. Over time, this reactive mindset will increase the risk of extended vehicle downtime, hamper system reliability, and drive-up overall maintenance costs.

3.12.2.(3) Capacity at OMF Central
OMF Central is currently operating at 130% of train capacity, forcing storage of trains on main-line tracks and performance of maintenance and cleaning tasks in less-than-ideal conditions. As additional trains arrive and as the system continues to expand, this lack of maintenance and

storage space will become an even more significant challenge, potentially leading to increased equipment failures, delayed repairs, and further disruptions to service reliability.

3.12.2.(4) Equipment and documentation

Some existing equipment in OMF Central (including core switches and backup power systems) has exceeded the recommended lifecycles. Limited documentation and sporadic asset management practices can create maintenance challenges, increase downtime, and slow troubleshooting when urgent repairs are needed.

3.12.3 Recommendations

3.12.3.(1) Strengthen redundancy and disaster recovery measures.

Review redundancy and disaster recovery procedures to replicate critical servers, switches, and SCADA hardware currently stored in the OMF data room; replication of these critical components will reduce vulnerability if this primary data room is compromised. Deploy real-time monitoring for temperature, humidity, and water intrusion.

3.12.3.(2) Address capacity constraints and optimize facility use.

Undertake a combined approach to streamlining facility use by applying Systematic Layout Planning (SLP) to evaluate and optimize the physical layout of the OMF; then support efficiency of the newly designed workspace through 5S (sort, set, shine, standardize, and sustain) methodology. First, SLP would identify optimal workflows by mapping out adjacency requirements, material flow, and process dependencies, ensuring that high-frequency tasks and critical equipment are placed in logical proximity. After the facility layout is defined, 5S principles can maintain an orderly environment, minimize wasted motion, and support continuous improvement. This dual focus on spatial arrangement (SLP) and daily workplace organization (5S) will help Sound Transit reduce clutter, streamline access to tools and equipment, and increase efficiency across maintenance activities.

Article 4. Review and Summary of Efforts Presented by Sound Transit

Sound Transit is currently taking a series of immediate actions to stabilize the light rail system and has asked for a review and simple analysis of these actions as part of this resiliency assessment report. To assist with this review, Sound Transit provided several PowerPoint presentations and the *Draft Emergency Assessment of Link Light Rail Service Reliability* (Appendix A), which provides context for the data presented within the PowerPoint presentations.

4.1 Review of Presentations Provided by Sound Transit

This section focuses on a review of the PowerPoint presentations, which include the following documents:

- 2024-11-25 Line Charts
- 2024-11-27 Disruptions
- 2024-11-27 Maintenance Deficiencies
- 2024-11-27 R2G Model Observations
- 2024-12-03 CEO Brief

Reviewing the presentations regarding monthly disruption data, maintenance audits, single-track constraints, and traction power modeling shows the challenges within the Sound Transit Link light rail system. In terms of monthly disruption patterns, the Lynnwood Link Extension (LLE) experienced spikes in disruptions during its pre-revenue testing (June and July 2024) and again shortly after opening (September and October 2024). If LRV-related incidents are excluded, disruptions trace back largely to traction power and signal failures, concentrated in high-use corridors such as the University District–Capitol Hill corridor.

System-wide maintenance logs show recurring deficiencies at certain stations like Spring District, Tukwila Int’l Blvd and the University of Washington Stations ranging from aging substation components and OCS issues to repeated signal switch failures or track circuit problems. These vulnerabilities typically appear where environmental factors, high traffic loads, or incomplete upgrades exacerbate equipment wear. Single-track operations in these areas face significant constraints, especially along Central Link tunnel segments, because a lack of crossovers or tight headways can force 20 minutes or more between trains under single tracking.

The traction power modeling presented by Sound Transit reveals that even modest increases in rail resistance or partial grounding faults can push R2G voltages into ranges that trigger protective relays, resulting in unscheduled outages. Doubling rail resistance (thus raising voltage along the rail to a point where a protective relay sees an unexpected or unsafe voltage resulting in a trip) or introducing an R2G short (drawing high fault current through other parts of the system resulting in a trip) can rapidly shut down service.

The following are considerations for Sound Transit as it continues its efforts around this data collection process:

- Confirm the source of the data used within the R2G model. If data are based on Sound Transit Requirements, revisit the model with actual field measurements (specifically rail-to-earth resistance).
- The R2G model appears to be largely focused on the tunnels downtown and north of downtown. Confirm if the assumptions are representative across the entire system or if differences in behavior are occurring outside of the tunnel section.
- Consider testing the system without the R2G functions enabled to see how the system performs.

4.2 Review of Summary Report Provided by Sound Transit

Subsequent to the submission of the PowerPoint presentations, Sound Transit provided a report titled, *Draft Emergency Assessment of Link Light Rail Service Reliability* (Appendix A). A review of this Sound Transit assessment shows that it focuses largely on technical and operational causes of disruptions, with clear gaps around asset management, maintenance practices, or governance frameworks (it ignores organizational remedies between Sound Transit and King County Metro. After reviewing service disruption data, the Sound Transit assessment finds that over half of all disruption hours come from factors other than strict equipment failure, such as training and commissioning issues. The assessment also recommends a focus on stronger pre-revenue testing as well as additional training for traction power and train control systems.

Article 5. Summary

5.1 Prioritization of Recommendations for Near and Long Term

As mentioned in Section 2.4, in consultation with Sound Transit staff, the team devised a rubric and matrix to help prioritize the recommendations in this assessment report. This section briefly reviews the prioritization matrix and provides a table listing all recommendations with their respective level of priority.

In addition to prioritizing the various recommendations, our team also analyzed findings against a set of "impact" criteria. Each finding (from Section 3.1 through Section 3.12) was assigned an approximate, qualitative rating (1 through 4) in each of the following four impact categories, which are described in Table 5:

- Impact on Public
- Safety
- Operational Risk
- Complexity

Providing these impact ratings for each finding was helpful during the prioritization process for each recommendation. (Table 6 lists all findings with their respective Impact ratings.)

Table 5. Four Major Impact Categories and Rating[1] for Each Category

Category	Low Impact (1)	Medium Impact (2)	High Impact (3)	Critical Impact (4)
Impact on the Public	Minor inconvenience (e.g., slight service delays)	Service disruptions affecting small segments	Large-scale service disruption (e.g., multiple stations or lines affected)	Complete system shutdown or major public dissatisfaction (e.g., during high traffic periods, like events)
Safety	Low-risk conditions; manageable with current safety protocols	Moderate risk (e.g., isolated safety incidents, minor injuries)	High risk (e.g., frequent safety concerns, potential for serious injury)	Critical safety issue (e.g., life-threatening conditions or major system failure leading to casualties)
Operational Risk	Inefficiencies present but do not affect overall system performance	Disruptions cause delays but can be managed with existing contingency plans	Frequent disruptions challenge operational capacity; may require additional resources	Threats to the continuity of operations; comprehensive review and changes needed
Complexity	Low complexity; simple mitigations or solutions	Moderate complexity involving multiple teams, but solvable in short term	High complexity requiring cross-departmental collaboration or technical integration	Very high complexity; systemic issues requiring long-term, costly, or large-scale solutions

[1] All rating values are approximate and highly qualitative in nature.

Table 6. Summary of Findings[2]

3.1- Governance and Organizational Strategy					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.1.2.(1)	Enforcement mechanisms within intergovernmental agreements	3	2	3	3
3.1.2.(2)	Roles and responsibilities	2	2	3	2
3.1.2.(3)	Information sharing and knowledge management systems	2	2	3	2
3.1.2.(4)	Decision-making	2	2	3	3
3.1.2.(5)	Lessons learned database	2	2	3	2
3.2 – Operations					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.2.2.(1)	Lynnwood Link Extension terminus	3	2	4	3
3.2.2.(2)	Crossovers and pocket tracks	3	1	3	3
3.2.2.(3)	Design requirements and operational needs	2	2	3	2
3.2.2.(4)	Deadhead times	2	1	3	2

Table 6 – Continued

3.3 – Maintenance					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.3.2.(1)	Resource allocation and staffing needs	2	2	3	3
3.3.2.(2)	Data visibility and systems integration	2	2	3	3
3.3.2.(3)	Accountability structure	2	2	3	2
3.3.2.(4)	Maintenance window processes	2	3	3	3
3.3.2.(5)	Adapting to rapid expansion	2	2	3	3
3.3.2.(6)	Reactive maintenance	3	3	4	3
3.3.2.(7)	Engineering feedback in maintenance	2	2	3	2
3.3.2.(8)	Digital data management and preventative maintenance	3	2	3	3
3.4 – Traction Power, Traction Power Substations, and Rail to Ground					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.4.2.(1)	Single points of failure	3	2	4	3
3.4.2.(2)	Interfaces for substation control functions	2	2	3	3
3.4.2.(3)	Rail-to-Ground	2	3	3	3
3.4.2.(4)	Testing and pre-revenue phases	3	2	3	2
3.4.2.(5)	Testing backup systems	3	3	4	3

Table 6 – Continued

3.5 – Train Control and Signals System					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.5.2.(1)	Signal system design headway and headways of vent zone signals	2	2	3	3
3.5.2.(2)	Signal system and headways in the Rainier Valley	3	2	4	3
3.5.2.(3)	Signal system limitations in the DSTT segment	2	2	3	3
3.5.2.(4)	Signal system equipment obsolescence	2	2	3	3
3.5.2.(5)	Signal system equipment reliability	2	2	3	2
3.5.2.(6)	Track switch snow melter installations	2	2	2	2
3.5.2.(7)	Signal house remote control	2	2	2	2
3.5.2.(8)	Signal house battery sizes	2	2	2	2
3.6 – Emergency Ventilation and Fire Alarm					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.6.2.(1)	Pine Street ventilation fans	2	3	3	3
3.6.2.(2)	Single train per ventilation zone	2	3	3	3
3.6.2.(3)	Design fire assumptions	2	3	3	2
3.6.2.(4)	Tunnel fire ventilation procedures	2	3	3	3

Table 6 – Continued

3.7 – Distributed Control Automation and Monitoring					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.7.2.(1)	Distribution Control Automation and Monitoring	2	2	4	4
3.7.2.(2)	Failure scenarios Testing	2	2	3	3
3.7.2.(3)	26 kV cables	3	2	4	4
3.8 - Climate					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.8.2.(1)	Risk to climate-related disruptions	3	2	3	3
3.8.2.(2)	Climate guidance in Sound Transit Requirements Manual	2	2	3	2
3.9 – Track Configuration and Structure					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.9.2.(1)	Lack of crossovers in key segments	3	2	4	4
3.9.2.(2)	Rail wear issues	2	2	3	3
3.9.2.(3)	Rail defects in embedded and girder rail	2	2	3	3

Table 6 – Continued

3.10 – Communications Network					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.10.2.(1)	Network architecture	4	2	4	4
3.10.2.(2)	Backup power equipment	3	2	4	4
3.10.2.(3)	Aging hardware	3	2	3	3
3.10.2.(4)	Layer 1/Layer 2 documentation	2	2	3	3
3.10.2.(5)	Separation between enterprise Information Technology and Operations Technology	3	2	4	4
3.10.2.(6)	Fallback procedures	2	2	3	3
3.10.2.(7)	Application of Sound Transit IT architecture backbone topology to operational network	3	3	3	3
3.10.2.(8)	Network monitoring practices	3	3	3	3
3.10.2.(9)	SCADA and alarm management	3	2	3	2
3.10.2.(10)	Building Management System	2	2	2	2
3.10.2.(11)	Cybersecurity	3	3	4	3
3.10.2.(12)	Equipment interoperability	3	2	3	3
3.10.2.(13)	Fiber capacity	3	1	3	3
3.10.2.(14)	Redundancy testing	3	2	3	3
3.10.2.(15)	Communications equipment asset management	2	2	3	3
3.10.2.(16)	Overall communications network preparedness for future expansions	3	2	4	4

Table 6 – Continued

3.11 – Vehicles					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.11.2.(1)	Additional analysis is required	2	2	3	2
3.11.2.(2)	Facility capacity and workforce	3	2	3	3
3.11.2.(3)	Vehicle system integration and wayside interfaces	3	3	3	3
3.11.2.(4)	Brake system contamination vs. software logic	3	3	3	3
3.11.2.(5)	On-board communications and software integration	3	2	3	3
3.12 – Operations and Maintenance Facilities					
Finding Number	**Finding**	**Impact on Public**	**Safety**	**Operational Risk**	**Complexity**
3.12.2.(1)	Single point of failure within the OMF	4	2	4	3
3.12.2.(2)	Maintenance culture	3	3	4	3
3.12.2.(3)	Capacity at OMF Central	3	2	4	4
3.12.2.(4)	Equipment and documentation	2	2	3	3

[2] All rating values are approximate and highly qualitative in nature.

Table 7 includes all recommendations within this assessment report. As described in Section 2.4 Rubric for Prioritization, priority is inferred from the combination of Benefit (rated from 1 to 5) and Effort (rated from 1 to 5). (Table 1 provides descriptions of Benefit and Effort ratings.) The Benefit and Effort scores are not definitive and should be refined through stakeholder consultation. Table 2 shows how each prioritization category fits within the Benefit-to-Effort matrix.

Recommendations for each major topic (e.g., 3.1 Governance and Organizational Strategy) are presented in order of priority from near-term priority (e.g., Worth Pursuing / Quick Win) to longer term priority (e.g., Low-Priority Tactic).

Table 7. Summary of Recommendations, Sorted by Priority

3.1 – Governance and Organizational Strategy				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.1.3.(2)	Clarify roles, responsibilities and decision-making	3	2	Worth Pursuing (Quick Win)
3.1.3.(3)	Implement recurring training and communication	3	2	Worth Pursuing (Quick Win)
3.1.3.(4)	Study alternative governance structures	3	2	Worth Pursuing (Quick Win)
3.1.3.(1)	Strengthen accountability and enforcement	4	3	High Priority
3.2 – Operations				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.2.3.(2)	Develop specific standard operating procedures	3	2	Worth Pursuing (Quick Win)
3.2.3.(3)	Revisit design requirements for operational requirements	3	3	High Priority
3.2.3.(4)	Implement strategies to minimize deadhead times	4	3	High Priority
3.2.3.(1)	Add crossovers to existing segments	4	4	Major Initiative
3.2.3.(5)	Build and maintain a lessons learned library	2	2	Low-Priority Tactic

Table 7 – Continued

3.3 – Maintenance				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.3.3.(3)	Enhance maintenance training programs	3	2	Worth Pursuing (Quick Win)
3.3.3.(6)	Enforce higher standards for contractor-led trainings	3	2	Worth Pursuing (Quick Win)
3.3.3.(7)	Establish clear documentation and as-built requirements in contracts	3	2	Worth Pursuing (Quick Win)
3.3.3.(8)	Integrate documentation with EAMS	3	2	Worth Pursuing (Quick Win)
3.3.3.(9)	Create accountability and ownership for turnover processes	3	2	Worth Pursuing (Quick Win)
3.3.3.(1)	Expand the capabilities with the EAMS or implement a new system.	4	3	High Priority
3.3.3.(2)	Adopt performance-based agreements and clear accountability	4	3	High Priority
3.3.3.(4)	Streamline maintenance access processes	4	3	High Priority
3.3.3.(10)	Embrace a proactive maintenance scheduling system	4	3	High Priority
3.3.3.(12)	Establish a unified data repository	4	3	High Priority
3.3.3.(5)	Allocate sufficient maintenance windows and resources	4	4	Major Initiative
3.3.3.(11)	Implement RAMS (Reliability/Availability/Maintainability/ Safety)	4	4	Major Initiative

Table 7 – Continued

3.4 – Traction Power, Traction Power Substations, and Rail to Ground				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.4.3.(3)	Perform a new system-wide traction power load-flow study	3	2	Worth Pursuing (Quick Win)
3.4.3.(5)	Review requirements for high rail-to-ground voltage	3	2	Worth Pursuing (Quick Win)
3.4.3.(7)	Perform periodic emergency and backup function testing	4	2	Top Priority (Quick Win)
3.4.3.(9)	Avoid test exceptions and enforce quality requirements during testing phases	3	2	Worth Pursuing (Quick Win)
3.4.3.(11)	Mandate standardized interfaces regardless of contracting delivery methods	3	2	Worth Pursuing (Quick Win)
3.4.3.(12)	Test system under degraded conditions	3	2	Worth Pursuing (Quick Win)
3.4.3.(2)	Establish a dedicated power control center	4	3	High Priority
3.4.3.(4)	Standardize Substation Communication Interfaces	3	3	High Priority
3.4.3.(6)	Establish a training protocol dedicated to traction power and signal maintenance	4	3	High Priority
3.4.3.(10)	Remove or reduce reliance on rail-to-ground monitoring systems	3	3	High Priority
3.4.3.(1)	Perform a systemwide audit of utility sources and add redundancy measures	4	4	Major Initiative
3.4.3.(8)	Adopt a main-tie-main system for future expansions	4	4	Major Initiative

Table 7 – Continued

Number	Recommendation	Benefit (1-5)	Effort (1-5)	Priority
3.5 – Train Control and Signals System				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.5.3.(5)	Review equipment lifecycle considerations during initial operations planning	3	2	Worth Pursuing (Quick Win)
3.5.3.(6)	Enhance signal system reliability	3	2	Worth Pursuing (Quick Win)
3.5.3.(8)	Add remote control capability for signal houses	3	3	High Priority
3.5.3.(1)	Revise signal system design headway and vent zone limitations for existing systems	3	3	High Priority
3.5.3.(4)	Implement and manage planned signal system obsolescence for existing systems	3	3	High Priority
3.5.3.(3)	Address DSTT limitations	4	4	Major Initiative
3.5.3.(2)	Address Rainier Valley segment limitations	4	4	Major Initiative
3.5.3.(7)	Revisit snow melter operations on existing systems	2	2	Low-Priority Tactic
3.5.3.(9)	Enhance signal house UPS battery capacity	2	2	Low-Priority Tactic
3.6 – Emergency Ventilation and Fire Alarm				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.6.3.(1)	Review and consider revising assumptions for tunnel ventilation and evacuation concepts	4	3	High Priority
3.6.3.(3)	Perform quantitative risk assessments	3	3	High Priority
3.6.3.(4)	Perform an engineering analysis	3	3	High Priority
3.6.3.(2)	Develop an overarching safety concept for tunnels	4	4	Major Initiative

