IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 2, August 2026

Impact Factor: 8.2

Incident Investigation of Locomotive Runaway in an Under-Construction Tunnel Using Fault Tree Analysis and Development of Safety Countermeasures

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Abstract: *This research investigates a high-potential locomotive runaway incident that occurred during underground metro tunnel construction in May 2024. The event involved a battery-powered tunnel locomotive hauling loaded muck cars during a reverse movement near a launching shaft. Four loaded muck cars were positioned on an approximately 4% gradient when braking effectiveness became inadequate, resulting in uncontrolled reverse acceleration toward the Tunnel Boring Machine (TBM). The locomotive and attached rolling stock ultimately collided with stored tunnel lining segments. No personnel were injured because emergency communication and evacuation were effective, but the event produced substantial equipment and productivity losses and exposed weaknesses in the transportation safety system.*

The study adopts a systems-based case-study methodology supported by documentary evidence, incident reconstruction, Root Cause Analysis (RCA), Heinrich's Domino Theory, Bird's Loss Causation Model, the Swiss Cheese Model, Fault Tree Analysis (FTA), and Bow-Tie Analysis. The analysis demonstrates that the event was not attributable to a single technical defect or individual action. Rather, it resulted from interacting operational, engineering, environmental, human and organizational weaknesses. Key contributors included improper parking on an incomplete track, reverse movement of a loaded locomotive, gradient-induced gravitational loading, lack of braking continuity between locomotive and muck cars, inadequate physical containment, and deficiencies in the existing HIRA/Safe Work Method (SWM) controls. Post-incident controls were evaluated using the hierarchy of controls and defense-in-depth principles. Major improvements included completion of both tracks, pneumatic air-hose connections to rolling stock, flap stoppers, designated STOP ZONES, improved Manchester Gate arrangements, strengthened brake inspection, revised HIRA/SWM, competency development and enhanced emergency communication. The study culminates in a six-pillar Tunnel Haulage Safety Framework covering engineering safety, operational safety, maintenance reliability, competency management, risk governance and emergency preparedness.

The principal contribution is a practical, system-oriented model for preventing recurrence of uncontrolled locomotive movement in underground construction environments while reducing dependence on individual operator intervention.

Keywords: underground construction; tunnel locomotive; runaway movement; braking system; gradient; Fault Tree Analysis; Bow-Tie Analysis; Root Cause Analysis; safety barriers; tunnel haulage

I. INTRODUCTION

Rapid urbanization has increased demand for mass rapid transit, and underground metro construction is increasingly used where surface space is constrained. Tunnel projects operate under confined conditions with restricted access and egress, temporary infrastructure, limited visibility, continuous machinery movement and challenging emergency-response conditions. Rail-mounted locomotives are therefore a critical part of underground logistics, transporting excavated muck, tunnel segments, materials and maintenance equipment between the TBM and launching shaft.

The source project involved twin bored tunnels and associated underground works under a DMRC Phase-IV contract. Tunnel haulage was supported by battery-powered locomotives, muck cars, segment cars, flat cars, temporary tracks, Y-switch arrangements, Manchester Gates and communication systems. The May 2024 dangerous occurrence demonstrated that routine haulage operations can become high-consequence events when several independent safeguards fail simultaneously.

1.1 Problem Statement and Research Gap

Most published railway safety work addresses public railways, mainline systems or mining applications. The source study identifies comparatively limited research focused specifically on locomotive transportation risks during metro tunnel construction. The combination of temporary track geometry, gradients, high haulage loads, confined spaces and rapidly changing work conditions creates a distinct safety problem that cannot be fully represented by conventional railway risk models.

1.2 Aim and Objectives

- To reconstruct the sequence of events leading to the locomotive runaway.
- To identify immediate, contributing and root causes using a systems perspective.
- To evaluate locomotive design, braking, gradient, loading, procedures and supervisory controls.
- To integrate RCA, FTA, Bow-Tie and accident-causation models.
- To evaluate the effectiveness of corrective and preventive measures.
- To develop a practical tunnel haulage safety framework for future projects.

1.3 Scope

The study covers tunnel locomotive operations, muck transportation, track configuration, gradients, braking systems, human factors, management systems, safety alerts, engineering modifications and risk-assessment practices. Detailed financial valuation beyond the reported incident cost and unrelated TBM-system analysis are outside the scope.

II. LITERATURE REVIEW AND ACCIDENT-CAUSATION PERSPECTIVE

Underground haulage is a socio-technical system in which equipment, temporary infrastructure, workers, supervisors, procedures and management controls interact continuously. Modern tunnel locomotives may include pneumatic braking, emergency stopping, dead-man controls, monitoring and communication systems; however, the safety of the complete convoy depends on the integrity and compatibility of all components.

2.1 Engineering and Human Factors

Gradient is a particularly important engineering parameter because gravitational force acts along the rail direction. As the gradient increases, the braking system must provide greater retarding force. The source records indicate gradients of approximately 2.8% to 4.02% in the relevant area. The incident configuration included five loaded muck cars, increasing the mass, kinetic-energy potential and braking demand.

Human and organizational factors were equally important. The decision to reposition the loaded locomotive occurred after unloading difficulties at the shaft. The operator's action therefore occurred within a broader system of production

DOI: 10.48175/IJARSCT-38134

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pressure, incomplete infrastructure, supervisory direction and existing work practices. Post-incident controls focused not only on worker behavior but also on design, maintenance, supervision and risk governance.

2.2 Heinrich's Domino Theory

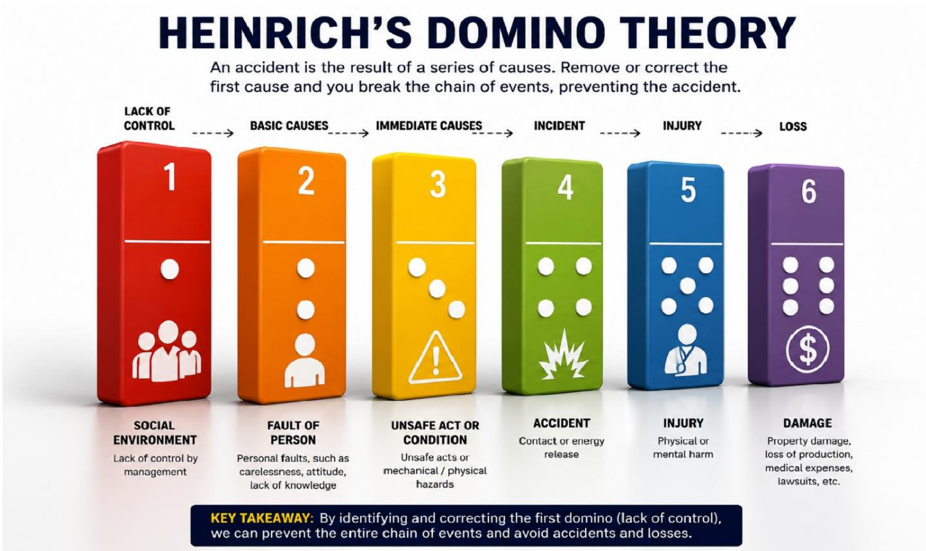

Figure 1. Heinrich's Domino Theory as reproduced in the source document.

The incident can be interpreted as a progression from systemic conditions to human/operational decisions, unsafe acts and conditions, loss of control, and property damage. The model is useful for explaining sequence, but it is limited when deeper organizational and barrier interactions must be examined.

2.3 Bird's Loss Causation Model and Swiss Cheese Model

Figure 2. Bird's Loss Causation Model applied in the source study.

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Bird's model expands accident analysis from unsafe acts to management control. The sequence is Lack of Control → Basic Causes → Immediate Causes → Incident → Loss. For the incident, weak operational restrictions and risk controls represented lack of control; gradient, loading and planning conditions represented basic causes; reverse movement and ineffective braking represented immediate causes; runaway movement was the incident; and collision/property damage represented loss.

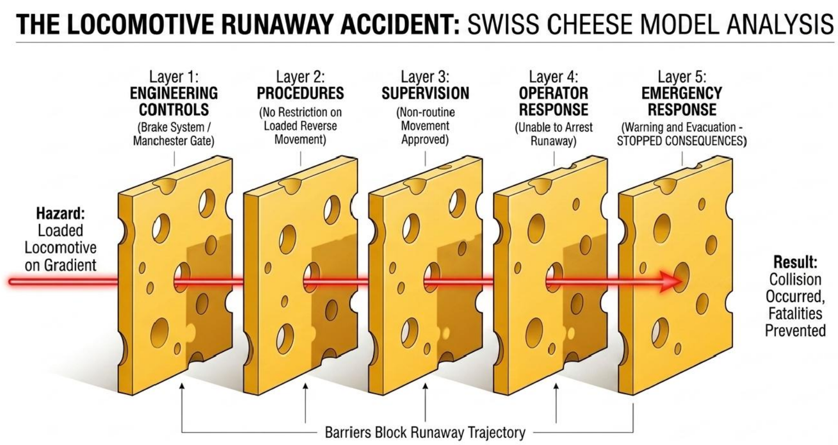

Figure 3. Swiss Cheese analysis of the locomotive runaway incident.

Reason's Swiss Cheese Model explains why the event progressed despite the existence of several controls. Engineering barriers, operating procedures, supervision and human intervention contained weaknesses. The emergency communication and evacuation barrier, however, functioned effectively and prevented personnel exposure to the runaway path.

2.4 Comparative Analytical Value

Method	Primary question	Value in this case
Heinrich Domino	What sequence led to the accident?	Clarifies progression from unsafe conditions to loss.
Bird Loss Causation	Which management/system weaknesses enabled the event?	Connects control failures with basic and immediate causes.
Swiss Cheese	How did multiple defenses fail together?	Shows alignment of latent and active failures.
FTA	What exact combinations can create the top event?	Provides logical AND/OR relationships and minimal-cut-set reasoning.
Bow-Tie	What threats, barriers and consequences surround the top event?	Integrates preventive and recovery controls.

III. PROJECT DESCRIPTION AND TUNNEL LOCOMOTIVE SYSTEM

The tunnel haulage system consisted of battery-powered locomotives operating on temporary rail tracks between the launching shaft and TBM. Primary rolling stock included 17 m^3 muck cars, segment cars and flat cars. A typical cycle transported excavated muck toward the shaft and returned segments and other materials toward the TBM.

3.1 Braking and Rolling-Stock Configuration

The locomotive incorporated pneumatic braking, emergency stopping and a dead-man switch. A critical investigation finding was that the locomotive was the only component with active braking capability during the incident

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configuration. The muck cars were not connected through air hoses, so the convoy's additional mass did not contribute corresponding braking capacity. This created a mismatch between hauled mass and available braking force.

3.2 Track Arrangement and Gradient

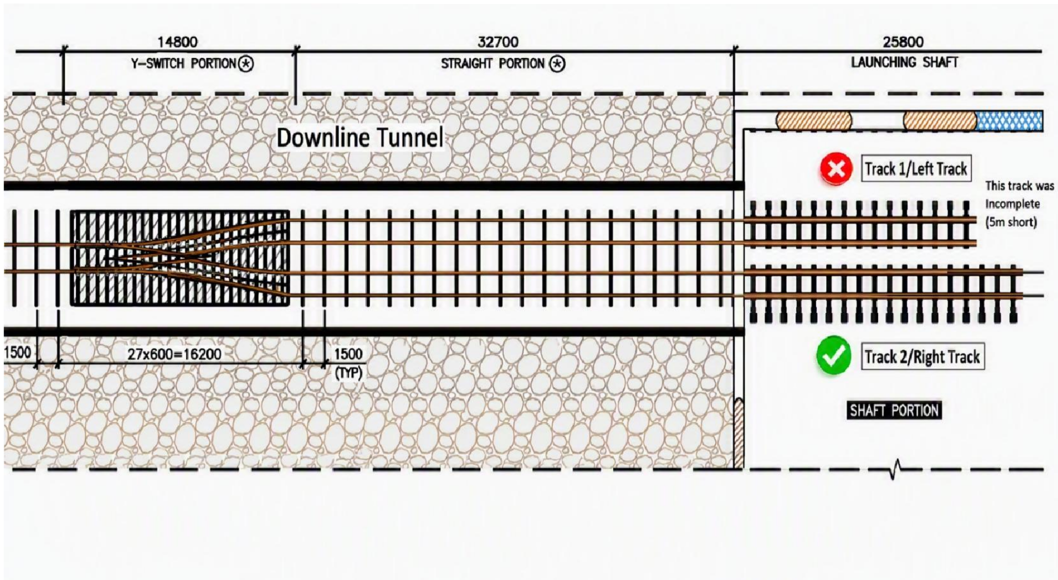

Figure 4. Tunnel track/launching-shaft arrangement from the source project documentation.