Table 7 – Continued

3.7 – Distribution Control Automation and Monitoring				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.7.3.(4)	Conduct emergency and scenario-based training	3	2	Worth Pursuing (Quick Win)
3.7.3.(5)	Conduct regular testing and simulations	3	2	Worth Pursuing (Quick Win)
3.7.3.(8)	Include operational staff, including King County Metro staff, during design reviews	3	2	Worth Pursuing (Quick Win)
3.7.3.(3)	Replace 26 kV cabling	4	3	High Priority
3.7.3.(2)	Establish a dedicated Power Control Center	4	3	High Priority
3.7.3.(6)	Evaluate future expansion design alternatives	3	3	High Priority
3.7.3.(1)	Within the DSTT, migrate DCAM system to a main-tie-main system	4	4	Major Initiative
3.7.3.(7)	Add sufficient redundancy and power source diversity in future tunnel designs	4	4	Major Initiative
3.8 – Climate				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.8.3.(2)	Adopt a resiliency hierarchy	3	2	Worth Pursuing (Quick Win)
3.8.3.(1)	Conduct a comprehensive climate hazard and vulnerability assessment	4	3	High Priority
3.8.3.(3)	Research and develop design consideration tools	3	3	Worth Pursuing (Quick Win)

Table 7 – Continued

3.9 – Track Configuration and Structure				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.9.3.(4)	Perform rail-wheel interface study	3	2	Worth Pursuing (Quick Win)
3.9.3.(5)	Investigate unresolved rail wear issues	3	3	High Priority
3.9.3.(1)	Add crossover (Option 1)—Place a crossover in the platform at Symphony or Pioneer Square Station	4	4	Major Initiative
3.9.3.(2)	Add crossover (Option 2)—Place a crossover using reverse curves at Symphony Station	4	4	Major Initiative
3.9.3.(3)	Add crossover (Option 3)—Place a crossover between Symphony and Pioneer Square Stations (via shaft)	5	5	Major Initiative

Table 7 – Continued

3.10 – Communications Network				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.10.3.(2)	Develop specialized role-based training for BMS training	3	2	Worth Pursuing (Quick Win)
3.10.3.(6)	Implement an ongoing EAMS configuration review	3	2	Worth Pursuing (Quick Win)
3.10.3.(1)	Establish a centralized network operations center	5	3	High Priority
3.10.3.(3)	Streamline alarm management practices	4	3	High Priority
3.10.3.(4)	Enhance cybersecurity measures	5	3	High Priority
3.10.3.(5)	Plan infrastructure upgrades for legacy systems	4	3	High Priority
3.10.3.(10)	Future-proof communications system design	4	3	High Priority
3.10.3.(11)	Plan for proactive replacement of end-of-life equipment	4	3	High Priority
3.10.3.(12)	Develop regional network hubs	3	3	High Priority
3.10.3.(7)	Separate operating and enterprise networks	5	4	Major Initiative
3.10.3.(8)	Transition from MPLS TCN to scalable technologies	4	4	Major Initiative
3.10.3.(9)	Implement ROADM/wavelength routing	4	4	Major Initiative
3.10.3.(13)	Implement geo-redundancy strategies	4	4	Major Initiative

Table 7 – Continued

3.11 – Vehicles				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.11.3.(1)	Perform supplemental analysis	3	2	Worth Pursuing (Quick Win)
3.11.3.(3)	Enhance training	3	2	Worth Pursuing (Quick Win)
3.11.3.(2)	Evaluate vehicle system integration and vehicle-to-wayside interface	4	3	High Priority
3.12 – Operations and Maintenance Facilities				
Number	**Recommendation**	**Benefit (1-5)**	**Effort (1-5)**	**Priority**
3.12.3.(1)	Strengthen redundancy and disaster recovery measures	4	3	High Priority
3.12.3.(2)	Address capacity constraints and optimize facility use	4	4	Major Initiative

5.2 Conclusion

As Sound Transit transitions from a capital-expansion focus toward a mature, service-driven organization, its long-term success will depend on transforming these findings and recommendations into a cohesive plan for operational resilience. Taken together, the recommendations outlined in this assessment provide a practical path forward with near-term “quick wins” to stabilize current challenges, as well as more comprehensive initiatives that will shape how Sound Transit sustains its services.

Reliance on intergovernmental agreements without robust accountability provisions contributes to recurring issues in standards enforcement and resource allocation. Introducing clearer enforcement mechanisms, performance metrics, and well-defined roles would help ensure consistently high operational and maintenance outcomes. Furthermore, reactive, narrowly constrained maintenance windows limit the agency’s capacity for proactive upkeep. Building more flexibility into track layouts, expanding maintenance windows, and investing in more formalized training can enable Sound Transit to meet the system’s operational demands, particularly as ridership increases.

A shift toward standardized, modular, and resilient infrastructure optimized for operations and maintenance backed by robust data acquisition and thorough asset management can reduce downtime and accelerate service restoration, even under degraded conditions.

Modernizing signal hardware, introducing advanced train protection in street segments, and strengthening network architecture and cybersecurity measures will improve day-to-day reliability and reduce incidents that disrupt service.

Pairing these recommendations with improving data management capabilities through “digital twin” concepts, integrated asset management systems, and structured knowledge-capture procedures can facilitate continuous improvements and avoid repeating design inefficiencies in future projects.

By strategically addressing these recommendations, Sound Transit can strengthen organizational accountability, promote robust operations and maintenance, and ensure that each new phase of expansion is delivered under a stable and resilient operating framework. This collective effort will better position the agency to maintain public confidence, streamline service delivery, and meet the region’s evolving transportation needs.

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Appendix A: Reports Provided by Sound Transit

Appendix A consists of the following two documents (one report and one memo), both provided by Sound Transit as part of this Resiliency Assessment report. These two reports appear as provided to HNTB and have not been modified other than to address typos and grammar, define acronyms upon first use, ensure that diagrams are largely readable, and to standardize fonts and formatting.

- Service Disruptions Due to ST2 LRV Faults Memorandum
- Draft Emergency Assessment of Link Light Rail Service Reliability Report

Subject: Link Service Disruptions Caused by ST2 LRV Faults

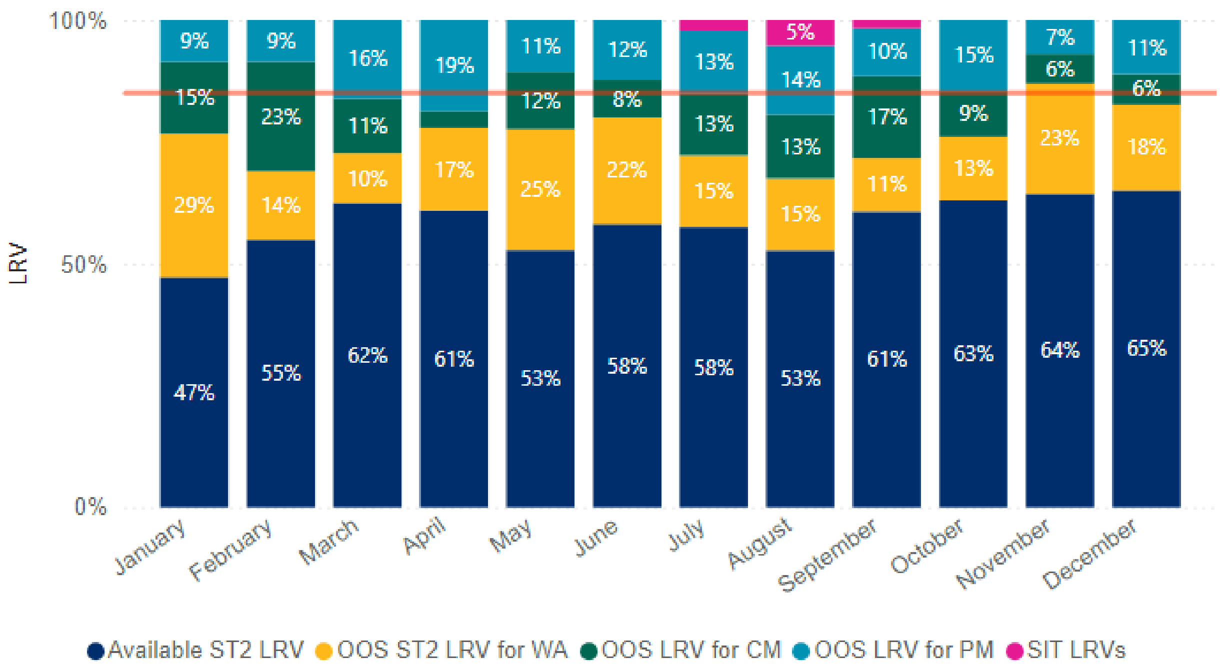
Prepared by: Shankar Rajaram, Executive Project Director – Revenue Vehicles

Date: 12/13/2024

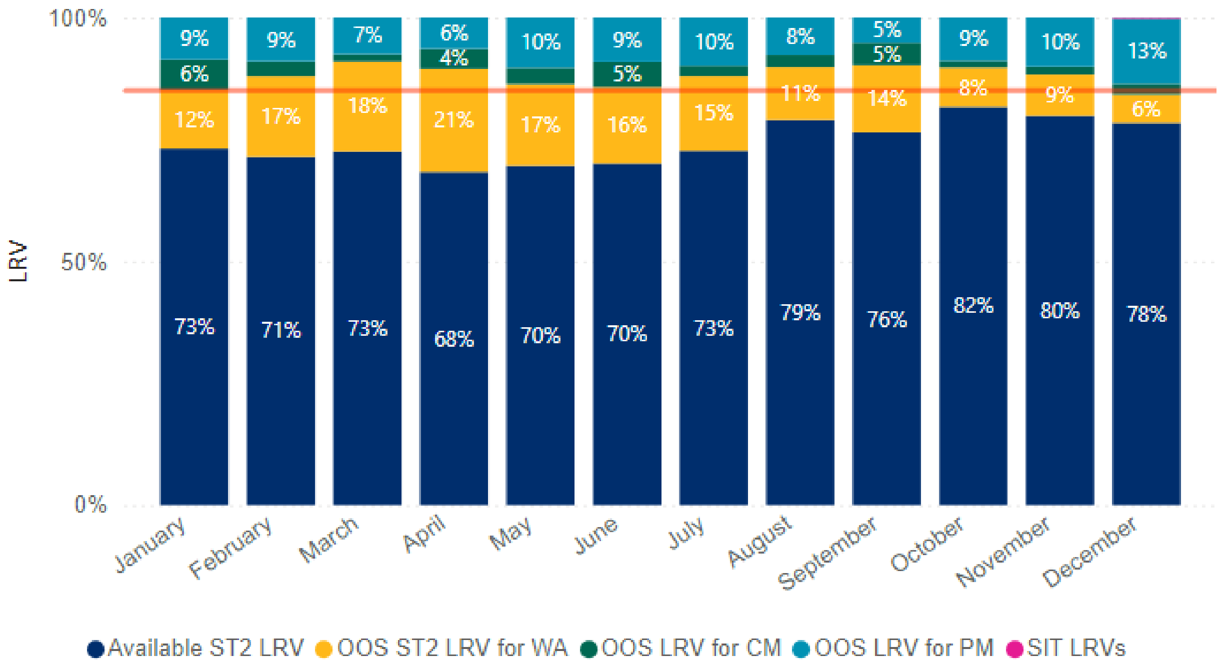
Overview:

The Series 2 light rail vehicles (LRV) entered revenue service in Q2 2021 and fleet expansion has been progressing at the rate of 3 LRVs per month in 2023 and 2024. As of 13 December 2024, 133 LRVs have entered service. As shown in the histograms below, the daily availability of vehicles for revenue service improved steadily from 2022 through 2024, but the trend started reversing when Lynnwood Link opened in September 2024. Two key factors that are believed to contribute to the reversing trend are the overnight storage of LRVs on the mainline due to operations and maintenance facility Central (OMFC) capacity constraints and shortage in electromechanics necessary to maintain the expanding fleet. Mitigations for both these factors have started as more electromechanics have joined OMFC in Q4 2024 and the vehicle maintenance team appears to have gotten past the initial learning curve.

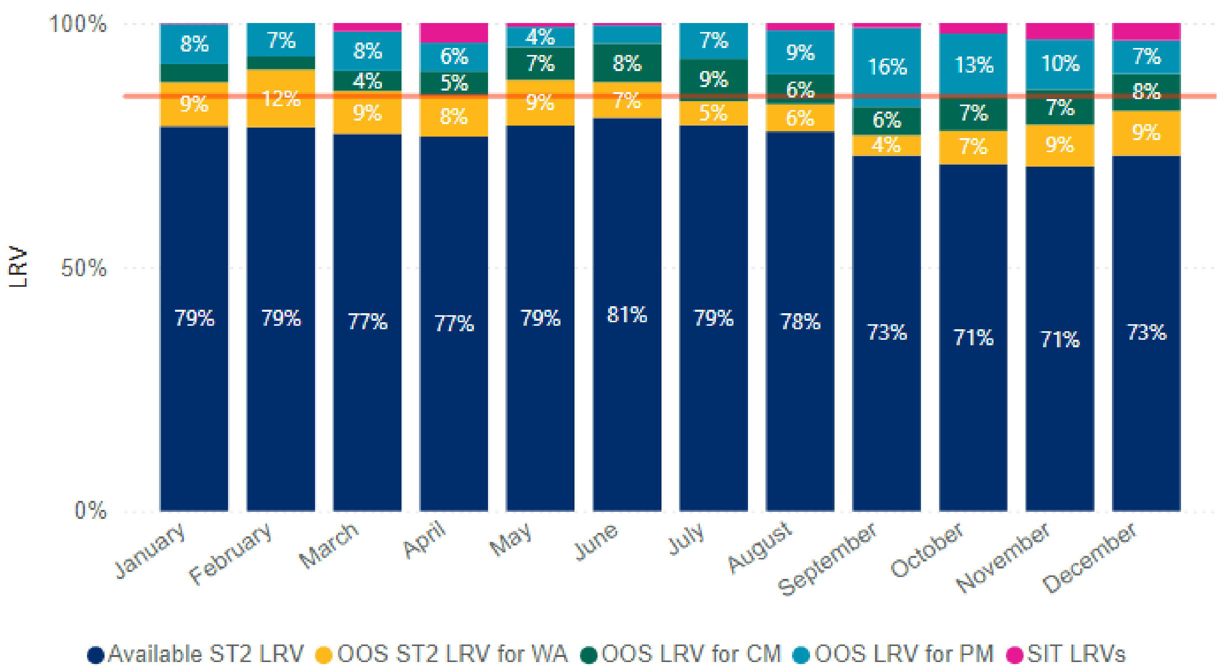
Monthly Availability in 2022:



Monthly Availability in 2023:



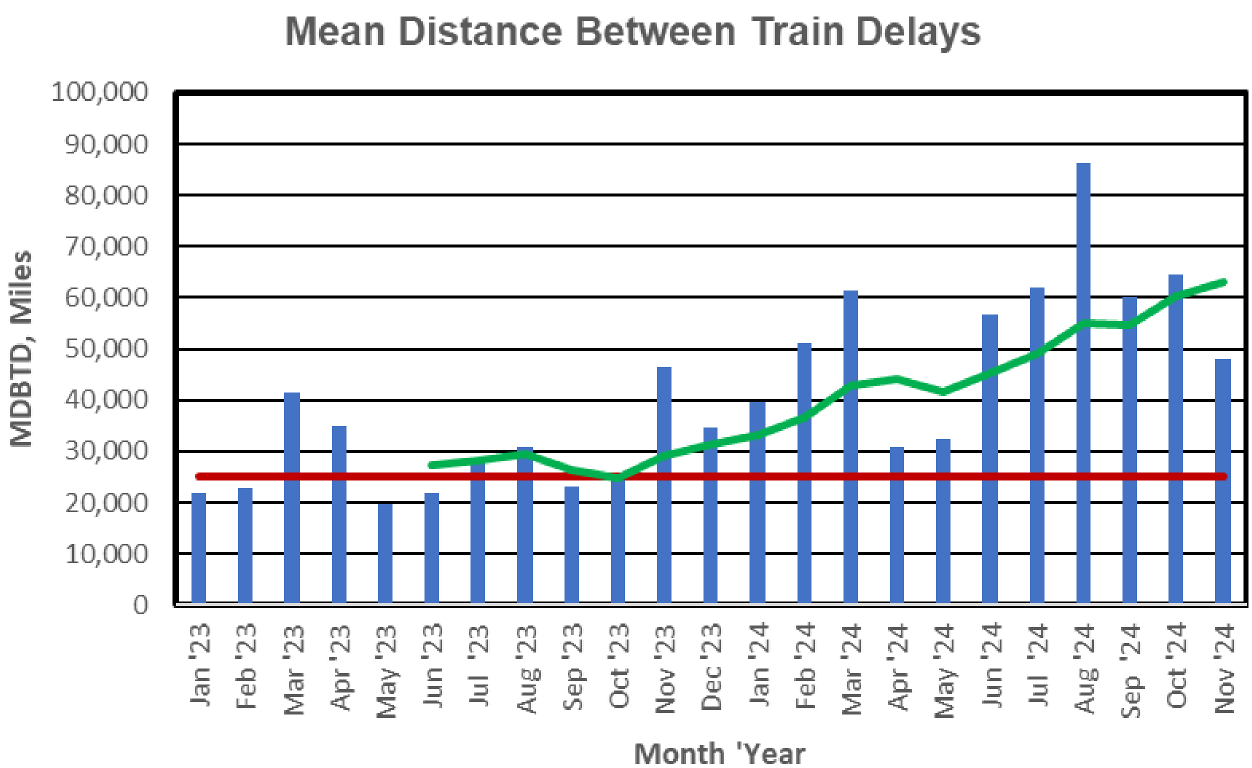
Monthly Availability in 2024:



OOS = Out of Service. WA = Warranty repairs, CM = Corrective Maintenance, PM = Preventative Maintenance, SIT = System Integration Tests

One of the key contractual reliability numbers (Mean Distance Between Train Delays or MDBTD) for Series 2 LRVs is 25K miles per month. The monthly average based on 12-months' data in 2023 was ~29K miles. Between June and November 2024, Series 2 LRVs had an average MDBTD of 60K+ miles.

Two invisible elements under scrutiny are (1) faults during service that result in less than 5-minute service delays due to workarounds applied to resume service, and (2) faults that result in major disruptions during peak service.



Focusing on major vehicle faults causing revenue service disruptions, the brake faults are a dominant factor. A major source of disruptive brake faults is pressure drop in the electronic hydraulic units (EHU) after leveling of the vehicles at station platforms. The EHUs serve the dual purpose of car leveling and braking functions.

Communications system is another major source of vehicle faults resulting in service disruptions. Various investigation methods are being used depending on the sub-system and interruption type, including:

- Investigating hydraulic fluid contamination sources in manufacturing
- Conducting field trials of test cases
- Improving software logic
- Reviewing maintenance quality assurance procedures

Although field trials have been ongoing for the last two years to mitigate the effects of EHU contamination, no tested solution has yet emerged as a clean fix for the problem. Both software and hardware solutions are pursued. As a latest initiative from Sound Transit (ST) leadership, in concert with Siemens and Knorr (brake supplier), a task force completed visits to manufacturing and assembly facilities to investigate the source of contamination. Knorr's personnel is also on site in Seattle since mid-October 2024 to support the brake fault investigation and resolution. Temporary mitigation is anticipated in Q1 2025. Similarly, communications system issues have been investigated since 2022 and a software fix has been undergoing field trials for close to one year. Televic's personnel have been on site in Seattle since summer 2024.