The launching shaft contained two tracks. The right-side track was complete and suitable for unloading, whereas the left-side track was approximately five metres short of completion. The loaded locomotive was parked on the incomplete track during the day shift, which later created unloading difficulties and contributed to the decision to reposition the convoy.

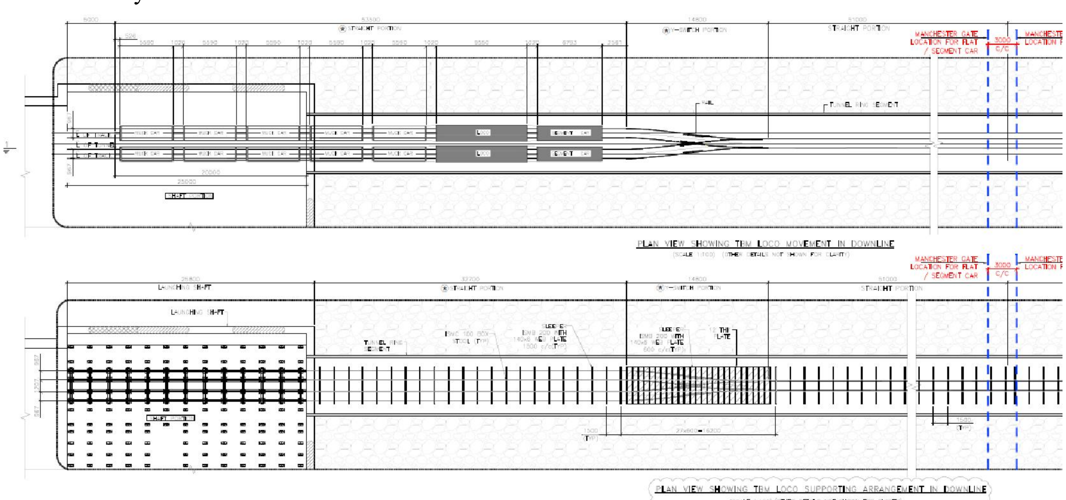

Figure 5. Engineering drawing/blueprint from the source file showing the track and gate arrangement.

The Manchester Gate was intended to provide physical containment. The investigation found that the gate was not locked during the incident and that its pre-incident location was not optimal for arresting a runaway after the gradient section.

IV. RESEARCH METHODOLOGY

The research uses a pragmatic, systems-based safety engineering philosophy. The incident is treated as a multidimensional socio-technical event rather than as a single-cause equipment failure. A case-study design was selected because the event involved a high-potential dangerous occurrence, extensive investigation documentation, multiple post-incident controls and direct lessons for future tunnel projects.

Figure 6. Overall research framework from the source study.

4.1 Data Sources

- Dangerous Occurrence Investigation Presentation and event-line records.
- DMRC safety-alert communications and revised operational restrictions.
- L&T compliance reports documenting corrective and preventive measures.
- Locomotive OEM inspection reports and third-party inspection certificates.
- Manchester Gate engineering drawings and modification records.
- Tunnel gradient surveys and track geometry records.
- Rolling-stock inspection and maintenance records.
- Updated HIRA and Safe Work Method documentation.

4.2 Analytical Procedure

Stage	Activity	Output
1	Document collection and evidence review	Verified incident evidence base
2	Event reconstruction	Chronology and decision points
3	RCA	Immediate, contributing and root causes
4	FTA	Logical failure combinations and minimal cut set
5	Bow-Tie	Threats, barriers, top event and consequences
6	Corrective-action evaluation	Effectiveness by hierarchy of controls
7	Framework development	Six-pillar tunnel haulage safety model

Reliability was strengthened through triangulation across multiple project documents. The study is intentionally evidence-based and does not attempt to assign personal blame; its purpose is system learning and prevention.

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V. INCIDENT RECONSTRUCTION AND EVENT CHRONOLOGY

The incident developed through a chain of interconnected operational decisions and conditions rather than occurring without warning. Mining of Ring No. 331 was completed at approximately 7:30 PM. The loaded locomotive and five muck cars were subsequently parked on the incomplete left-side track. After the night shift began, unloading difficulties were encountered, leading to a decision to change tracks by reversing the loaded convoy.

Time	Event	Safety significance
07:30 PM	Mining of Ring No. 331 completed	Loaded haulage cycle initiated
07:45 PM	Loaded locomotive parked on left track	Incomplete-track condition introduced
08:00 PM	Night shift commenced	Shift handover context
08:35 PM	Operator and foreman reached shaft	Unloading operation
08:55 PM	One muck bucket unloaded	Initial operation successful
09:06 PM	Further unloading difficulty	Operational problem develops
09:07 PM	Instruction to change track	Critical decision point
09:07 PM	Reverse movement initiated	Loaded reverse movement begins
09:10 PM	Last muck car crossed Manchester Gate	Convoy enters critical section
09:10 PM	Locomotive halted on ~4% gradient	High braking demand
09:10 PM	Brake effectiveness lost	Runaway begins
09:11 PM	Emergency warning transmitted	Recovery barrier activated
09:11 PM	Worker evacuation initiated	Personnel exposure reduced
09:13 PM	Collision with stored segments	Loss event
06:30 AM next day	Muck buckets recovered	Recovery operation
05:30 PM next day	Recovery completed	Operational restoration

The chronology shows that the decisive transition occurred when a loaded convoy was reversed, crossed the gate and stopped on the gradient. Once braking effectiveness became inadequate, gravity became the dominant driving force.

Root Cause Analysis was used to distinguish visible immediate causes from deeper system conditions. The investigation established that the event was a transportation-system failure involving human decisions, engineering configuration, workplace conditions, barrier design and risk-management deficiencies.

VI. IMMEDIATE CAUSES FACTORS

6.1 Immediate Causes

Reverse movement of a loaded locomotive/muck-car convoy.
Locomotive stopped on an approximately 4% gradient.
Braking effectiveness became inadequate.
Available physical containment did not arrest the runaway.

6.2 Human and Supervisory Factors

Unsafe task performance associated with a non-routine reverse maneuver.
Supervisory decision to change tracks while the convoy remained loaded.
Failure to challenge or stop an unsafe instruction.
Insufficient formal authorization for abnormal locomotive movement.

6.3 Technical and Environmental Factors

Only the locomotive provided active braking effort; muck cars lacked air-hose brake continuity.
Gradient-induced acceleration increased the retarding-force requirement.

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Track arrangement was incomplete and created the operational problem that triggered repositioning.
Manchester Gate was not locked and its location did not provide effective runaway arrest after the gradient.

6.4 Risk-Management and Design Factors

Existing HIRA/SWM did not adequately address brake failure during reverse movement on a gradient.
Control measures were not sufficiently detailed for the specific runaway scenario.
Physical safety barriers were not designed around the worst-case hazard pathway.
Temporary infrastructure changes were not fully integrated into dynamic risk assessment.

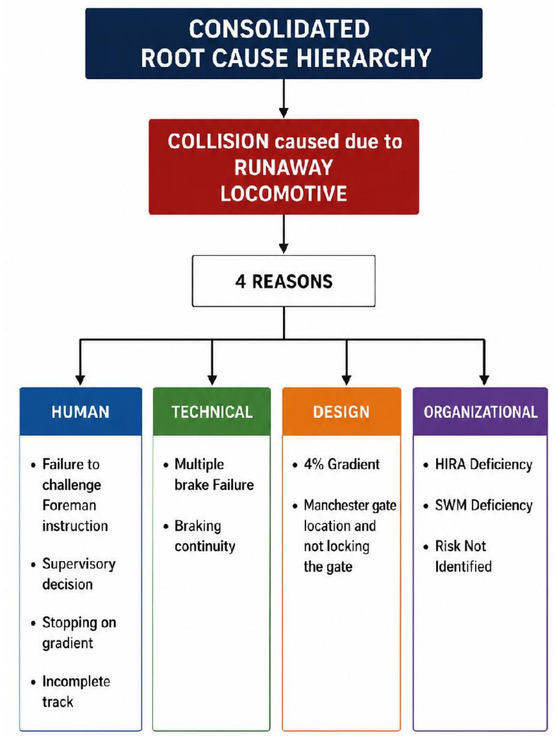

Figure 9. Root-cause hierarchy from the source study.

The central root-cause conclusion is that the incident resulted from alignment of several system weaknesses rather than from a single isolated error.

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6.5 Integrated Root-Cause Model

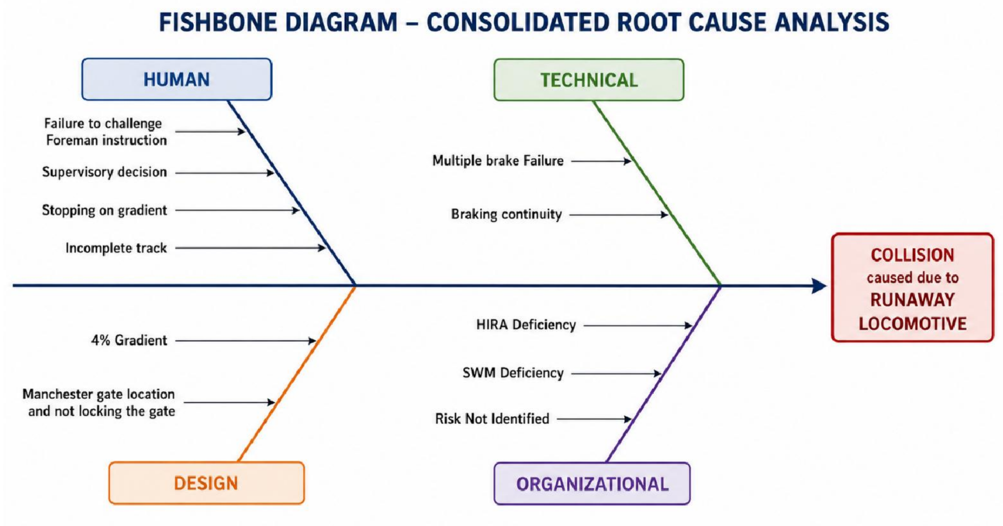

Figure 8. Fishbone/Ishikawa root-cause diagram reproduced from the source study.

The fishbone analysis organizes the contributing factors into engineering, human, environmental, organizational and design dimensions. This is important because tunnel haulage safety is inherently interdisciplinary: the braking system cannot be assessed independently of the mass being hauled, the gradient cannot be separated from parking rules, and a physical gate cannot be evaluated without considering its location relative to the hazard trajectory.

Cause category	Key findings	Prevention implication
Engineering	Braking continuity absent; braking demand increased by gradient/load	Design the complete convoy braking system and verify worst-case stopping performance
Human	Reverse movement decision; limited challenge of unsafe instruction	Formal authorization and competency-based decision making
Workplace	Incomplete track and gradient exposure	Complete infrastructure before use; designate level STOP ZONES
Barrier design	Gate not locked and poorly positioned	Locate physical barriers after hazard-generating gradients
Management	HIRA/SWM scenario gap	Use dynamic risk assessment and management-of-change controls
Emergency	Communication and evacuation worked	Maintain redundant communication and practiced evacuation

The analysis supports a defense-in-depth strategy: the safest system is one in which a single operational deviation cannot create an uncontrolled-energy event because independent engineering barriers remain effective.

VII. FAULT TREE ANALYSIS (FTA)

FTA was adopted as the principal engineering analysis tool. The top event was defined as 'Uncontrolled Runaway of Locomotive Toward TBM Area'. The top event requires both the development of uncontrolled movement and failure of the systems intended to arrest or control that movement.