Both the EHUs and the communication system have been placed under fleet defect. The next section discusses the known issues and findings for these two major contributors (brakes and communications system) to LRV reliability.

Another factor that appears to be contributing to brake fault-related disruptions is the learning curve in responding to minor brake faults during revenue service. ST and King County Metro (KCM) have taken steps in Q4 2024 to improve the fault response instructions and training for operators and Link Control Center staff. This step seems to have helped over the last four weeks by cutting down the duration of individual disruption events caused by LRV faults.

Findings:

In November 2024, a team comprising Siemens, Knorr Breme, Sound Transit and Hatch representatives visited the manufacturing, assembly and commissioning facilities to ascertain how the brake hydraulic units are handled. The team visited Knorr's facility in Berlin and Westminster, a Siemens facility in Sacramento, California, and Sound Transit's maintenance facilities in Seattle and Bellevue, Washington. On November 30, Siemens submitted the key findings and observations from the trip and following is the summary of key findings/observations identified in the trip report:

- There was no smoking gun as to how impurities entered the EHUs. However, impurities entering the EHUs was possible in manufacturing and assembly areas.
- Characterizing the type and size of particles found in the EHUs needs to be pursued.
- Tearing down an EHU off a car that has not had any supply pressure failures would help in the analysis. (Target is January 2025.)
- It is highly recommended to simplify the flushing procedure for the assembly process in Sacramento and for the commissioning and maintenance activities in Seattle. (Target is January 2025.)
- There is consensus that GS valve is leaking that results in faults. Contamination is agreed to be a contributing factor. But there may also be other factors contributing to the faults.
- The answer to the questions "Why Aux On and Aux Off stops the leaks in most cases?" and "Why leak stops almost always after pressure drops to zero?" could open the doors for the root cause of leaks and to find a durable solution. Also, a more nuanced approach to when to use Aux Off/Aux On as a practical workaround to brake fault failures is being developed by Siemens/VM. A small team will continue to meet frequently and critically investigate signal records to answer the above questions.

Another factor that appears to have contributed to the prolonged duration of brake fault-related disruptions since Lynnwood Link opened is the learning curve in responding to minor brake faults during revenue service. ST and KCM have currently taken steps to improve the fault response instructions and training for operators and Link Control Center staff.

The following are the field trials with potential hardware solutions that are currently underway to diagnose root cause and effective mitigation strategy for brake faults. The list also presents the current status of the field trials for these test groups as of December 12, 2024.

1. Test case with filters to ports has 10 LRVs in the test pool and has cumulatively completed 612,487 miles over a period of 284 days in revenue service and have 114 faults.
2. Test case with new manifold has 2 LRVs in the test pool and has cumulatively completed 47,623 miles over a period of 112 days in revenue service and have 0 faults.
3. Test case with EHUs cleaned at Knorr facility has 1 LRV in the test pool and has completed 23,304 miles over a period of 79 days in revenue service and has 1 fault.

4. Test case of GS valves with integrated filter screens has 3 LRVs in the test pool. 0 faults over the course of 24 days and have completed 8,048 miles.

In addition, a software solution to detect valve leaks and clear the faults is pursued. The software solution is in the parameter refinement stage and expected to be trialed in January 2025.

To address communications faults, a software solution is being implemented.

The following table summarizes the dominant fault types that majorly contribute to service disruptions and the potential fixes that are currently tested.

System Component	Reason for Interruptions	Cause	Types of Fixes	Additional Fixes
Brake System	Brake fault due to pressure drop after leveling action at station platforms.	Valve Leak Type 1	Cleanliness of hydraulic unit hardware Cleanliness of hydraulic fluid Improving the resilience of hydraulic system.	Prevent cascading failure evolution that prolongs service disruptions by 1) improve training materials and clarity of instructions to operators to triage and clear faults that occur during service.
		Valve Leak Type 2	Workmanship issues	
		Valve Controls	Refined software logic	
Communication System	Communication system elements failing to function normally.	Rear view camera blackout, malfunction of several passenger information displays and communication interfaces.	Software fixes	Consider hardware replacements on a case-by-case basis.

Recommendations:

- The overall recommendation for brake fault investigation is to find the most effective solution (hardware and/or software) to fix disruptions from brake faults by Q1 2025 and implement it fleet wide from Q2 2025.
  - Complete the refinement of trial software for valve leak detection by mid-January 2025 and start field trials of this software.
  - Increase the fleet pool for brake fault test groups with hardware solutions to accelerate the validation of the respective solutions' efficacy.
  - Investigate other issues, maybe a campaign to look into potential workmanship issues on EHU systems.
- For the communication system, prioritize the implementation of the software improvement fleetwide.
- Prioritize the training of operators and Link Control Center staff with simplified fault response instructions to efficiently clear faults during operations and prevent potential cascading failure evolution that could lead to prolonged service disruptions.

Table of Contents: Emergency Assessment of Link Light Rail Service Reliability

1.0 Scope of the Assessment Effort

An outlined in the October 23rd 2024 MEMO from Craig DeLalla, Acting Chief Engineer to Moises Gutierrez, DCEO Capital Delivery and Russ Arnold, DCEO Service Delivery entitled *Emergency Assessment of Link Light Rail Service Reliability*, the key scope of these assessment efforts consists of four work streams. These four work steams consist of: review of Link service disruptions due to equipment failure in 2024; review Link maintenance records; perform an independent condition assessment of Link's traction power, signals, and rail equipment; and perform a peer agency review of our findings and state of good repair standards. In the following discussions, a fifth work stream was added for the field review and assessment of our rail-to-ground system. Since the rail-to-ground system is a subsystem of our traction power system, this fifth work stream has a lot of overlap with the condition assessment work stream for traction power; never the less, since this subsystem has caused numerous disruptions, and its operation has direct impact on rail worker safety as well as infrastructure and signals maintenance, its assessment warrants its own work stream.

2.0 2024 Failures Review

Goal: Review of all failures that caused service disruptions in 2024 to define trends, systemic issues, and their potential causes.

Deliverable: A report describing the assessment and a prioritization of efforts for maintenance improvements or system upgrades.

Status: COMPLETE

The following is the list of documents delivered.

2024-11-27 Service Impacts.xlsx: This spreadsheet lists all service disruptions posted by LCC to alertsense.com between January 1st 2024 and November 27th 2024. Disruptions have been associated with any related EAMS work orders opened to resolve them and categorized by location, Equipment Asset Class, Equipment Asset Sub Class, Root Cause Class. A live version of this spreadsheet is being maintained weekly by engineering staff.

2024-12-03 Disruptions.pptx: This represents the key analysis and findings from the Service Impacts spreadsheet. The key findings are summarized below in the findings section for 2024 Failures Review.

2024-12-05 Thoughts on the management of service disruptions.docx: This document contains recommendations on the key roles and their associated duties in the identification, communication, and resolution of a major service disruption. These recommendations are aimed at improving resolution time by streamlining the ways information is gathered from the field crews and centralizing the direction of those crews in the identification and resolution of the issue causing the disruption.

Note 1: Since no single source of service disruption data exists at the agency, this report will focus on service disruption as reported by LCC. Duration is from first disruption report to report of return to normal service. It is acknowledged that these start and end times for the disruptions are not always precise, due to delays in LCC receiving field information as well as delays in their report of that data, but it is assumed that they are notionally correct. Total disruption hours is simply the sum of these disruption durations, regardless of the level of disruption experienced by the passengers (a.k.a, it makes no account for the difference in passenger impact between a single delayed train or a full bus bridge).

Note 2: This report uses Link Light Rail Sub-System names such as Traction Power or Signals that are often shared by the worker of the related craft. It should be understood that the report is referring to the functionality or failure of that Sub-system in regard to service disruptions and of the craft workers of the same name.

Finding 2.1: Traction Power and Signals are the major causes of service disruption hours.

There have been 177 disruptions recorded in 2024 to November 27th, resulting in a total of 432 hours of disrupted service. As can be seen in Figure 2.1, Traction Power (TES) is the largest cause of service disruption hours with 238 hours or 55% of the total, followed by Signals (SIG) with 94 hours or 22 %; these two disciplines alone account for 77% of all service disruption hours.

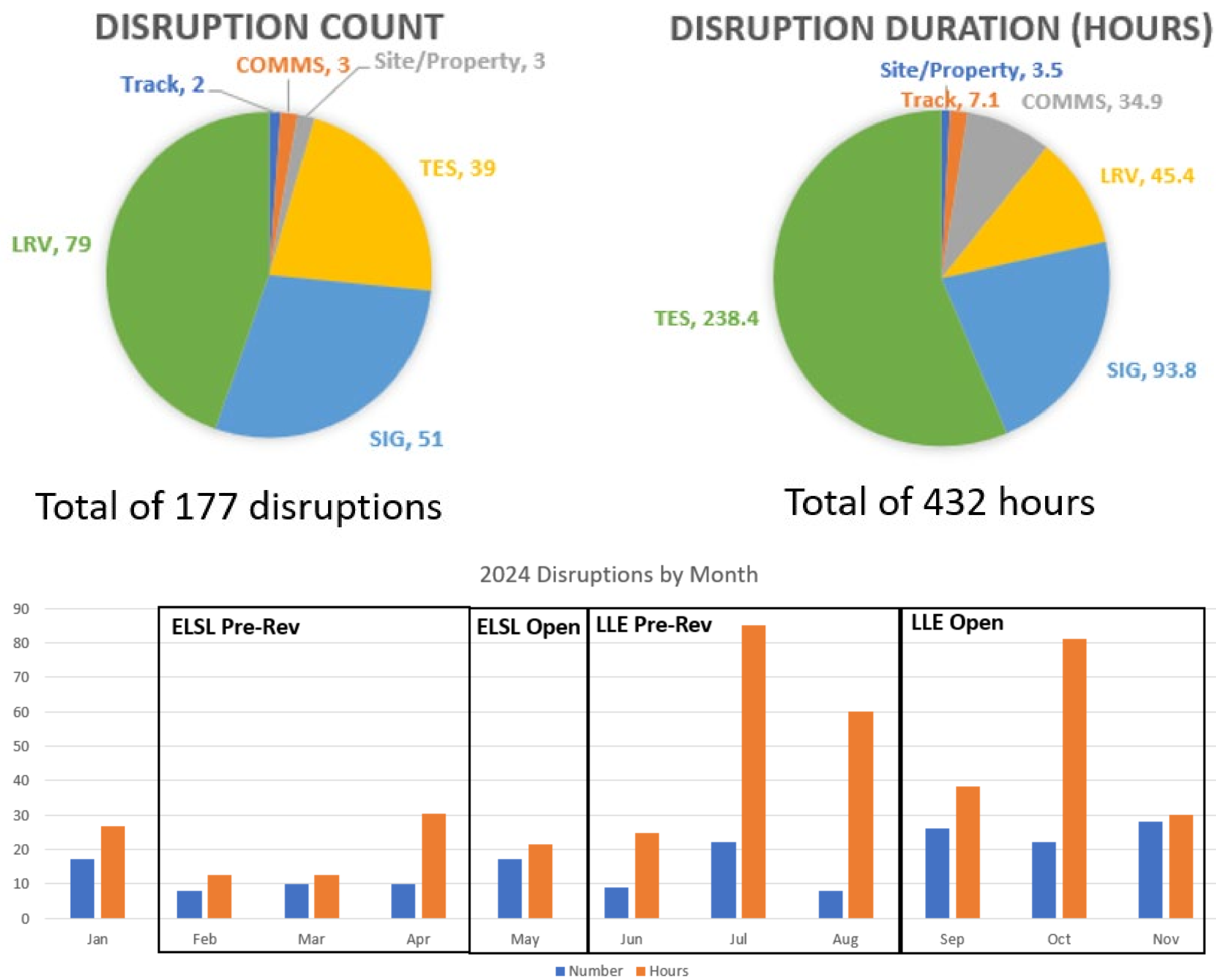
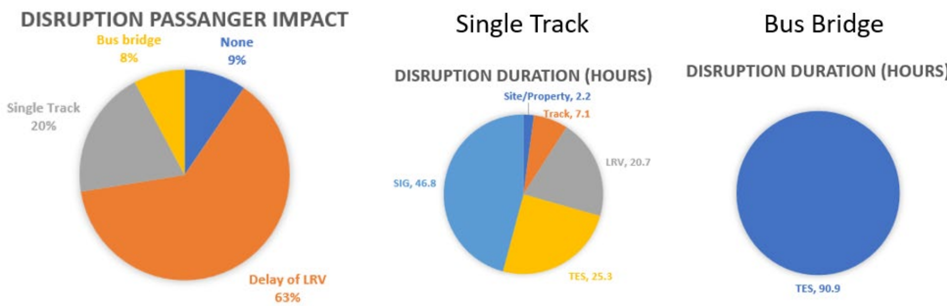


Figure 2.1: Service Disruptions in 2024 to November 27th

Finding 2.2: Traction Power disruptions take the longest to resolve and are the most disruptive to our passengers.

Reviewing disruption's impact and duration as shown in Figure 2.2, it can be seen that 72% (most) of disruptions have limited or no impact to revenue service, 28% cause the need to single track or bus bridge, which is highly disruptive to our passengers. Most, 70%, of Single-Track disruptions were caused by Signals or Traction Power, and all Bus Bridge disruptions were caused by Traction Power. In addition, Traction Power (TES) disruptions took an average 6.1 hours to resolve, compared to 1.8 for signal or 0.6 (35 min) for LRV disruptions. Taken together, these two sets of facts make Traction Power disruptions by far the most disruptive to our passengers.



Average Duration	Disruption Hours
TES	6.1
SIG	1.8
LRV	0.6
Other	5.6
Total	**2.4**

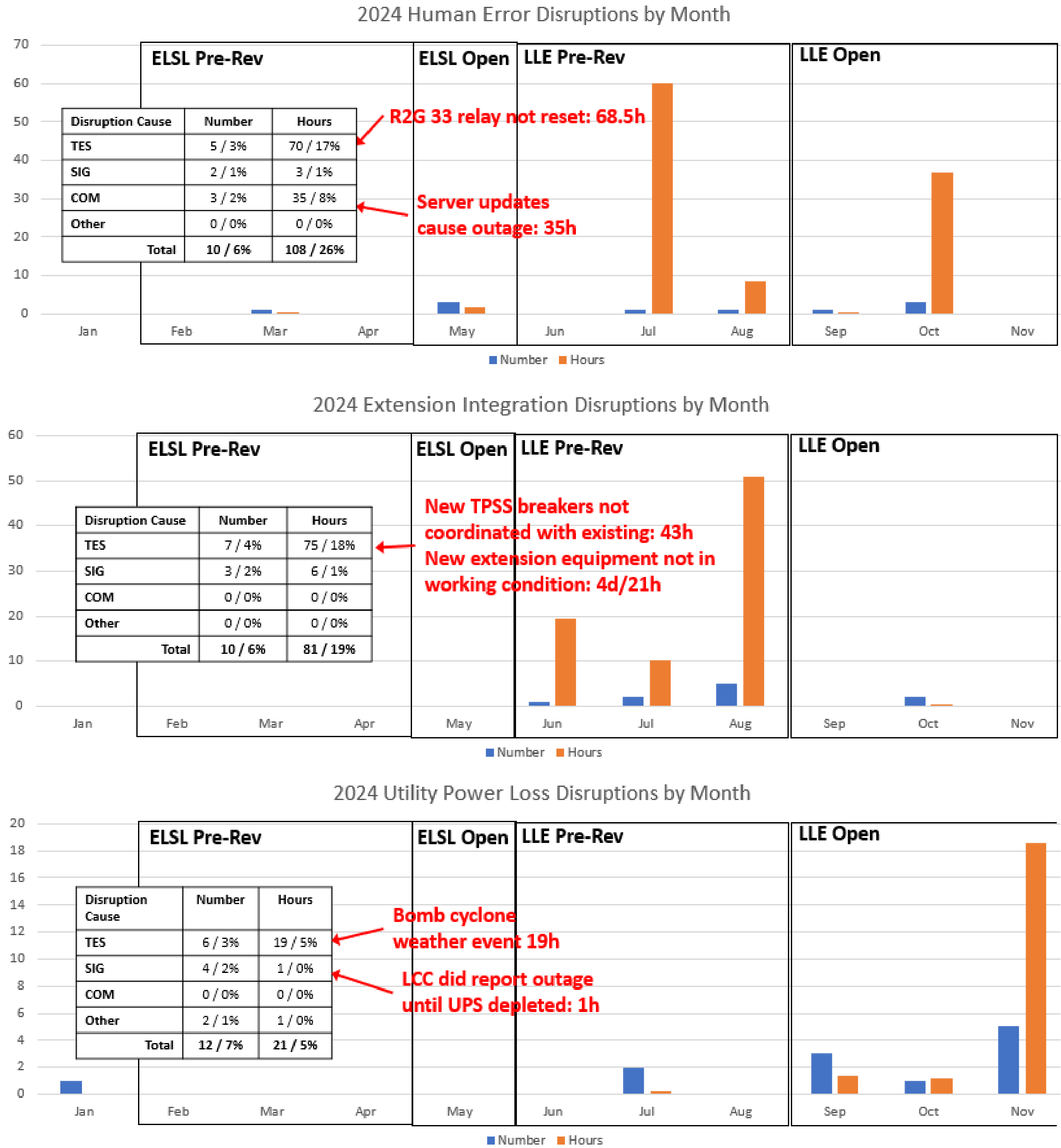
Figure 2.2: Service Disruptions Impact and Duration

Finding 2.3: Over half of disruption hours are due to causes other than equipment failure, including lack of familiarization training on new equipment, lack of change control on communication networks and servers, and Traction Power equipment not being properly coordinated or tested on new alignments.

Of the 177 disruptions in 2024, only 144 of them can be attributed to equipment failures that could have been prevented through improvements in maintenance or design. The other 33 are associated with root causes that as an agency we have less ability to control from re-occurring in the future. These include:

- 189 hours and 21 instances are associated with bringing new systems online through the capital program
    - 108 hours and 11 disruptions due to human error mostly associated with insufficient familiarization training of personal on new equipment associated with the new East Link Starter Line (ELSL) and Lynwood Link Extension (LLE), as well as lack of documentation and change control of communication network and server updates
    - 81 hours and 10 disruptions due to Expansion Work failures during the Pre-Revenue integration phase that impacted revenue service
- 21 hours and 12 disruptions due to Utility Power Loss mostly associated with an atypical winter storm

In total, the 33 disruptions accounted for 219 hours of total disruption duration, or 51% of the total. The more detailed breakdown of these disruptions can be seen in Figure 2.3.



Disruption Cause	Number	Hours
TES	5 / 3%	70 / 17%
SIG	2 / 1%	3 / 1%
COM	3 / 2%	35 / 8%
Other	0 / 0%	0 / 0%
Total	10 / 6%	108 / 26%

Disruption Cause	Number	Hours
TES	7 / 4%	75 / 18%
SIG	3 / 2%	6 / 1%
COM	0 / 0%	0 / 0%
Other	0 / 0%	0 / 0%
Total	10 / 6%	81 / 19%

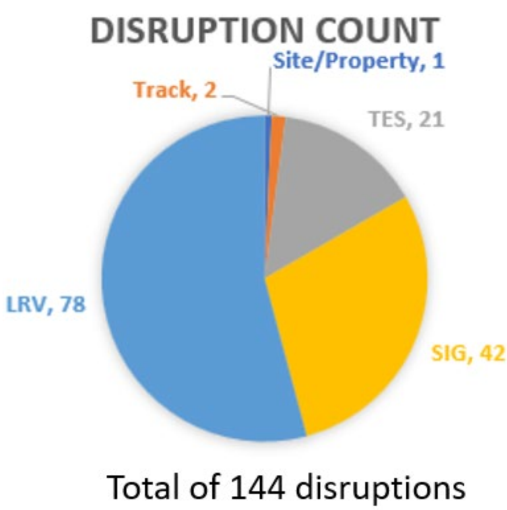
Disruption Cause	Number	Hours
TES	6 / 3%	19 / 5%
SIG	4 / 2%	1 / 0%
COM	0 / 0%	0 / 0%
Other	2 / 1%	1 / 0%
Total	12 / 7%	21 / 5%

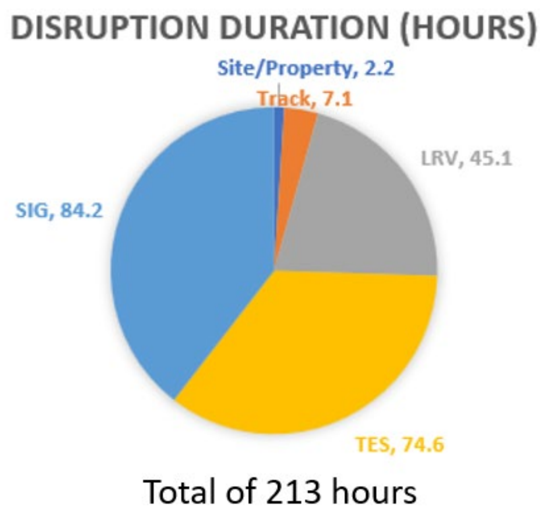
Figure 2.3: Non-Equipment Failure Service Disruptions

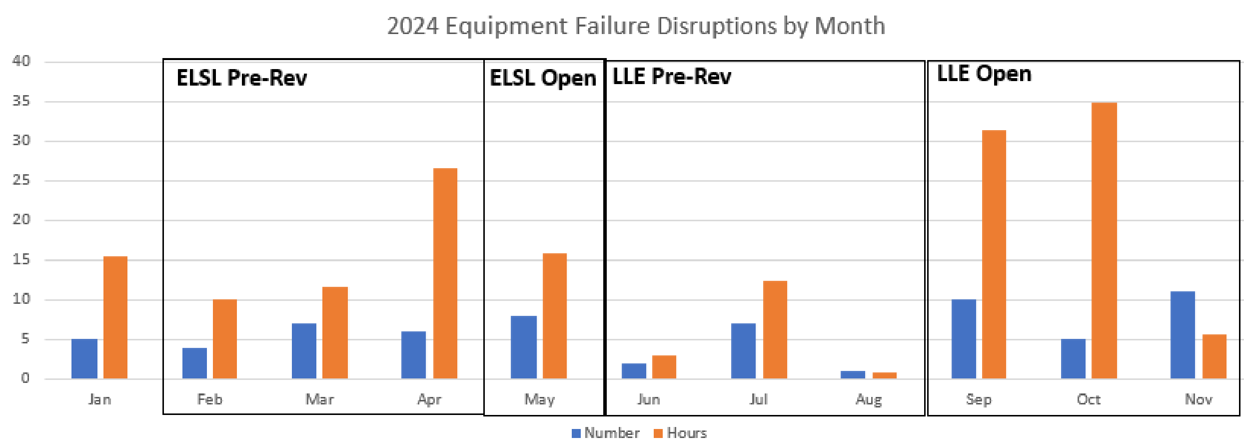
Finding 2.4: Line 2 is experiencing equipment failures at a rate 3x that of Line 1, likely due to poor installation and commissioning quality.

The other 144 disruptions attributed to equipment failures account for 213 hours or 49% of the total in 2024 to November 27th. LRV accounts for 78 disruptions with a total of 45 hours or 11% of the total disruption hours. All other equipment failures account for 66 disruptions, with a total of 168 hours or 40% of the total disruption hours, with once again Traction Power and Signals dominating the lead for cause of the disruption hours.

Figure 2.4 provides the breakdown of equipment failure disruptions by type, month, and location. Reviewing Figure 2.4 we find that East Link (Line 2) accounts for 29 of the 66 equipment failure disruptions. While this is only 44% of the total, East Link is both much shorter then Line 1 (7 miles vs 32 miles) and much newer (opened 6 months ago vs an average age of 9 years for Line 1). Taking these considerations into account, East Link's record of 4.1 equipment failure disruptions per mile of track in 2024 is dismal compared to Line 1's 1.5 equipment failure disruptions per mile of track in 2024. For a line with an average equipment service age of under a year, to be failing at a rate nearly 3 times that of Line 1, with an average equipment service age of 9 years, hints at underlining quality issues with the installation and commissioning of the equipment put into revenue service.

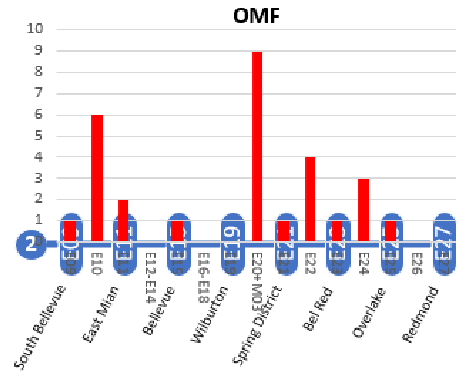






All Equipment Failure Disruptions w/o LRV

Disruption Cause	Number	Hours
TES	21 / 12%	75 / 18%
SIG	42 / 24%	84 / 20%
COM	0 / 0%	0 / 0%
Other	3 / 2%	9 / 2%
Total	66 / 37%	168 / 40%



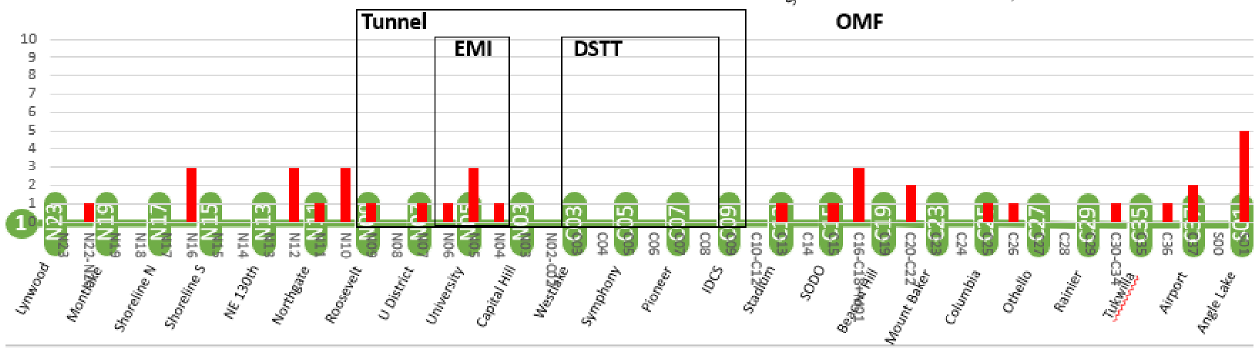
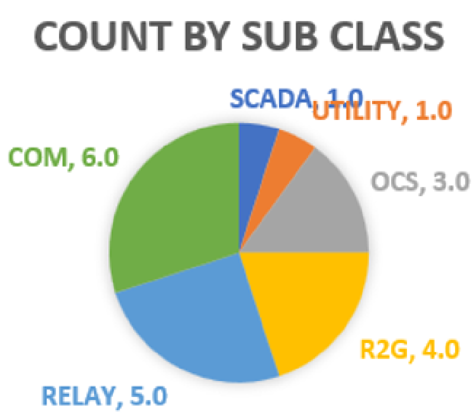


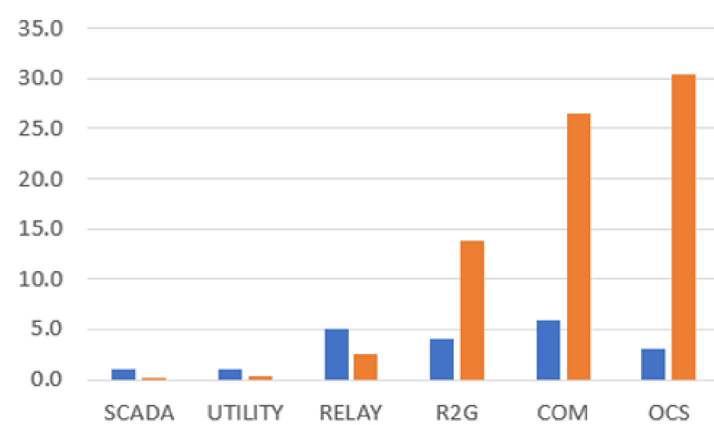
Figure 2.4: Equipment Failure Service Disruptions in 2024 to November 27th

Finding 2.5: Traction Power equipment failures resulting in service disruptions are primarily due to OCS condition in the tunnel Electro Magnetic Interference (EMI) zone, traction power substation (TPSS) network design stability issues on Line 2, lack of rail-to-ground (R2G) coordination in the EMI zone, and lack of TPSS breaker setting coordination on LLE.

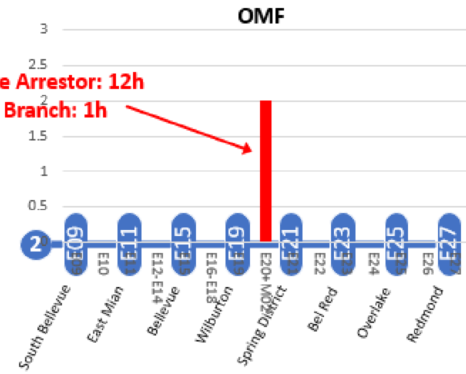
Figure 2.5 provides a summary of the subcategories of failures as well as their locations and major causes.

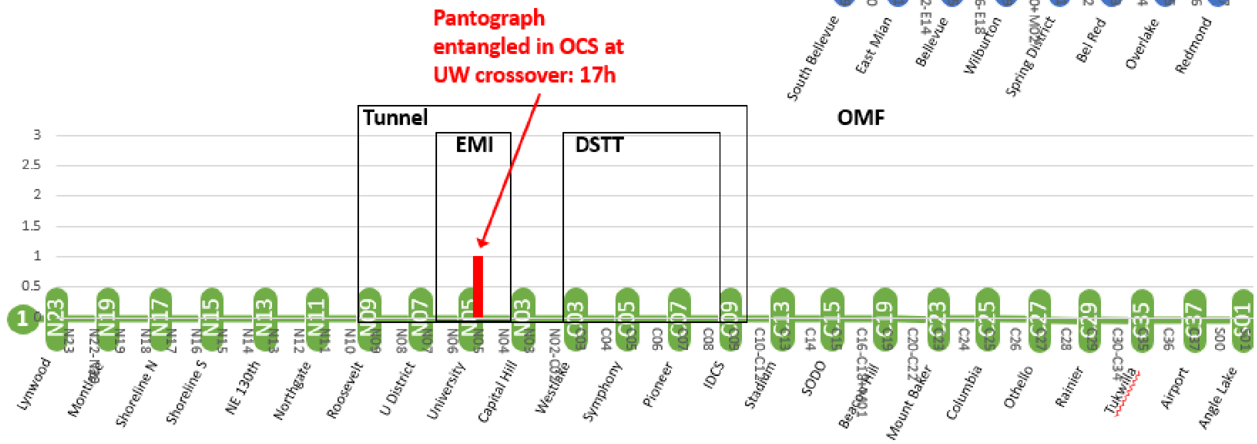
Traction Power: Equipment Failures



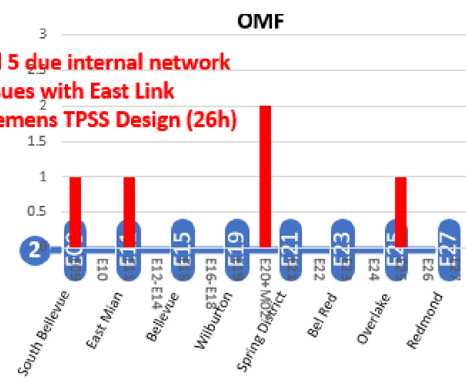


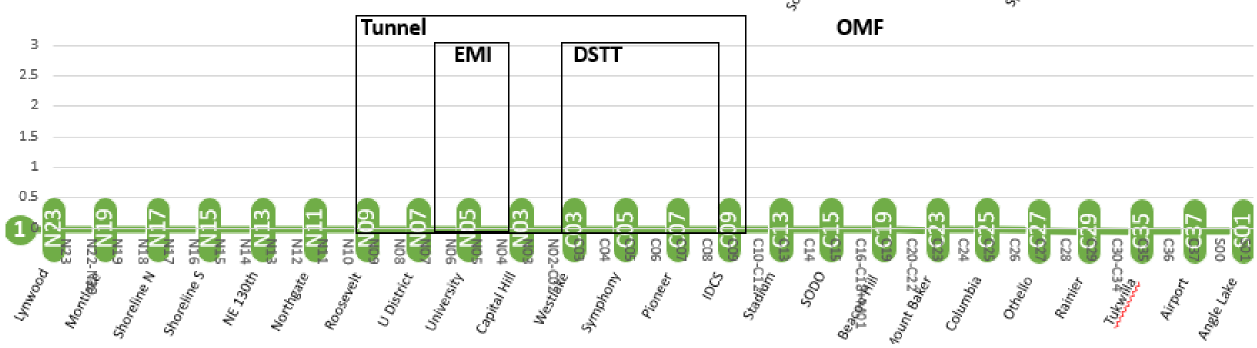
Traction Power: OCS





Traction Power: Communications





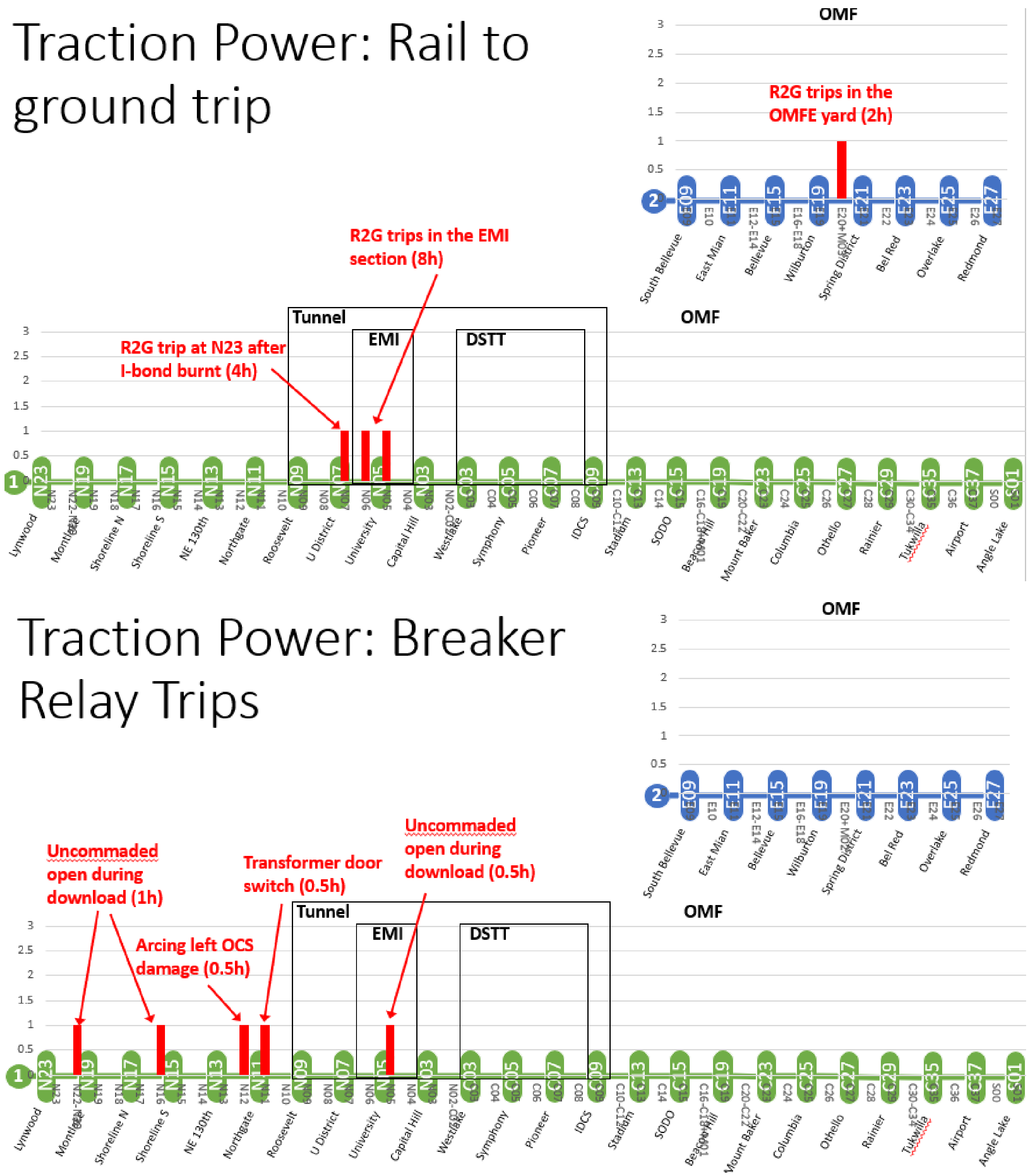
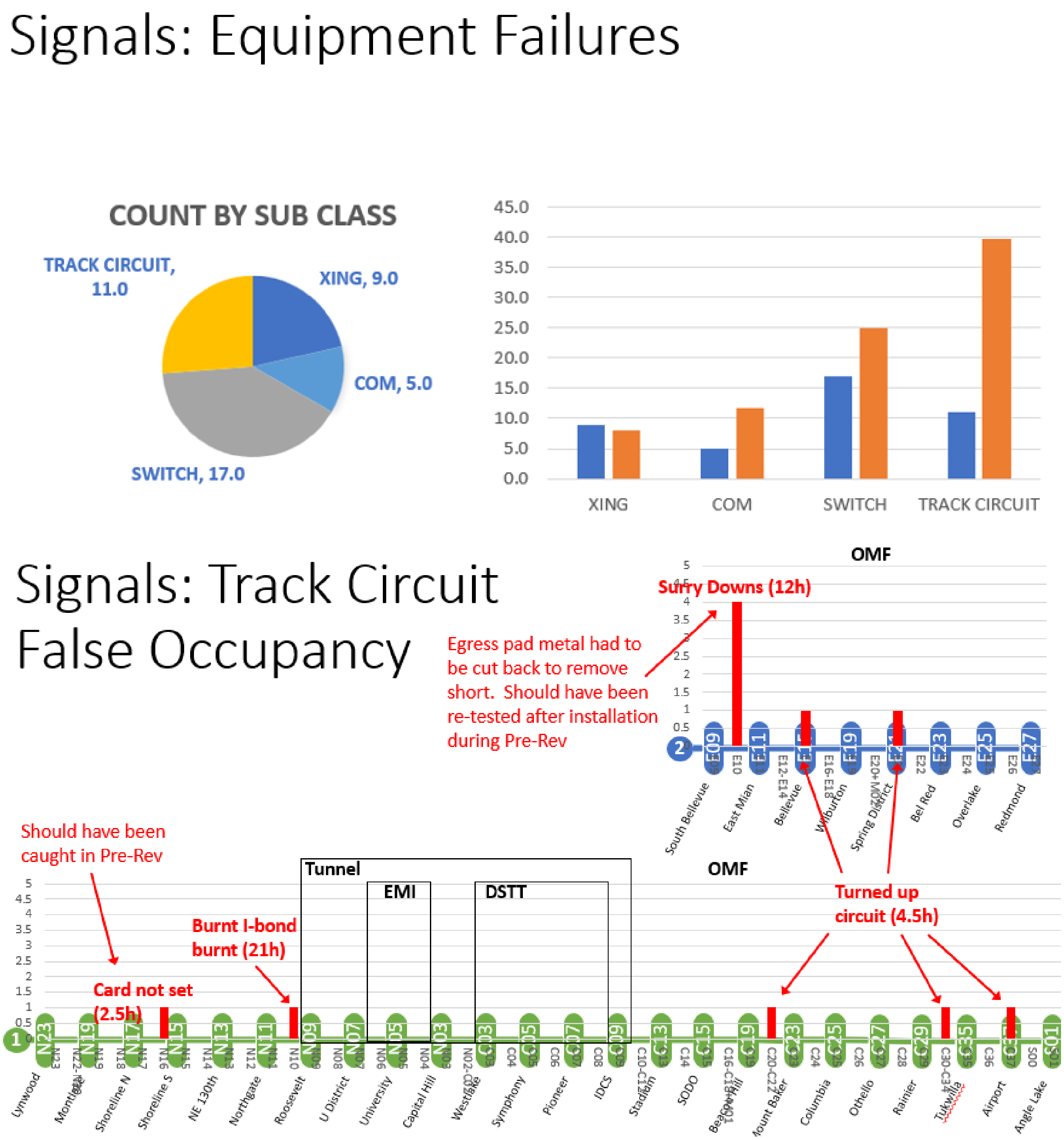