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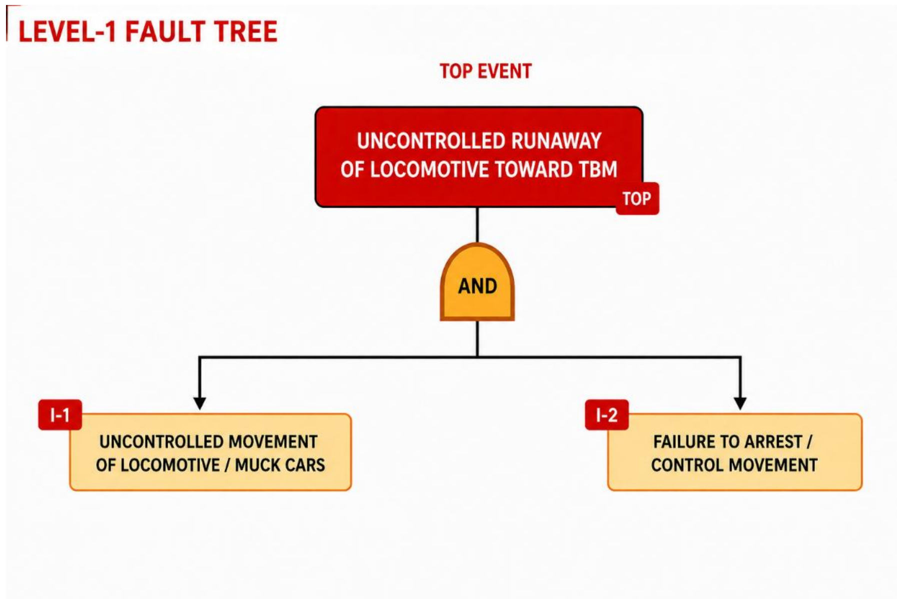

Figure 9. Level-1 Fault Tree for the top event.

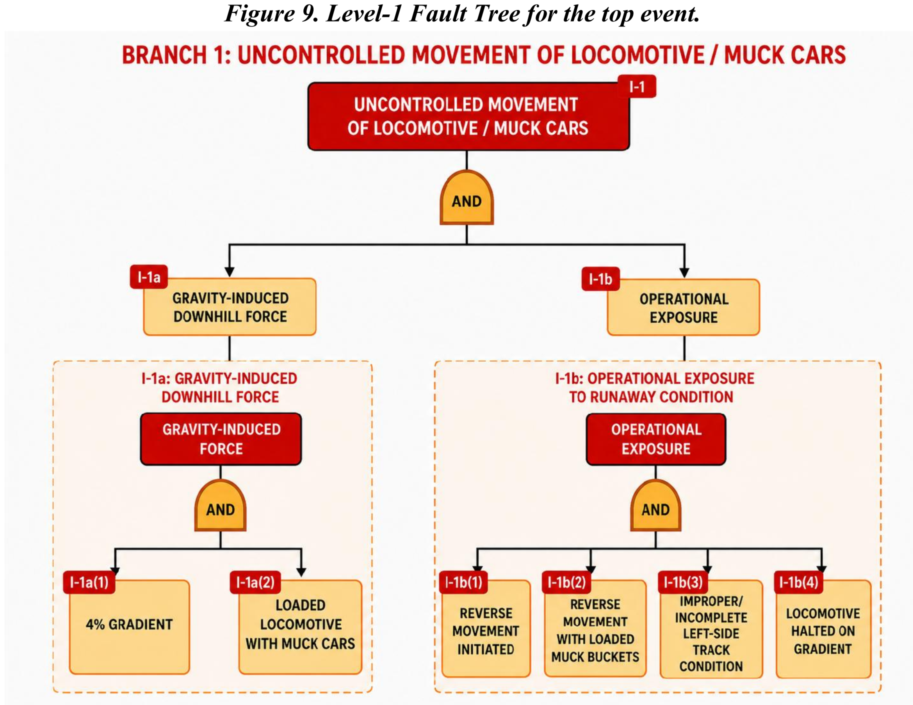

Figure 10. Branch 1: uncontrolled movement of locomotive/muck cars.

Branch 1 required two conditions: (i) gravity-induced downhill force, represented by an approximately 4% gradient together with a loaded locomotive; and (ii) operational exposure to a runaway condition through reverse movement, loaded muck cars, incomplete track and stopping on the gradient.

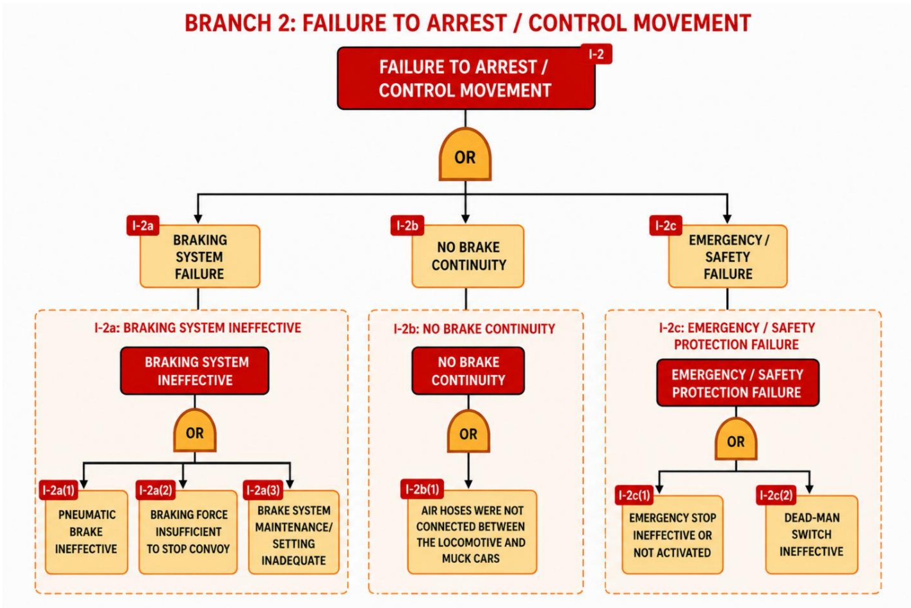

Figure 11. Branch 2: failure to arrest/control movement.

Branch 2 identified three independent pathways: ineffective braking, lack of brake continuity between locomotive and muck cars, and failure of emergency/safety protection. Because any one of these pathways could defeat stopping capability, they were represented through an OR relationship.

7.1 Boolean Logic, Minimal Cut Set and Bow-Tie Assessment

TOP EVENT = [(B1 AND B2) AND (B3 AND B4 AND B5 AND B6)] AND [(B7 OR B8 OR B9 OR B10 OR B11 OR B12)]

Code	Failure/condition
B1	Approximately 4% gradient present
B2	Loaded locomotive with muck cars
B3	Reverse movement initiated
B4	Reverse movement with loaded muck buckets
B5	Improper/incomplete track
B6	Halt/stop on gradient
B7	Pneumatic brake ineffective
B8	Braking force insufficient
B9	Brake maintenance/setting inadequate
B10	Air hoses not connected
B11	Emergency stop ineffective/not activated
B12	Dead-man switch ineffective

The principal minimal cut-set interpretation is that the runaway required the movement-enabling conditions B1–B6 together with at least one stopping/barrier failure from B7–B12. Therefore, removing any mandatory movement condition or ensuring the effectiveness of braking/safety barriers would interrupt the accident sequence.