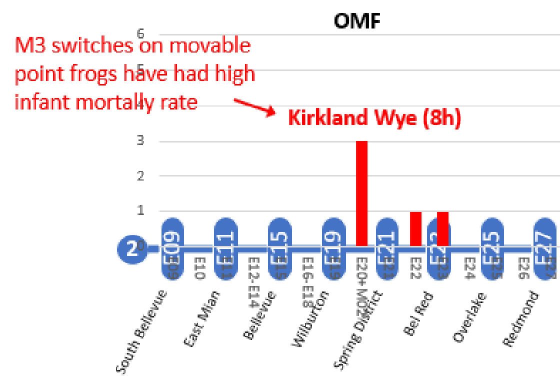
Figure 2.5: Subcategories of Traction Power equipment failures as well as their locations and major causes

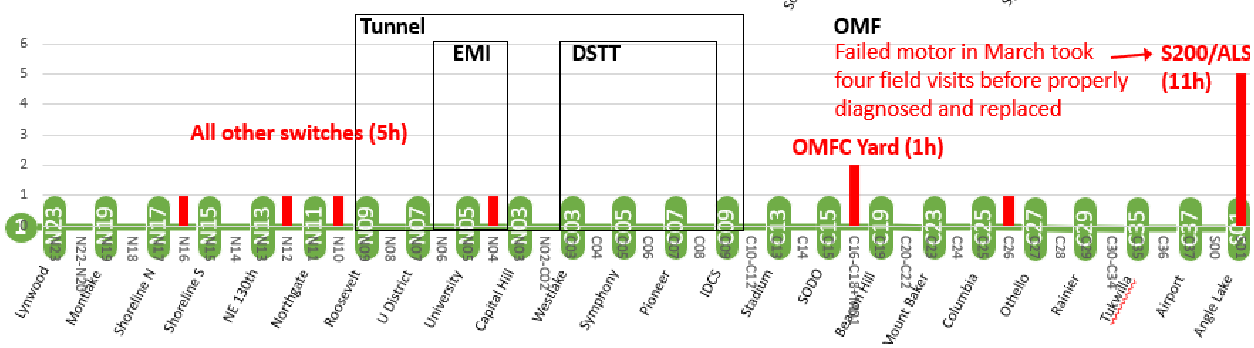
Finding 2.6: Signal equipment failures are primarily due to false occupancy due to rail to earth shorts on new extensions, switches out of correspondence at the S200 crossover and the Kirkland Way and 130th/132nd Crossing exit gates.

Figure 2.6 provides a summary of the subcategories of failures as well as their locations and major causes.

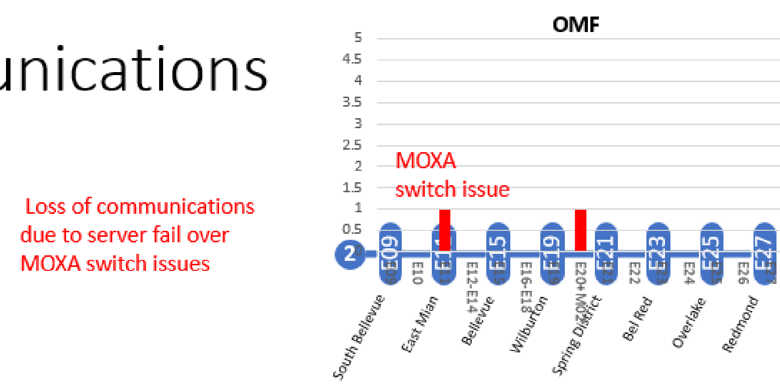


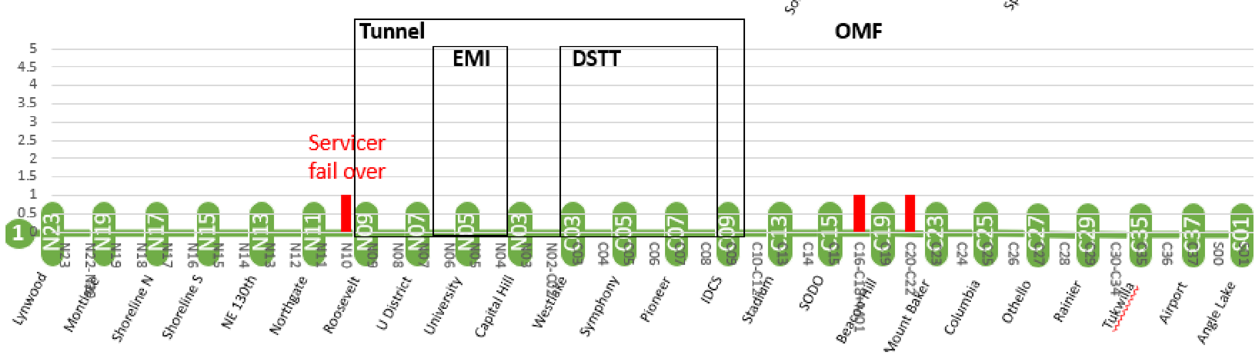
Signals: Switch out of correspondence





Signals: Communications





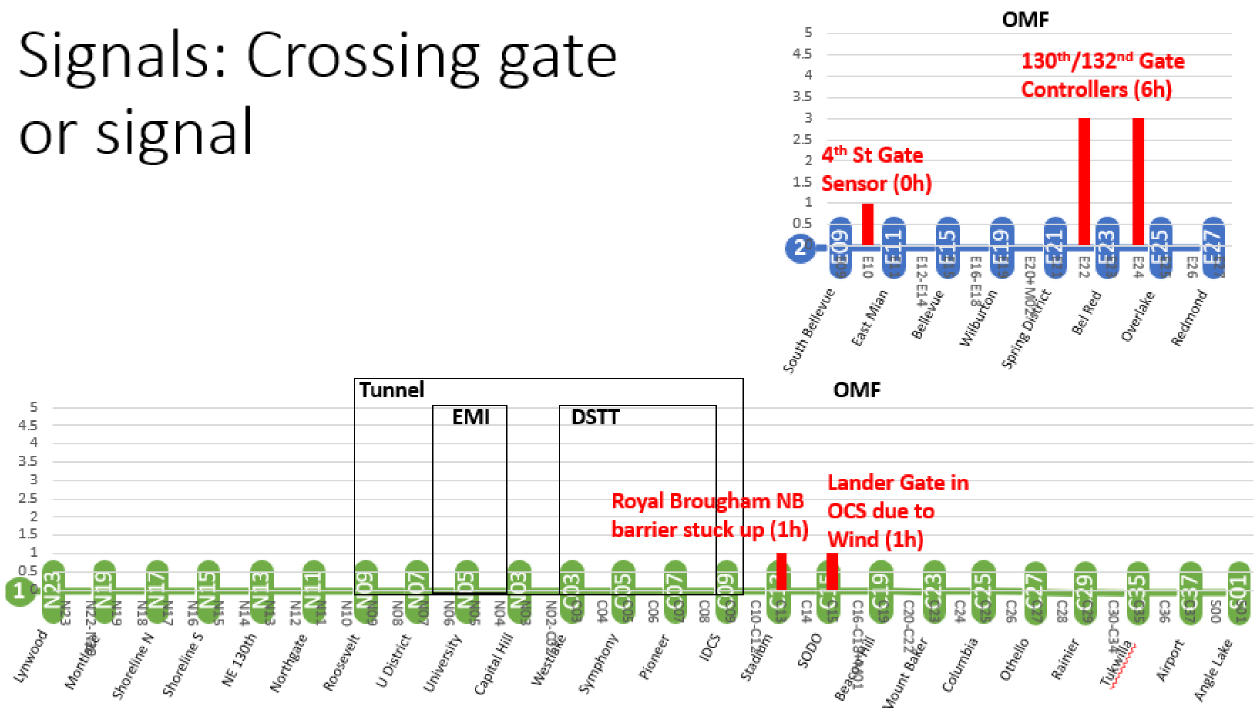


Figure 2.6: Subcategories of Signals equipment failures as well as their locations and major causes

Finding 2.7: All other equipment failures, excluding LRV failures, account for only 1% of total service disruption hours.

The full break down can be found in the list below, but the main takeaway is clear: to reduce future service disruptions, effort should be spent on training and maintaining of Traction Power and Signals and resolving early lifecycle LRV equipment issues, in that order.

Note: ##d = number of disruptions / ##h = total disruption hours / and ##% = percent of total disruption hours in 2024

1. **TES (39d/239h/56%)**
   a. **New Extension Integration (7d/75h)**
      i. New TPSS breakers not coordinated with existing di/dt settings (1d/43h)
      ii. New extension equipment not in working condition (4d/21h)
      iii. Signal I-bond cover shorted to ground (1d/10h)
      iv. Test train ran into dead OCS (1d/1h)
   b. **Human Error (6d/70h)**
      i. Lack of training that R2G 33 door reset causes R2G trips (2d/68.5h)
      ii. Lack of training that PLC reset and ETS COMs loss causes trips (4d/1.5h)
   c. **OCS Equipment Failure (3d/31h)**
      i. Pantograph entangled in OCS (1d/17h)
      ii. New extension surge arrester failure (1d/13h)
      iii. Tree branch grounding (1d/1h)
   d. **TPSS internal COMs (5d/26h)**

        i. Unstable TPSS Network equipment configuration (5d/26h)

    e. **Utility Power Loss (7d/20h)**
        i. Bomb cyclone weather event (5d/19h)
        ii. Local power outage (2d/1h)
    f. **Rail to Ground Trip (4d/14h)**
        i. R2G around EMI zone (3d/12h)
        ii. R2G in OMFE yard (1d/2h)
    g. **Breaker Relay settings (5d/3h)**
        i. Un commanded open in LLE (3d/2h)
        ii. Door switch on transformer door (1d/1h)
        iii. Un commanded open in EMI zone (1d/0h)
    h. **Other (2d/0h)**
        i. SCADA indication issues (2d/0h)

2. **SIG (51d/94h/22%)**
    a. **Human Error (2d/3h)**
        i. High rail vehicle trailed switch (2d/3h)
    b. **New Extension Integration (3d/6h)**
        i. New extension equipment not in working condition (2d/4h)
        ii. Did not pay utility bill for new Signal house (1d/2h)
    c. **Utility Power Loss (4d/1h)**
        i. LCC did report outage until UPS depleted (4d/1h)
    d. **Track Circuit False Occupancy (11d/40h)**
        i. Failed Impedance bond (1d/21h)
        ii. Egress pad in contact with rail at Surrey Downs (4d/12h)
        iii. Track circuit needed tuning (5d/5h)
        iv. Circuit card not set (1d/2h)
    e. **Switch out of correspondence (17d/25h)**
        i. At S200/ALS crossovers (5d/11h)
        ii. At an OMF yard entrance or exit (5d/9h)
        iii. At other non-mainline crossovers (7d/5h)
    f. **Signal communications loss (5d/12h)**
        i. Interlockings lost correspondence with SCADA (3d/11h)
        ii. Unable to make call in/out of OMFC yard via TWC (2d/1h)
    g. **Crossings (11d/9h)**
        i. 130th/132nd Crossing exit gates (6d/7h)
        ii. DSTT tunnel barrier stuck (1d/1h)
        iii. Bel-Red traffic controller integration (4d/1h)

3. **LRV (79d/45h/11%)**
    a. Unknown fault (25d/11h)
    b. Break fault (24d/9h)
    c. Propulsion fault (8d/8h)
    d. Pantograph failure (5d/6h)
    e. Door fault (12d/5h)
    f. Communication fault (3d/3h)
    g. Traffic accident (2d/3h)

4. **COM (3d/35h/8%)**
    a. Human error (3d/35h)
5. **Other (5d/10h/3%)**
    a. Rail break (2d/7h)
    b. Tree on tracks (1d/2h)
    c. IDS utility power loss (2d/1h)

Recommendation 2.1: Standardize the tracking, response, and resolution of service disruptions (432h).

At the start of this effort, it was surprising that no single definition of what constituted a service disruption existed, and while several groups within the agency were tracking revenue service metrics, field failures, and disruption responses, no single database existed that captured the full picture of when a disruption occurred, how it affected passengers, what caused it, how and when it was resolved, and whether any follow on work was needed to prevent it from occurring again. Instead separate databases consisting of **alertsense.com,** which our Link Control Center (LCC) used to communicate when a disruption occurred and when it was resolved, **Everbridge** which was used by our safety to manage the safety response and passenger care plan (often, but not always associated with a service disruption), and finally **Enterprise Assets Management Systems (EAMS),** which holds the Repair request and field crew notes associated with the investigation and repair of the underlying issue causing the disruptions. The document **2024-12-05 Thoughts on the management of service disruptions.docx,** provides recommendations on the key roles and their associated duties in the identification, communication, and resolution of a major service disruption. These recommendations are aimed at improving resolution time by streamlining the ways information is gathered from the field crews and centralizing the direction of those crews in the identification and resolution of the issue causing the disruption. Key to achieving this is the standardization of when and what is posted by LCC on **alertsense.com** when an incident commend is stood up by LCC via **Everbridge,** the requirement that all disruption investigations and repairs be done under an **EAMS Work Order (WO)** and that a single database compile the disruption data from these three sources for trending an analysis such as was conducted under this effort.

Recommendation 2.2: Tie training to asset types to ensure crews are trained on new equipment, and system operational concepts, before pre-revenue (68h)

Our current King County Metro (KCM) crew training assumes consistency of equipment along the alignment, relies heavily on on-the-job training, and provides no assurance that employees are trained on the functions, troubleshooting, and repair of equipment prior to being fielded to do the work. A restructuring of our training program to tie training to asset types could ensure that when new equipment is added in the field, the crews responsible for the maintenance and operations of that equipment would receive training on it prior to being asked to service it in the field. This would have prevented 68 hours of service disruption associated with a new Rail to Ground device on LLE not having its 33 device reset properly, as well as many hours of TPSS troubleshooting, which starts with the download and analyses of alarms from the breakers and PLCs, something that KCM crews should be trained for but were repeatedly found to be unable to perform.

Recommendation 2.3: Require more complete commissioning and a system validation period on new extensions prior to placing them into revenue service (49h)

It is clear from Line 2's nearly 3 times field equipment failure rate, as well as specific failures such as the metal walkways shorting out the track at Surrey Downs on ELSL and the unset card at north Shoreline on LLE, that our extension contractors are not doing a thorough enough job of commissioning our traction power and signals equipment prior to turning it over to use for revenue service. To combat this, the Asset Transition Office (ATO) is in the process of developing stricter commissioning requirements as well as adding a validation period to all new extensions prior to handover to the agency-controlled, pre-revenue service period. It is estimated that if these programs had been instituted in ELSL and LLE, nearly 49 hours of service disruptions could have been avoided.

Recommendation 2.4: Require new extensions to coordinate Traction Power equipment settings with the exiting alignment (43h)

Every new extension is required to provide a Traction Power protection coordination study to ensure both adequate protection of the Traction Power equipment and avoidance of nuisance or cascading outages. However, experience on LLE which introduced a new TPSS breaker manufacturer showed that by not considering the protection setting on the existing alignment which is also part of the same electrical distribution systems, the coordination study of the new equipment can fail to resolve nuisance and cascading outages. To this end, Engineering is developing a Notice to Designers (NTD) to require that all new Traction Power protection coordination studies include the exiting alignment protection devices and studies. It is estimated that if NTD had been implemented on LLE, nearly 43 hours of service disruptions could have been avoided.