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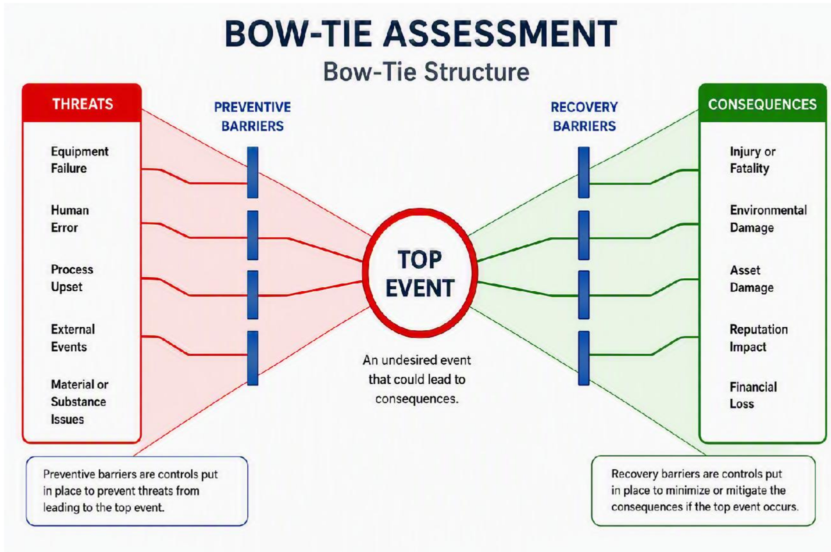

Figure 12. Bow-Tie structure used to connect threats, barriers, top event and consequences.

Bow-Tie analysis complements FTA by placing preventive barriers on the threat side and recovery barriers on the consequence side. The case is especially instructive because preventive barriers were defeated while communication and evacuation operated successfully as recovery barriers.

8. Corrective and Preventive Measures

Post-incident actions were evaluated against the identified root causes and the hierarchy of controls. The source study emphasizes that elimination and engineering controls provide more robust risk reduction than administrative controls alone.

Measure	Control level	Reported effectiveness	Primary risk addressed
Prohibit reverse movement with loaded muck cars	Elimination	High	Unsafe operating practice
Complete both launching-shaft tracks	Engineering	High	Infrastructure constraint
Connect air hoses to muck cars/rolling stock	Engineering	Very High	Brake continuity
Install flap stoppers	Engineering	High	Runaway containment
Establish STOP ZONES	Engineering	High	Gradient exposure
Relocate/strengthen Manchester Gate	Engineering + admin	Very High	Physical containment
Daily/joint brake inspections	Maintenance	High	Brake degradation
Emergency/dead-man function checks	Maintenance	High	Safety-device failure
Revise HIRA and SWM	Administrative	High	Risk-assessment gap
Banksman and gate-locking controls	Administrative	Moderate–High	Human dependence at barriers
Job-specific training and competency	Training	Moderate	Decision/skill gaps
Communication and evacuation improvements	Recovery	High	Consequence reduction

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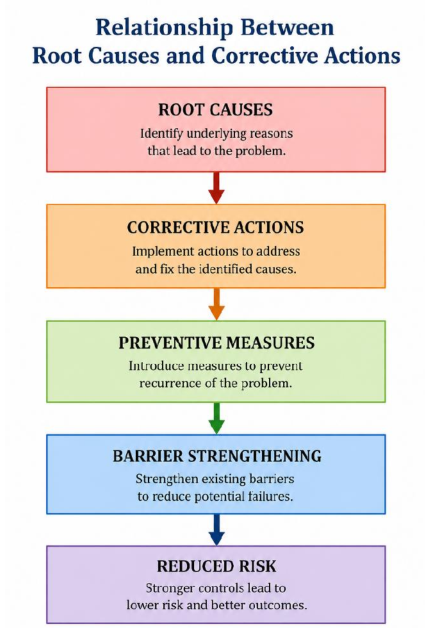

Figure 13. Relationship between root causes and corrective actions.

The combined effect was a shift from a system dependent on operator control toward a defense-in-depth system with independent engineering, administrative and recovery barriers.

8.1 Economic Impact and Hierarchy of Controls

Although the dangerous occurrence caused no reported personnel injury, the source investigation records a direct financial impact of approximately ₹1.01 crore. Equipment damage/replacement was approximately ₹97.6 lakh, while productivity and disruption losses were approximately ₹3.4 lakh.

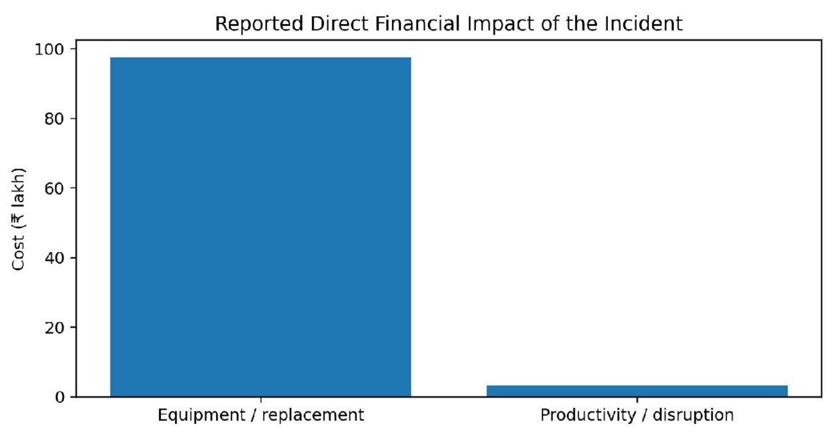

Figure 14. Reported incident cost breakdown derived directly from the source study values.