Recommendation 2.5: Map our communication networks and servers and place them under formalized change control (35h)

To date, in 2024 all service disruptions due to communication network outages are likely due to simple human error introduced when updating or troubleshooting the system. These errors caused 35h of service disruption without including the current multiweek Train Control Network intermittent outage that is currently ongoing at the time of this writing. While institutionally unacceptable, it is understandable that human errors are common in our communication networks, since to date no one has provided a consolidated map of our existing network paths and connected equipment. In addition, very little of the network configuration and equipment has been placed under change control. These facts have led to a culture of network engineers making undocumented field changes as they see fit, based on tribal knowledge of current configurations, in an effort to maintain or troubleshoot the system. This combination is a recipe for human errors to occur, as they have. To reduce these errors in the future, it is recommended that the current network be mapped by producing a Network Riser Diagram as defined in section 1201.4.3 of the Sound Transit Requirement Manual. Once this as-built riser diagram is complete, all subsequent changes to it should be subject to change control under the Change Review Board (CRB) process.

Recommendation 2.6: Require layer 3 networks and failover testing for TPSS communications (26h)

The TPSS network outages on Line 2, and the subsequent power outages they caused, were due to an unstable and poorly commissioned layer 2 network architecture provided by Siemens for that extension.

While the other extensions use a different TPSS network supplier and are expected to not suffer from the same instabilities, engineering is not leaving it to chance and has issued an NTD to require layer 3 TPSS network architecture and failover testing. If this NTD had been implemented on ELSL, it is expected that 26 hours of service disruptions could have been avoided.

Recommendation 2.7: Institute more hands-on field troubleshooting training for Signals crews (23h)

Two major causes of signal-related service disruptions to our system this year were due to a track circuit being shorted to ground by a metal walkway at Surrey Downs and a failed switch motor on S200 crossover. The metal walkway at Surrey Downs took four troubleshooting field visits between July and October to finally find and resolve the issue, while the failed switch motor on S200 crossover took five visits over two days in March. In both cases the failure mode and final repair were fairly straightforward and should have been resolved in the first one or two field visits. The fact that it took a total of 9 field visits and 23 hours of service disruption to resolve these two failures speaks to insufficient troubleshooting and repair skills on our KCM signals crews. Admittedly, many of the signals personnel were new hires this year in an effort to staff up for ELSL and LLE openings, but nevertheless it seems likely that an increase in hands-on field troubleshooting training for signal crew personal would likely reduce the number of visits and hours needed to resolve straightforward equipment failure disruptions.

3.0 Maintenance Record Review

Goal: Review maintenance records for OCS, Signals, and Rail, for adherence to industry best practices and documenting and repair of issues found.

Deliverable: A detailed prioritized list of issues found (and repaired)

Status: COMPLETE

The following is the list of documents delivered.

2024-11-21 Work Orders 2024.xlsx: A report from Enterprise Asset Management System (EAMS) administration team breaking down 2024 labor hours by Work Order (WO) type, and will as age of open WOs.

2024-11-27 Power WO Labor Report_Nov2023_Nov2024.xlsx: A report from KCM providing a detailed breakdown of labor hours for the Traction Power crews.

2024-12-13 Labor Report.pptx: A summary report of labor hour analysis and findings.

PM Masters for TRACK, SIGNALS, and TRACTION POWER circa 2017: These preventative maintenance (PM) masters are from 2017 and clearly out of date, as they do not reflect new alignments added since that date but are the most current masters available. Word-of-mouth interviews indicate that since 2017, many of the weekly and monthly PMs have been eliminated to reduce the workload as the alignment has grown.

Checklists for TRACK, SIGNALS, and TRACTION POWER, Monthly, Quarterly, and Annual PMs (14 total): Current PM Checklist from EAMs representing all the information that is given to crews about how to conduct a Preventative Maintenance service job.

2024-11-05 Eng Notes Known Issues.docx: Note from interviews with the engineering managers of Track, Signals, and Traction Power regarding known issues or deficiencies on the operating alignment that Engineering is aware of. Most, but not all, of these known issues have current Service Projects or Engineering Service Requests (ESR) under which they are intended to be resolved.

Open Repair REPORTS for SIGNALS and POWER on Central Link, North Link, and East Link (6 total): Direct queries of EAMS for Repair WOs that were opened in the past two years and are currently still open.

Line 1 and Line 2 Track Charts marked up with Open Repairs and Engineering Known issues (3 total): Graphical track charts marked up with all known issues from Engineering, Open EAMS Repair WO, as well as OCS hard spots found with the Telemattica system, and poor Rail to Ground isolation locations noted in Corrpro reports.

2024-12-16 Maintenance Deficiencies.pptx: A summary presentation of found maintenance deficiencies as well as a single track headway analysis of our alignment showing where additional maintenance could be conducted under daytime or nighttime single tracking.

Finding 3.1: Of all the trades King County Traction Power has by far the largest maintenance debt.

Traction Power has a backlog of open Preventive Maintenance (PM) and Repair work orders for the trade, which is nearly twice that of any other trade as shown in Figure 3.1. If the open PM, Repair, and Support work orders are multiplied by the average time to compete each and then that total divided by the average number of man-hours available in the trade per month, we can calculate the backlog in month of manhours. For Power this works out to be 3.2 man-hour months, compared to 0.8 manhour months for Track. Both Traction Power and Track have concerningly slow rate of closing Repair orders with the median Traction Power Repair order staying open for 3 to 6 months and the median Track Repair order staying open for 1 to 2 years;, while both of these numbers are concerning, Traction Power slow repair rate combined with their large maintenance debt makes it clear the trade is not being staffed and managed in a way compatible with maintaining a good state of repair.

Central Link - Open Work Orders - As Of 11/21/24

	PM			Repair			Contractor Support				
	Open Work Order Count	Avarage Days Open	% of Total Work Orders	Work Order Count	Avarage Days Open	% of Total Work Orders	Work Order Count	Avarage Days Open	% of Total Work Orders	Total Work Orders	Total Labor Hours
POWER	106	53	27%	214	166	55%	69	110	18%	389	328
SCADA	19	28	18%	35	35	32%	54	18	50%	108	81
SIGNAL	42	30	44%	52	53	54%	2	76	2%	96	159
TRACK	25	21	21%	93	177	78%	1	491	1%	119	689

Central Link - Open Work Orders - Days Open Breakdown - As Of 11/21/24

		< 7 Days	14 Days	30 Days	3 Months	6 Months	6-12 Months	1-2 Years	2 year +	Total
POWER	PM		9	25	31	23	17	1		106
	Repair	15	4	23	39	39	12	22	60	214
	Contractor Support	5	4	10	23	11	10	3	3	69
SCADA	PM	19								19
	Repair	4	3	3	9	11	5			35
	Contractor Support	19	4	6	19	6				54
SIGNAL	PM	28	2	11	1					42
	Repair	12		1	11	13	7	5	3	52
	Contractor Support				1		1			2
TRACK	PM	13	8	2	2					25
	Repair	6	2	7	9	3	11	13	42	93
	Contractor Support								1	1
	Total	121	36	88	145	106	63	44	109	

Figure 3.1: 2024 Open Work Orders by type and trade

Finding 3.2: Traction Power spends too much time on PMs and Other work and too little time on Repairs.

As can be seen in figure 3.2, Traction Power spends 53% of their time on PMs compared to 11% on repair. This split seems lopsided compared to Signal's 23%/74% split or Track's 31%/45% split. Also, Power's average PM consumes 18.6 man-hours, nearly twice Track's or 8 times Signal's. This seems to indicate Traction is spending too much time on PMs instead of repairs. Likely this imbalance is due to either being severely under staffed or highly inefficient in conducting their PM tasks. In addition, the breakdown of the labor hours for Power over the past 12 months (in figure 3.3) shows that 31% of hours were spent on other tasks not associated with PM or Repair. In addition, 17% of the total hours were Overtime for Power in the past 12 months. This data seem to indicate that the workforce may be both distracted by a myriad of demands and burned out by the constant demand of overtime. Once again, it is clear the trade is not being staffed and managed in a way compatible with maintaining a good state of repair

	Ave Hours Per PM	Ave Hours Per Repair	Ave Hours Per Support
POWER	18.6	10.5	28.3
SCADA	3.8	5.7	42.1
SIGNAL	2.5	34.7	122.8
TRACK	10.4	23.5	307.1

Central Link - Closed Work Orders - 1/1/24-11/21/24

	PM			Repair			Contractor Support			Total Work Orders	Total Labor Hours
	Work Order Count	Labor Hours	% of Total Work Hours	Work Order Count	Labor Hours	% of Total Work Hours	Work Order Count	Labor Hours	% of Total Work Hours		
POWER	609	11,329	53%	230	2,423	11%	268	7,594	36%	1,107	21,346
SCADA	432	1,622	8%	523	2,969	14%	402	16,936	79%	1,357	21,528
SIGNAL	1,303	3,215	23%	302	10,468	74%	4	491	3%	1,609	14,174
TRACK	1,103	11,502	31%	708	16,640	45%	29	8,907	24%	1,840	37,049

Figure 3.2: 2024 Closed Work Orders by type and trade

PM				Repair				Others			
Direct		Indirect		Direct		Indirect		Direct		Indirect	
Regular	Overtime	Regular	Overtime	Regular	Overtime	Regular	Overtime	Regular	Overtime	Regular	Overtime
14,174	2,920	16	9	10,862	2,429	22	22	519	691	11,399	1,247
17,094		25		13,291		44		1,210		12,646	
17,118				13,334				13,856			
44,309											

Figure 3.3: A breakdown of Traction Power labor hours for the past 12 months

Finding 3.3: PM Checklists for Traction Power, Signals, and Track lack many basic maintenance tasks, as well as entire classes of equipment.

Only a cursory review of the PM checklist currently provided in EAMS to instruct KCM crews clearly shows that they are insufficient to ensure a good state of repair. Without an exhaustive review, let the following examples provide evidence of the current checklist's deficiencies.

1) TP OCS Quarterly and Annual PM Checklists
    a) Lacks any checks for height or stager of OCS.
    b) Lacks any check for condition of Section Insulators (SI).
    c) Includes measurement of OCS wear, but fails to state where measurements should be taken, or instruction to record the wear value, making any kind of predictive maintenance program imposable.
    d) Includes inspection of OCS Balance Weight Assemblies but provides no criteria to determine whether the Weight Assemblies have sufficient free space above and below at the current temperature to guide when adjustment is needed to prevent an OCS loss of tension.
    e) Includes instruction to inspect the HVAC system, despite OCS not having any.

2) TP TPSS Monthly, Quarterly, and Annual PM Checklists
    a) Provides no step to download, review and address alarms noted on the Local Control Management System (LCMS) other than for the 64 ground relay.
    b) Includes a step to download rail-to-ground System (R2G) software and swap cards but nothing about reviewing alarms or testing operation of the system.
3) SIGNALS Interlock Monthly and Quarterly PM Checklists
    a) Includes static checks only and lacks a check to verify operation a throwing the switch.
    b) Lacks any kind of measurement of motor current or point adjustment, making any kind of predictive maintenance program impossible.
4) SIGNALS Signal House Monthly, Quarterly, and Annual PM Checklists
    a) Includes Quarterly track circuit walks but fails to check for debris or equipment that could short track to ground.
    b) Includes track circuit testing but lacks any kind of measurement of current or voltage making any kind of predictive maintenance program impossible.

Finding 3.4: Traction Power records show OCS damage in the EMI zone, stray current in the DSTT, OCS hard spots near Tukwila, as well as a concerning number of non-functional breakers or incorrect SCADA indication.

By far, Traction power has the largest number of known maintenance deficiencies; many of these are grouped, such as OCS damage in the EMI zone, stray current in the DSTT, and OCS hard spots near Tukwila as shown in figure 3.4. Others are scattered throughout the alignment, such as 16 open repair orders for non-functional breakers or 12 open repair orders for incorrect SCADA indication. While the result of the first maintenance deficiencies will likely be failed equipment directly leading to a service disruption, the result of the second group is an increase of service disruption length due to system inflexibility and poor field information.

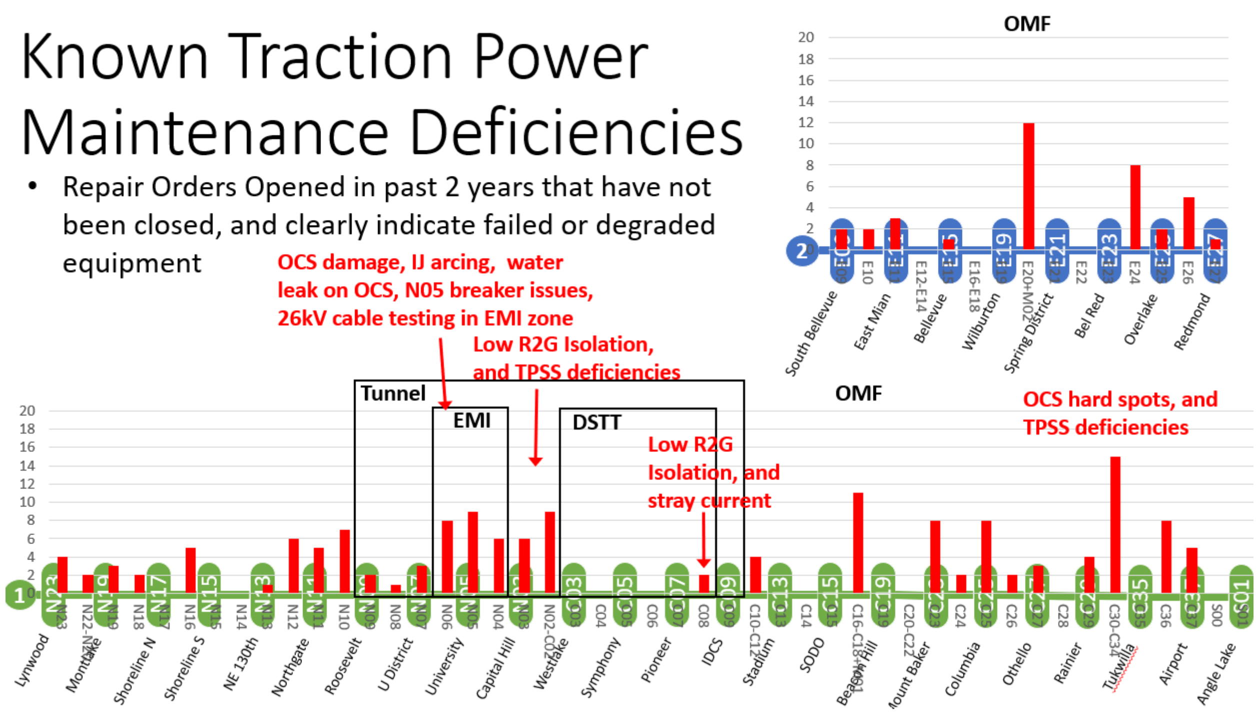


Figure 3.4: Known Traction Power Maintenance Deficiencies

Finding 3.5: Signal records show a high number of switch adjustment issues in OMFE and the Kirkland Way and traffic controller interface issues in the Bel-Red street-running territory.

The Signal System has a far lower level of known maintenance deficiencies then Traction Power. Nevertheless, review of the records shows a generally high number of open switch adjustment Repair work orders, most noting shavings on the lock rod, and a large number of them located at OMFE and the Kirkland Way territory, as shown in Figure 3.5. As can also be seen in Figure 3.5, there are a number of traffic controller interface issues in the Bel-Red street-running territory.

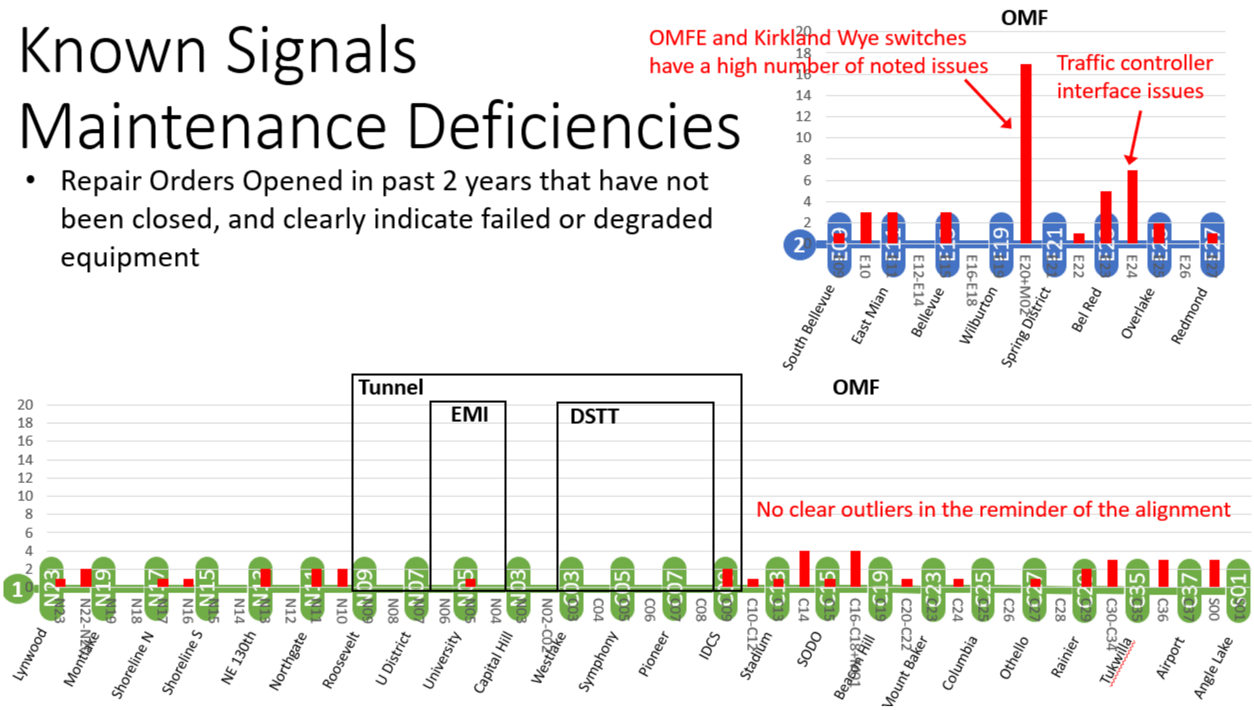


Figure 3.5: Known Signals Maintenance Deficiencies

Recommendation 3.1: Reprioritize Traction Power crew work to achieve a 30% PM, 50% Repair, and 20% Other split of labor hours (20%*239h=48h)

The maintenance debt currently accrued by the Traction Power crews cannot be remedied without reprioritizing repairs above both preventative maintenance and other activities, like contractor support. The traction power team must be held responsible for every open repair WO. The leadership shall assign a priority level and manage the work using a schedule and contractor support where necessary. Recovery may require deferring other work, such as contractor support or Employee In Charge (EIC) support of other trades, as well as monthly PMs. There is a goal of reducing the maintenance debt to under two weeks by the end of 2025 by targeting a labor hour split of 30% PM, 50% Repair, and 20% Other. For accountability, these goals shall be visualized by monthly EAMS reports.