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Hierarchy level	Examples from the case	Relative robustness
Elimination	Prohibit reverse movement with loaded muck cars	Highest
Engineering	Air hoses, flap stoppers, STOP ZONES, track completion, gate relocation	High
Administrative	HIRA/SWM revision, SOPs, inspections, banksman	Moderate
Training	Job-specific training, competency awareness	Supporting
Recovery	Communication, evacuation, head count	Consequence reduction

The economic evidence reinforces the strategic value of prevention. The dominant cost component was equipment/replacement loss, while the potential human consequence was substantially more severe than the realized outcome. Investment in physical controls is therefore justified not only from a safety perspective but also from project continuity and business-resilience perspectives.

IX. DISCUSSION AND DEVELOPMENT OF THE TUNNEL HAULAGE SAFETY FRAMEWORK

The investigation demonstrates that tunnel locomotive safety must be managed as a complete transportation system. The most important technical lesson is that braking capability must be evaluated across the locomotive and connected rolling stock, under the actual gradient, load and operating configuration.

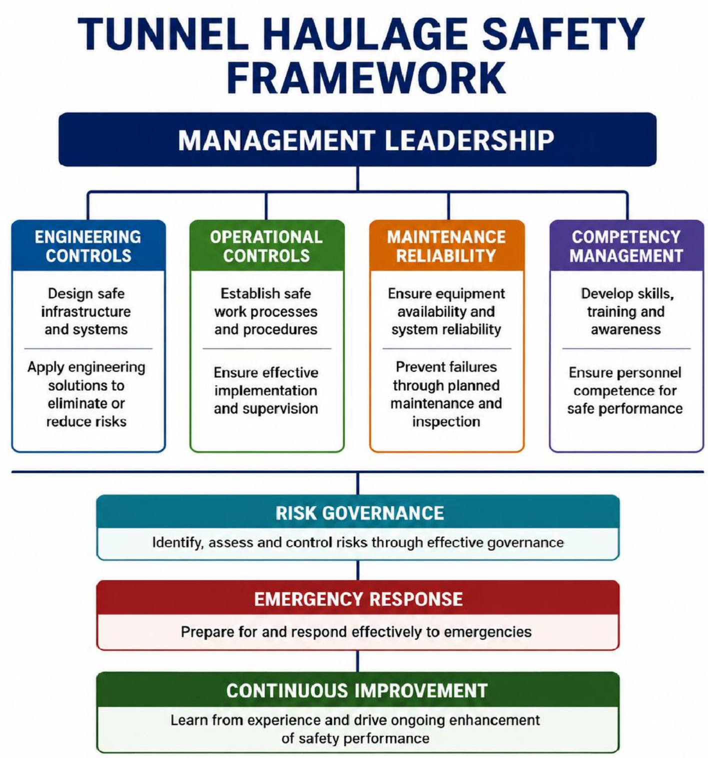

Figure 15. Tunnel Haulage Safety Framework developed in the source study.

9.1 Six Integrated Safety Pillars

Pillar	Core controls
1. Engineering Safety	Fail-safe braking; brake continuity; flap stoppers; runaway protection; gate placement; STOP ZONES; gradient management

2. Operational Safety	No loaded reverse movement; defined parking; track-change protocols; banksman; movement authorization; shift handover
3. Maintenance Reliability	Daily brake verification; air-hose inspection; emergency-stop/dead-man testing; pneumatic-system inspection; OEM audits
4. Competency Management	Locomotive operation; gradient awareness; risk perception; emergency drills; SWM implementation; abnormal decision-making
5. Risk Governance	Periodic HIRA review; dynamic risk assessment; management audits; control-effectiveness review; near-miss learning; leadership involvement
6. Emergency Preparedness	Walkie-talkies; backup communication; evacuation plans; drills; assembly; head-count protocols

The framework is intended to create multiple independent barriers so that failure of one control does not immediately produce loss of control.

9.2 Reliability, Risk Governance and Emergency Response

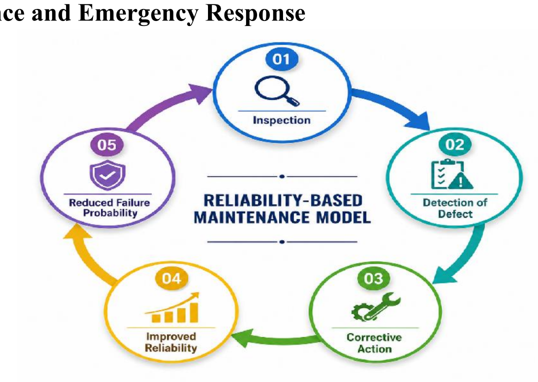

Figure 16. Reliability-based maintenance model from the source study.

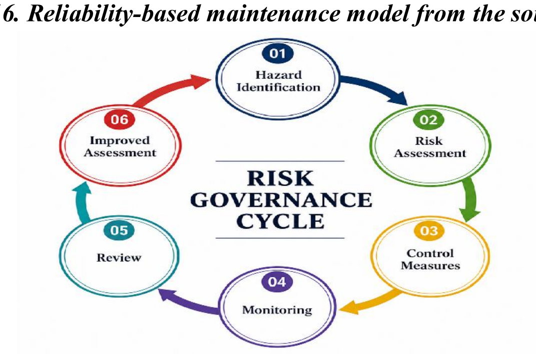

Figure 17. Risk governance cycle from the source study.

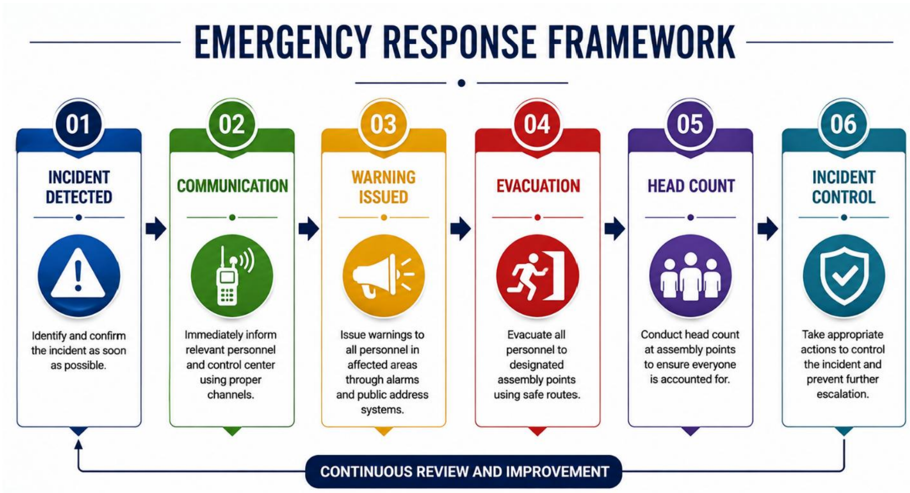

Figure 19. Emergency response framework from the source study.