Recommendation 3.2: Increase available repair hours by removing unnecessary work restrictions (20%*239h=48h)

Current work restriction allowing only KCM personnel to provide (EIC) duties, only KCM Power crews providing lockout/tagout protection for our Traction Power Crews on working on live equipment, performing work within the right-of-way during revenue service hours, requiring train on adjacent track to slow when single tracking around a work zone, and other restrictions limiting many activities to only our 4-hour, non-revenue service period should be reviewed for potential removal, as their nominal impact on employee safety is likely far outweighed by their detrimental impact on state of good repair. In addition, whenever possible, work conducted in our non-revenue service period should be evaluated for the use of a late-night, single-track action to extend the available work window.

Recommendation 3.3: Replace the current Traction Power PM checklists with an asset structured standard maintenance program (20%*94h=19h)

Engineering has currently released a TPSS Maintenance Standard and is in the process of releasing an OCS Maintenance Standard. The standards address many of the current checklist's noted deficiencies, and their implementation could substantially reduce service disruptions due to equipment failures. It is recommended that the implementation of this standard in EAMS be prioritized, with a target to complete it by the end of the first quarter of 2025.

Recommendation 3.4: Replace the current Signals PM checklists with an asset structured standard maintenance program (20%*84h=17h)

It is recommended that engineering prioritize the release of a Signals Maintenance Standard. The standards could address many of the current checklist's noted deficiencies, and its implementation could substantially reduce service disruptions due to equipment failures. It is recommended that the implementation of this standard in EAMS be prioritized with a target to complete it by the end of the fourth quarter of 2025.

Recommendation 3.5: Complete 16 open Repairs for non-functional breakers and switches to avoid disruptions due to human error (20%*70h=14h)

Due to the likelihood of resulting in extended disruptions due to human error, it is recommended that the following Repair work orders in EAMs be prioritized.

CLKPWR-2023-701,727,818,1151;

CLKPWR-2024-297,458,796,988,1004;

ELKPWR-2024-70,637;

NLKPWR-2024-232,361,424,481,528;

Recommendation 3.6: Complete 12 open Repairs for incorrect SCADA indication to avoid disruptions due to human error (20%*70h=14h)

Due to the likelihood of resulting in extended disruptions due to human error, it is recommended that the following Repair work orders in EAMs be prioritized.

CLKPWR-2023-849,917,1343;

CLKPWR-2024-277,459,1005,1137;

ELKPWR-2024-28,349;

NLKPWR-2024-183,272,298;

Recommendation 3.7: Complete 16 open Repairs for track switch adjustment to avoid disruptions due to out of correspondence switches (0.5*25h=13h)

Due to the likelihood of resulting in disruptions, it is recommended that the following Repair work orders in EAMs be prioritized.

CLKSIG-2023-1118,1120,1798,1960;

CLKSIG-2024-1042,1208,1373,1517;

ELKSIG-2024-42,43,749,1304,1305,1310,1312;

NLKSIG-2024-542

Recommendation 3.8: Complete 14 open Repairs for OCS equipment to avoid disruptions due to Pantograph entangled (50%*17h=9h)

Due to the likelihood of resulting in disruptions, it is recommended that the following Repair work orders in EAMs be prioritized.

CLKPWR-2023-160,161,182,816,1252,1287,1313;

CLKPWR-2024-16,208,746,955,1029,1194;

ELKPWR-2024-131

4.0 Independent Condition Assessments

Goal: ST will bring in an independent team of installer and maintenance experts to perform a detailed wayside inspection of the state of good repair of TPSS R2G, OCS, Signals, LRV Pantographs, and Rail.

Deliverable: A detailed prioritized list of issues found

Status: IN PROGRESS

The following is the list of documents delivered.

2022-01-31 Corrpro - Sound Transit - Stray Current Evaluation Report DSTT.pdf: This report is from our stray current monitoring consultant Corrpro based on measurements of track-to-earth isolation and stray current they conducted in the DSTT.

2024-11-12 EMI IJ Inspection.pptx: Pictures from the KCM inspection of all four EMI zone isolation Insulated Joints (IJs) in November 2024.

2024-11-22 Telemattica impact numbers for past three months on Line 1.pdf: A track chart marked up of Line 1 with all the OCS hard spots recorded by our Telemattica system over the past three months.

Note: Neither of our two Telemattica systems are deployed on Line 2, so no similar mark-up could be done for that Line.

2024-12-06 LRV Pantograph Wear Inspection.pptx: Photos of pantograph horn wear patterns collected during 10,000 mile PM inspections for LRV servicing Line 1 and Line 2.

2024-12-18 Scope of Work - Link Light Rail Thermal Surveys.pdf: The survey scope of work for thermal inspecting of our tracks. Note that this work was awarded to Nadar Aerial Imaging in December and they are expected to start this effort in January with completion by mid-March.

Three Inspection OCS Quotes: OCS inspection quotes form Telemattica, RailPod, and SelectraVision.

The following are the working notes regarding the ongoing efforts for Condition Assessment of the Traction Power (TES) systems that are not yet complete.

1. **TES (39d/239h/56%)**
    a. **OCS Equipment Failure (3d/31h)**
        i. Video of OCS with Live Wire train in tunnel – MK, DONE (Need report)
        ii. Move one Telemattica LRV back to East Link – TBD
        iii. Review East Link Telemattica data for hard spots – MK, TBD
        iv. MEC Hi-Rail Pantograph sweep in Tunnels and ELSL - MK, ETC
        v. Survey height, stagger, and wear of all OCS with Rail Pod system – Jeff, TBD
    b. **Rail to Ground Trip (4d/14h)**
        i. Inspection report from DSTT track cleaning – Jeff, TBD
        ii. Thermal survey of track – Shaw + Nolan, IN PROGRESS

Finding 4.1: The DSTT has high levels of Stray Current due to poor Track-to-Earth isolation.

The Corrpro report from 2022 shows locations between Pioneer and IDS Stations as well as between Westlake and University (now Symphony) Stations have Track-to-Earth isolation of less than 10 Ohms per 1000 ft, with our minimum state of good repair criteria I to be over 200 Ohms per 1000 ft, as shown in figure 4.1. This in turn is causing high levels of spray current that is likely damaging the tunnel structure. While KCM did clean the DSTT in early 2024, it is likely this condition still exists as an inspection of DSTT track drains in December 2024 showed many of them clogged with matter to the point of direct contact with the running rails (see Figure 4.2). This contact provides a direct electrical path to ground and is likely the cause of the low Track-to-Earth isolation.

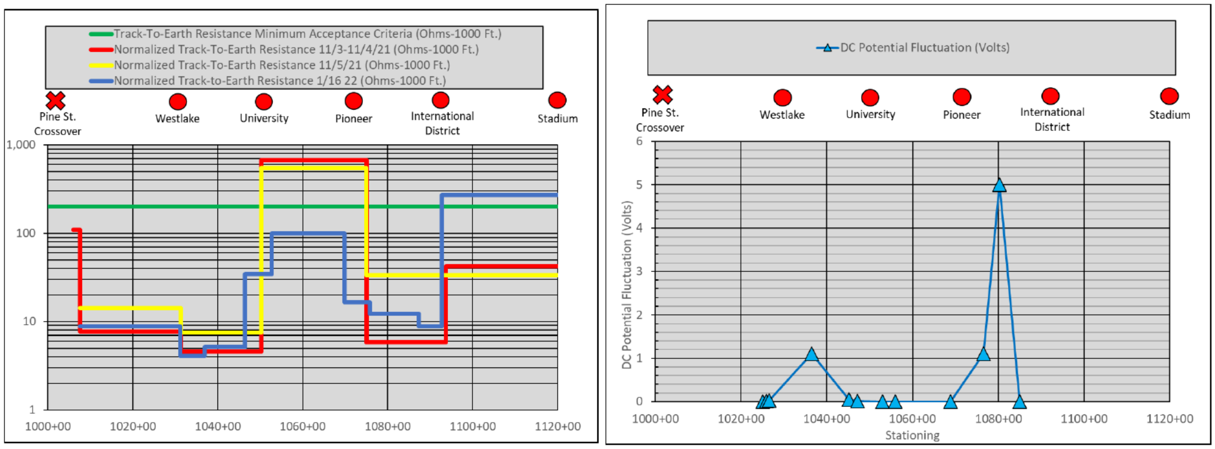


Figure 4.1: Poor Track-to-Earth isolation in the DSTT is causing high levels of Stray Current

Figure 4.2: Clogged DSTT track drains making direct contact with rails

Finding 4.2: The isolation IJs of our EMI zone show signs of arcing on both the northbound and southbound tracks and do not have properly placed coast signs.

After reports from LRV operators of arcing on the track, all four EMI Zone isolation IJs were inspected in November. Both exiting IJs were found to have evidence of arcing (see Figure 4.3). Of those two, only the IJ at Cross Passage (CP) 19 was found to have a coast sign reminding LRV operators to coast over the IJ to prevent arcing. However, even those signs were not sufficiently spaced to allow a four car consist to pass over the IJ, likely due to the fact that only three car consist were being run at the time they were placed.

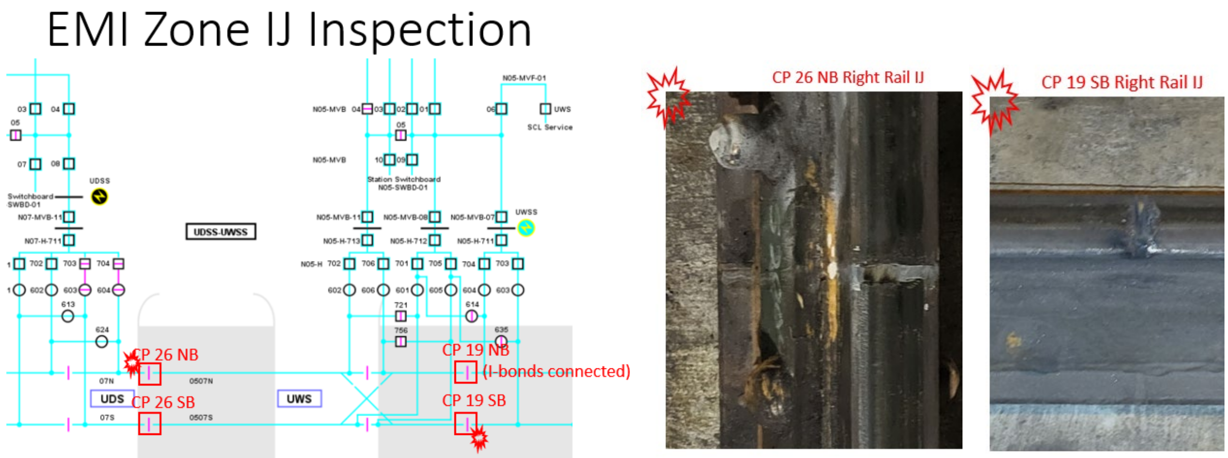


Figure 4.3: Signs of arcing on EMI Zone IJs

Finding 4.3: Our Telemattica OCS monitoring system on Line 1 is recording significant Pentagraph impacts between Rainer Beach and Tukwila stations.

We currently have two LRVs outfitted with Telemattica OCS monitoring systems. Both are currently on Line 1 leaving Line 2 with not such monitoring. In the past three months, these systems have recorded four locations of significant Pentagraph impacts between Rainer Beach and Tukwila Stations, as shown in Figure 4.4. Three of the impact are well over 1000, which is a level that Houston Metro considers as cause for emergency response and OCS repair. While our Sound Transit Traction Power Superintendent periodically checked the Telemattica alarms, and verbality stated that he was previously aware of these locations, no action had been taken at the time of this report.

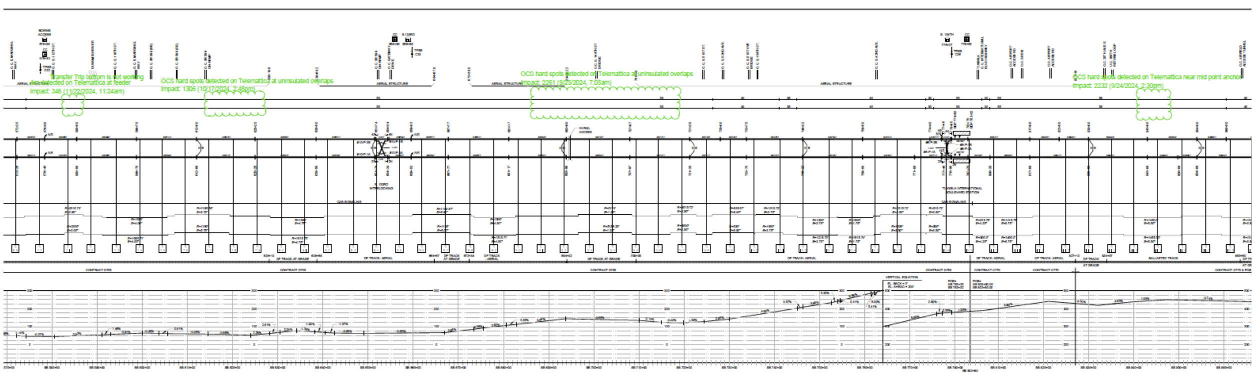


Figure 4.4: Four locations of significant Pentagraph impacts recorded our Line 1 Telemattica OCS monitoring system in the past three months

Finding 4.4: Pentagraph horn wear patterns on Line 2 LRVs indicate a significant issue with OCS security.

Inspection photos of pentagraph horn wear patterns on Line 1 and Line 2 show Line 1 has relatively good OCS security with wear patterns between 20% and 30% past the knee of the horn, as shown in Figure 4.5. Line 2, however, has wear patterns between 80% and 90% past the knee of the horn and in some cases signs of arc spatter, indicating arcing as well as poor OCS security that may soon lead to pentagraph entanglement.

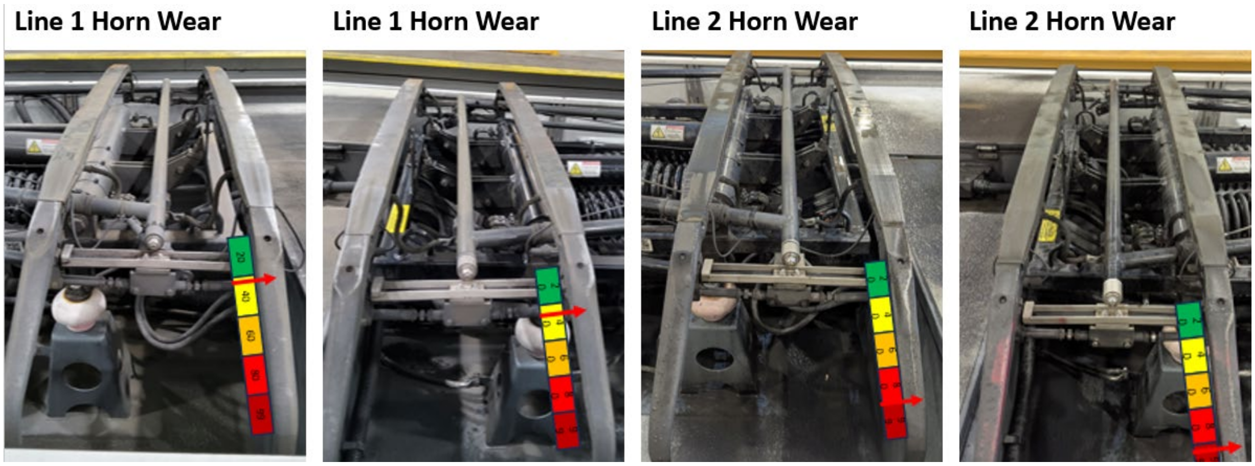


Figure 4.5: Inspection photos of pentagraph horn wear patterns on Line 1 and Line 2

5.0 A rail-to-ground field review

Goal: Review of current rail-to-ground system design and field performance.

Deliverable: A report of recommended design and/or operational improvements.

Status: PENDING

The following is the list of documents delivered.

APTA Paper - Rail Grounding Systems.pdf

2024-11-12 Summary of R2G Units Installed Along Sound Transit's Traction Power Substations (TPSS) Memo.pdf

2024-11-27 R2G model observations.pptx

2025-01-06 Rail Voltage Data Comparison.docx

NTO-1007 R2G Stage 3 Settings Change_3A.pdf

The following are the working notes regarding the ongoing efforts for rail-to-ground field review that are not yet complete.

1. **TES (39d/239h/56%)**
   a. **Rail to Ground Trip (4d/14h)**
      i. Collect R2G Voltage in EMI zone - Corrpro + Nolan, IN PROGRESS
      ii. Collect R2G Voltage in CLK and NLK – Corrpro + Nolan, IN PROGRESS
      iii. Analyze (histograms, FFTs, and Trigger curves) – Ruth + Nolan, IN PROGRESS

iv. Model EMI zone rail currents with jumpered IJs – MK, IN PROGRESS
v. NTO to Jumper EMI IJs at NB north end and SB south end, open up NB south end, and move coast signs to open IJs – Nolan, JAN
vi. NTO to change R2G stage 1 and 2 voltages and remove transfer trip - Nolan, ECT Q1

Findings:

Findings and recommendations have not yet been compiled.

6.0 Peer Agency Review

Goal: Review of the failures and state of good repair information provided above to determine if other Agency lessons learned and experiences can be implemented.

Deliverable: A report of peer agency lessons learned

Status: COMPLETE

The following is the list of documents delivered.

2024-11-14 Houston Metro notes.docx: Interview notes from an interview with Dwayne Lehnert regarding Traction Power and OCS operations and maintenance (O&M) practices for Houston Metro.

2024-11-22 TriMet notes.docx: Interview notes with Gene Wallis regarding Traction Power and OCS O&M practices at TriMet.

2024-12-10 LA Metro rail to ground practice.pdf: Email notes conversation with LA Metro as part of the West Coast Systems Agency Consortium.

2024-12-19 Minneapolis Metro notes.docx: Interview notes with Steve Hamilton of Metro Transit regarding their EMI zone as rail-to-ground system.

Finding 6.1: Houston Metro has had success with automated inspection technologies for OCS, Rail, and switch motors.

Houston Metro has been using Telemattica OCS monitoring for over three years with good success in reducing response time to developing OCS issues. Houston Metro has the system set to send an email to trigger an inspection for any impact over 300. Impacts over 1000 are considered an all-hands-on-deck emergency. See Figure 6.1 for an example of the Telemattica OCS monitoring system interface.

Houston Metro has been using RailPod for about three years to inspect rail as well as OCS height and stagger every 6 months and are looking to add OCS wear capability as well. Has greatly improved consisting of PM inspections. See Figure 6.2 for an example of the RailPod OCS stagger monitoring system interface.

Houston Metro is currently looking at ZenTrack to monitor track switch through motor current. Has not yet implemented but tests seem positive. See Figure 6.3 for an example of the ZenTrack monitoring system interface.

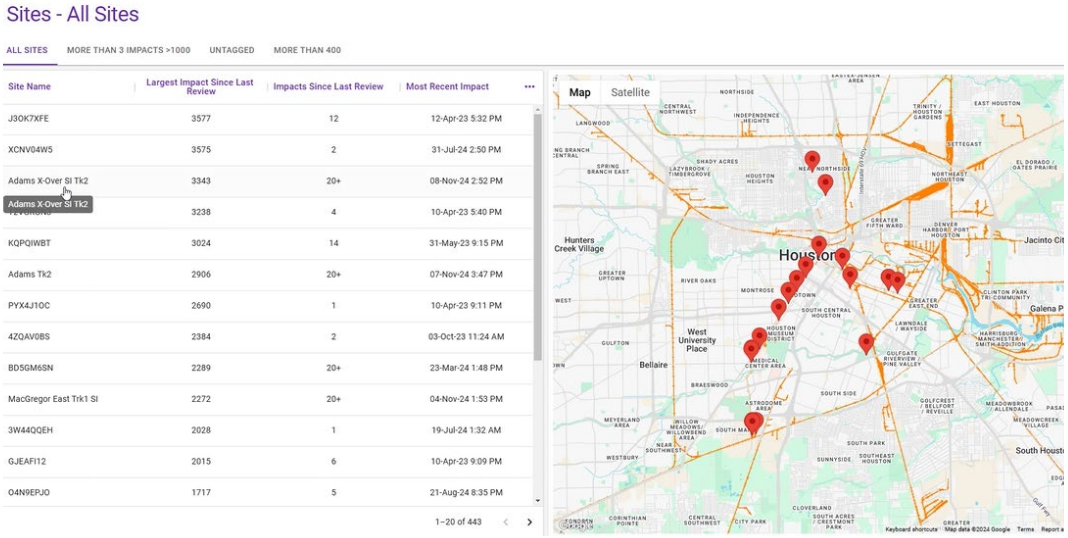


Figure 6.1: Telemattica monitoring of Houston Metro OCS

Figure 6.2: RailPod example of OCS stagger alarm

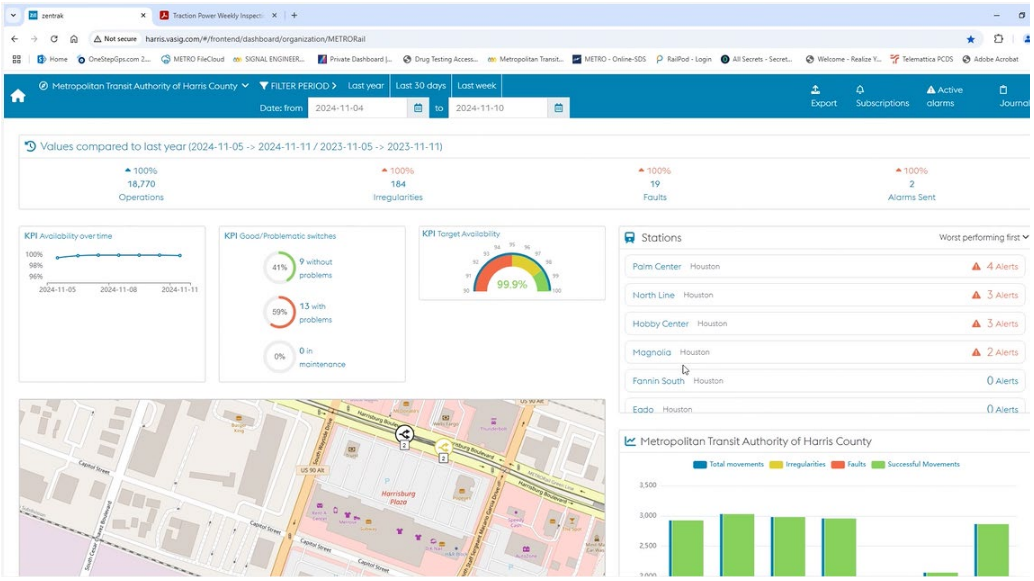


Figure 6.3: ZenTrack monitoring of Houston Metro switch motors

Finding 6.2: Most other interviewed agencies have similar Rail-to-Ground monitoring systems and settings, but do not transfer trip Rail-to-Ground alarms as we do.

TriMet has a R2G system that monitors voltage only and open local breakers above 75V for 2 seconds. TriMet used to have large number of R2G events every winter due to Utility trips in storms but has since corrected with setting adjustments and filters.

Houston Metro has an R2G system that open breakers above 75V. They have 26 TPSSs, roughly one every mile, but does not see many R2G alarms; lots more hot structure alarms.

LA Metro has an R2G system that triggers on 75V, but only ground the rail, it does not trip the local breakers or transfer trip to adjacent substations. They have had a similar problem with rail-to-ground voltages being much higher than in design simulations.

Minneapolis Metro uses the same Siemens R2G units in their TPSSs that we do. They have not had any issues with R2G trips but do see higher voltage when testing their EMI section, which involved isolating that section of rail from the rest of the system. Note: their EMI section is not normally isolated as ours is.

Finding 6.3: Minneapolis has an Electro Magnetic Interference (EMI) zone that is not isolated and seems to work well without causing rail voltage spikes.

The Minneapolis Metro EMI zone was designed by LTK to suppress EMI were the alignment comes within 70ft of a University's sensitive equipment. Their EMI zone is not isolated on the OCS or the rails. During design, isolating the rails was considered but untimely rejected due to the concern of voltage spikes as trains passed though the zone. They currently conduct annual testing in conjunction with the university. They have noticed voltage spikes and arcing when they isolate the rail around their EMI zone during testing.

Recommendation 6.1: Look at adding automated inspection technologies for OCS, Rail, and switch motors to improve PM efficacy and consistency.

Based on Houston Metro's feedback and industry surveys, the recommendation is to use the RailPod system to inspect the Track and OCS every 6 months as part of the Track and OCS PMs. In addition one of our Telemattica systems should be operated on each of our two lines, with quarterly reports provided by Telemattica and real-time email alerts set to our Power superintendent for any impact above 300 to trigger an inspection. Last track switch motor monitoring with ZenTrack, Wayside System Data Management Module (WSDMM), or similar system should be implemented for all mainline switches and crossing gates to enable condition monitoring of these devices.

Recommendation 6.2: Disable the R2G transfer trip function, letting alarms clamp rail-to-ground and open local breakers only.

By retaining the clamping function and local breaker trip, our R2G system could provide the rail voltage and stray current protection it does now, without being as disruptive to passenger service.

Recommendation 6.3: Look at removing EMI zone rail isolation to reduce rail voltage spikes.

Due to our EMI zone design being slightly different than that of Minneapolis Metro's, some modeling would be necessary to ensure the EMI suppression would still be sufficient to meet the University of Washington's needs with the rails tied in. However, assuming that these needs could be met, a tied-in system would eliminate the IJ arcing we are currently experiencing and may also reduce the Rail voltage spike sufficient to allow us to lower our R2G alarm setting to the same 75V threshold used by most other agencies.

7.0 Appendix 1: Prioritized List of Actions

A working list of actions grouped by disruption type.

BIC: Engineering, Operations, Extension Project

STATUS: Pending, Done

1) TES (39d/239h/56%)
- **a) New Extension Integration (7d/75h)**
  - i) New TPSS breakers not coordinated with existing (1d/43h)
    - (1) DD for TES coordination study with existing alignment – Ming, Jan
  - ii) New extension equipment not in working condition (4d/21h)
    - (1) Add system validation period (ATO) - DONE
  - iii) Signal I-bond cover shorted to ground (1d/10h)
    - (1) DD to standardize I-bond covers - DONE
  - iv) Test train ran into dead OCS (1d/1h)
    - (1) Extensions to control OCS and Rail interface via single end back feed - DONE
- **b) Human Error (6d/70h)**
  - i) Lack of training that R2G 33 door reset causes R2G trips (2d/68.5h)
    - (1) NTO to eliminate 33 device on R2G door – Nolan, 12/20

ii) Lack of training that PLC reset and ETS COMs loss causes trips (4d/1.5h)
  (1) Prohibit security using FCC rooms for breaks - DONE
  (2) DD for TPSS network architecture and fail over testing – Karl, Jan
iii) General
  (1) Established a more comprehensive training program with updates based on equipment changes - TBD

c) OCS Equipment Failure (3d/31h)

i) Pantograph entangled in OCS (1d/17h)
  (1) Check tension, height, and stagger in tunnel crossovers– Jeff, 12/9 to FEB
  (2) Complete 14 open Repairs for OCS equipment: – Jeff, 12/9 to FEB
    (a) CLKPWR-2023-160,161,182,816,1252,1287,1313;
    (b) CLKPWR-2024-16,208,746,955,1029,1194;
    (c) ELKPWR-2024-131
  (3) Mitigate leak on OCS – Jeff + Kyle, ETC TBD
  (4) Get one Telemattica train back on East Side – Jeff, ECT
  (5) Inspections of any hard spots over 1000 within a week - Ron, ECT
  (6) NTO for balance weight range check procedure and frequency – Clarissa, Jan
ii) New extension surge arrester failure (1d/13h)
  (1) Add system validation period (ATO) - DONE
iii) Tree branch grounding (1d/1h)
  (1) Review and update vegetation control SMP – XXX, ECT
iv) General
  (1) Procure dry ice blaster for cleaning of contaminated insulators – Ron, ECT
  (2) Quarterly Telemattica reports of OCS condition – Ron, DONE
  (3) Automated inspection of height, stagger, and wear (RailPods) – Jeff, ETC
  (4) Update PM program based on asset structure and OCS maintenance standard that includes OCS height, stagger, and wear tracking at all supports and Sis - Nolan, Q1

d) TPSS internal COMs (5d/26h)

i) Unstable TPSS Network equipment configuration (5d/26h)
  (1) DD for TPSS network architecture and fail over testing – Karl, Jan

e) Utility Power Loss (7d/20h)

i) Bomb cyclone weather event (5d/19h)
  (1) Update at AC breaker timing settings – Ming, ECT
ii) Local power outage (2d/1h)
  (1) NTO for SIG UPS alarm reprioritized to level 1 – Mike Bauck, ECT
  (2) Dedicated power monitoring at LCC – Jeff, ECT
iii) General
  (1) Update PM program based on asset structure and Electrical maintenance standard that includes a UPS maintenance program – Elizabeth K, Q1

f) Rail to Ground Trip (4d/14h)

i) R2G around EMI zone (3d/12h)
  (1) NTO to change R2G stage 3 voltage to 240 V – Nolan, DONE
  (2) Clean track and drains in DSTT with vac truck – Jeff, IN PROGRESS
  (3) Post-clean measurement of Track to Earth – Corrpro + Nolan, ETC XXX
  (4) NTO to Jumper EMI IJs at NB north end and SB south end, open up NB south end, and move coast signs to open IJs – Nolan, JAN

        (5) Jumper EMI IJs at NB north end and SB south end, open up NB south end, and move coast signs to open IJs – Jeff, Q1
        (6) NTO to change R2G stage 1 and 2 voltages and remove transfer trip - Nolan, ECT Q1
    ii) R2G in OMFE yard (1d/2h)
        (1) NTO to change R2G stage 1 and 2 voltages and remove transfer trip - Nolan, ECT Q1
    iii) General
        (1) Close open Repair for burnt thyristor at C23-TPSS: CLKPWR-2023-210 - DONE
        (2) Procure thermal camera for track inspection – Ron, ECT
        (3) R2G alarm monitoring with thermal inspection of issue areas - TBD
        (4) Track to earth and stray current testing every two years – Ron ECT
        (5) Annual thermal survey to check bond cable health - TBD
        (6) Continue R2G measurement at all TPSSs reviewed quarterly - TBD
        (7) Rail cleaning program informed by the above - TBD
        (8) Update PM program based on asset structure and TPSS maintenance standard that includes R2G thyristor inspection – Nolan, DONE
        (9) Update PM program based on asset structure and Track maintenance standard that includes a IJ inspection and cleaning – Jason, DONE

g) Breaker Relay settings (5d/3h)
    i) Un-commanded open in LLE (3d/2h)
        (1) Eliminate -di/dt and rise Mx to 5000A for coordination (Warranty) – Ming, ECT
        (2) NTO Raise DC breaker line test to 500V – Nolan, DONE
    ii) Door switch on transformer door (1d/1h)
        (1) Relace mechanical switch with pressure type on LLE: NLKPWR-2024-282 – Jeff, ECT
    iii) Un-commanded open in EMI zone (1d/0h)
        (1) NTO to Jumper EMI IJs at NB north end and SB south end, open up NB south end, and move coast signs to open IJs – Nolan, JAN
    iv) General
        (1) Complete 9 open Repairs for non-functional protective circuits:
            (a) CLKPWR-2024-424,990,1014,1015,1017,1018
            (b) NLKPWR-2024-281
            (c) L800 Punch List TES-177, TES-184
        (2) Complete 18 open Repairs for non-functional breakers and switches:
            (a) CLKPWR-2023-701,727,818,1151;
            (b) CLKPWR-2024-297,458,796,988,1004;
            (c) ELKPWR-2024-70,637;
            (d) NLKPWR-2024-232,361,424,481,528;
            (e) L800 Punch List OCS-15, TES-186
        (3) Update PM program based on asset structure and TPSS maintenance standard – Nolan, DONE

h) Other (2d/0h)
    i) SCADA indication issues (2d/0h)
        (1) Complete 14 open Repairs for incorrect SCADA indication:
            (a) CLKPWR-2023-849,917,1343;
            (b) CLKPWR-2024-277,459,1005,1137;
            (c) ELKPWR-2024-28,349;
            (d) NLKPWR-2024-183,272,298;

(e) L800 Punch List TES-139,TES-169
(f) L830 Punch List TES-N09- Replace Simatic PLC CPU
(2) Stand up SCADA maintenance program with ticket system for indication issues and false alarms – Jeff, ECT

2) SIG (51d/94h/22%)

a) Human Error (2d/3h)

i) High rail vehicle trailed switch (2d/3h)
(1) Operator training - DONE

b) New Extension Integration (3d/6h)

i) New extension equipment not in working condition (2d/4h)
(1) Add system validation period (ATO) - DONE
ii) Did not pay utility bill for new Signal house (1d/2h)
(1) Update utility handoff procedure - DONE

c) Utility Power Loss (4d/1h)

i) LCC did report outage until UPS depleted (4d/1h)
(1) NTO for SIG UPS power loss alarm to be set to priority 1 – Karl, TBD
(2) Update PM program based on asset structure and Electrical maintenance standard that includes a UPS maintenance program – Elizabeth K, Q1

d) Track Circuit False Occupancy (11d/40h)

i) Failed Impedance bond (1d/21h)
(1) Add IJ inspection and clean to track maintenance standard – Jason, DONE
ii) Egress pad in connect with rail at Surrey Downs (4d/12h)
(1) Add system validation period (ATO) - DONE
(2) Require re-test of track to earth after all wayside equipment installs (ATO) - DONE
iii) Track circuit needed tuning (5d/5h)
(1) Centralized tracking of annual track circuit settings – Will, DONE
iv) Circuit card not set in LLE (1d/2h)
(1) Add system validation period (ATO) - DONE
v) General
(1) Update PM program based on asset structure and Track maintenance standard that includes IJ inspection and cleaning – Jason, DONE
(2) Track to earth and stray current testing every two years – Ron, DONE
(3) Rail cleaning program informed by the above - TBD

e) Switch out of correspondence (17d/25h)

i) At S200/ALS crossovers (5d/11h)
(1) Replace failed motor – DONE (March)
(2) END of Line logic update: L800 Punch List SIG-38
ii) Kirkland Way for movable point frogs (5d/9h)
(1) Add system validation period (ATO) – DONE
(a) M3 used in Kirkland Way for movable point frogs have had high infant mortally rate.
iii) At other non-mainline crossovers (7d/5h)
(1) Weekly sweeps and cleaning of MLK switches – Will, DONE
(2) Add IDS merge switches to weekly's after ELE tie in – Will, Q2 2026
(3) Close 16 open Repairs for switch adjustment:
(a) CLKSIG-2023-1118,1120,1798,1960;
(b) CLKSIG-2024-1042,1208,1373,1517;

(c) ELKSIG-2024-42,43,749,1304,1305,1310,1312;
(d) NLKSIG-2024-542

iv) General
(1) Add remote monitoring of all mainline switches – Andre, ETC XXX
(2) Update PM program based on asset structure and Signal maintenance standard that includes monthly switch inspection and cleaning and weekly frequency for targeted switches – Andre, TBD

f) Signal communications loss (5d/12h)

i) Interlockings lost correspondence with SCADA (3d/11h)
(1) VHLC reset issue: L800 Punch List SIG-39 - ECT
(2) Add system validation period (ATO) - DONE

ii) Unable to make call in/out of OMFC yard via TWC (2d/1h)
(1) Add system validation period (ATO) - DONE

g) Crossings (11d/9h)

i) Crossing gate/arm failure (6d/7h)
(1) 130th and 132nd exit gate crossing issue with loop holding gate up. EGM module gets hung up. Project warranty - ECT
(2) Add system validation period (ATO) - DONE

ii) DSTT tunnel barrier stuck (1d/1h)
(1) Close open Repair for NB track barrier: CLKSIG-2023-1327

iii) Bel-Red traffic controller integration (4d/1h)
(1) Add system validation period (ATO) - DONE

iv) General
(1) Gate current monitoring – WSDMM (see if needed) - ECT

3) LRV (79d/45h/11%)

a) Pantograph failure (5d/6h)
i) Update LRV PMs to include monitoring of pantograph horn wear – Chris K, ECT

4) COM (3d/35h/8%)

a) Human Error (3d/35h)
i) Map our communication networks and servers and place them under formalized change control – Karl, ECT

5) Other (5d/10h/3%)

a) Rail Break (2d/7h)
i) Update PM program based on asset structure and Track maintenance standard that includes annual rail defect inspection – Jason, DONE

b) Tree on tracks (1d/2h)
i) Review and update vegetation control SMP – XXX, ECT

c) IDS Utility Power Loss (2d/1h)
Dedicated power monitoring at LCC – Jeff, ECT