Reliability-based maintenance should treat braking and safety devices as critical functions. Trend analysis of inspection findings, verification of pneumatic continuity and periodic OEM audits provide a stronger basis than reactive repair alone. Risk governance should ensure that HIRA and SWM remain dynamic as temporary track geometry, gradients, equipment configuration and work methods change.

9.3 Safety Performance Indicators

Leading indicators	Lagging indicators
Brake inspections completed	Locomotive derailments
Locomotive movements audited	Brake failures
HIRA reviews completed	Runaway events
Training attendance	Lost-time injuries
Competency certification status	Property-damage incidents
Near-miss reports	Emergency-response performance

The framework should be monitored using both leading and lagging indicators. Leading indicators provide early warning of barrier degradation, while lagging indicators demonstrate actual safety outcomes.

X. KEY FINDINGS AND TECHNICAL INTERPRETATION

10.1 Finding 1 – The Incident Was a System Failure

10.2 Finding 2 – Gradient Converted Brake Deficiency into Runaway

The approximately 4% gradient was a critical severity amplifier. Once braking capability became inadequate, gravitational force accelerated the loaded convoy toward the TBM. Gradient management must therefore be integrated into loading limits, parking locations, movement rules and emergency planning.

10.3 Finding 3 – Convoy Braking Must Be Treated as a System

The lack of pneumatic continuity meant that the locomotive alone was responsible for controlling the convoy. The corrective air-hose connection directly addresses this vulnerability and is one of the strongest technical improvements.

10.4 Finding 4 – Physical Barriers Must Follow Hazard Pathways

A barrier is only effective when its location, locking status and design correspond to the worst-case hazard trajectory. The Manchester Gate experience demonstrates that barrier presence alone does not guarantee barrier effectiveness.

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10.5 Finding 5 – Emergency Communication Prevented Injury

The emergency warning and evacuation actions were successful recovery barriers. The event therefore provides a positive lesson: redundant communication and practiced evacuation can prevent injuries even after preventive barriers fail.

10.6 Finding 6 – Dynamic HIRA is Essential

The original HIRA/SWM did not adequately address brake failure during reverse movement on a gradient. Temporary tunnel infrastructure changes can rapidly invalidate static assumptions; risk assessment must therefore be linked to management of change and operational authorization.

XI. RECOMMENDATIONS FOR FUTURE TUNNEL PROJECTS

Based on the integrated findings, the following recommendations are proposed for underground metro and tunnel construction projects using rail-based haulage:

Adopt fail-safe braking that automatically moves the system toward a safe state after loss of power, pressure or operator control.

Provide pneumatic braking continuity across locomotives and connected rolling stock and verify it before each operational shift.

Prohibit reverse movement of loaded muck locomotives except where an engineered, formally authorized method specifically demonstrates equivalent safety.

Complete and inspect temporary track infrastructure before operational use; prevent workarounds created by incomplete track.

Locate parking and switching arrangements on level sections wherever practicable and establish engineered STOP ZONES outside gradients.

Use independent physical runaway-arrest devices such as flap stoppers and correctly positioned Manchester Gates.

Require formal authorization and dynamic risk assessment for non-routine locomotive movements.

Implement joint brake inspections involving operations, mechanical maintenance and EHS personnel, with traceable records.

Test emergency stops, dead-man switches, pneumatic pressure and air-hose continuity as critical safety functions.

Strengthen competency assessment for operators, foremen, engineers and banksmen, with periodic revalidation rather than one-time training.

Integrate temporary track changes, gradients and haulage configurations into HIRA/SWM through management-of-change controls.

Maintain redundant communication, evacuation drills, assembly procedures and head-count protocols.

Use leading indicators to detect weakening barriers before a runaway or collision occurs.

Conduct periodic independent audits of the complete haulage system, including engineering design, operations, maintenance and risk governance.

11.1 Future Research

Future studies may extend this case using quantitative braking-force and stopping-distance models with complete mass distribution, real-time speed/pressure data and detailed gradient profiles. Multi-project datasets could also be used to compare tunnel haulage incidents and develop probabilistic reliability models for braking, containment and human-intervention barriers.

XII. CONCLUSIONS

The May 2024 locomotive runaway was a high-potential dangerous occurrence produced by the interaction of technical, operational, environmental, human and organizational weaknesses. The initiating operational decision was

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reverse movement of a loaded locomotive to resolve an unloading/track-arrangement problem. This placed the convoy on a gradient under conditions where braking demand was high.

FTA showed that the top event required a combination of movement-enabling conditions and failure of at least one stopping or safety barrier. This is significant because it demonstrates that the accident was preventable through multiple intervention points. Bow-Tie analysis further showed that preventive barriers were inadequate while emergency communication and evacuation successfully limited the consequences.

The most important engineering improvements were completion of the track arrangement, establishment of braking continuity through air hoses, installation of flap stoppers and STOP ZONES, and relocation/strengthening of Manchester Gate controls. Administrative and competency measures complemented these engineering controls through revised HIRA/SWM, inspections, supervision and training.

The study therefore concludes that tunnel haulage safety should be managed using a defense-in-depth philosophy supported by six integrated pillars: engineering safety, operational safety, maintenance reliability, competency management, risk governance and emergency preparedness.

XIII. RESEARCH CONTRIBUTION

The principal contribution of the study is the integration of accident-causation theory with engineering safety analysis to produce a practical Tunnel Haulage Safety Framework. The framework converts lessons from a single dangerous occurrence into a structured prevention model that can be adapted to future underground metro construction projects.

XIV. LIMITATIONS

The study is based on a single incident and documentary evidence. Complete real-time operational data, full weight distribution and detailed quantitative braking calculations were not available. Accordingly, the findings are intended as an evidence-based safety case and framework rather than a probabilistic prediction for every tunnel project.

REFERENCES AND SOURCE BASIS

The research paper is based primarily on the attached source document and the references contained within it. The following references are selected from that source to support the analytical framework.

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IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, August 2026
Impact Factor: 8.2

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DOI: 10.48175/IJARSCT-38134