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A Study on the Business Continuity Plan (BCP) Response Strategies for the Transport Vulnerable Through Urban Railway Lithium-ion Battery Fire Scenarios

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Abstract

Purpose: The purpose of this study is to analyze the fire risks associated with lithium-ion batteries in personal mobility devices (PMs) within urban railways and to propose emergency response strategies from a Business Continuity Planning (BCP) perspective to prevent and address these risks. In particular, the study aims to derive an effective safety management model by analyzing the critical impact that the physical vulnerability of underground spaces and thermal runaway phenomena have on the evacuation of vulnerable road users. **Research Method:** Scenarios were constructed based on existing railway accident databases and the Daegu subway fire case by setting variables such as fire scale, location of occurrence, and ventilation characteristics. Through this, the impact on the evacuation environment within underground spaces, such as the diffusion speed of toxic gases and reduced visibility during a lithium-ion battery fire, was quantitatively examined. **Results:** Analysis of the thermal runaway phase confirmed that heat transfer between battery cells begins approximately 2 to 5 minutes after the fire breaks out, leading to the rapid spread of toxic gases. In particular, the dense smoke generated by the fire drastically reduces visibility, revealing a survival threshold where voluntary evacuation by passengers becomes impossible. This suggests that an initial response system distinct from that for ordinary fires and the securing of special evacuation routes for the disabled are essential **Conclusion:** Given the unique characteristics of lithium-ion battery fires, it is urgent to introduce early off-gas detectors and expand specialized suppression equipment, such as Class D fire extinguishers and suffocation extinguishing blankets. Furthermore, to minimize casualties and maintain urban railway functions, an integrated safety management model must be established to secure a "30-minute golden time" for passenger safety in the subway environment by upgrading emergency response manuals for each accident stage and strengthening on-site response capabilities

Keywords : Lithium-ion battery. Urban rail fire, Personal Mobility Device (PM), Thermal Runaway. Business Continuity Plan (BCP). Transportation.

JEL Classification Code : R41,I38,D81

1. Introduction

1.1. Background and Necessity of the Study.

With the recent widespread adoption of Personal Mobility (PM) devices, carrying and boarding batteries on urban railways has become commonplace; however, this has also increased the risk of thermal runaway in lithium-ion batteries. Unlike ordinary fires, lithium-ion battery fires possess unique combustion characteristics: they begin with the release of off-gases, rapidly emit large quantities of toxic gases, and cause a drastic reduction in visibility.

In particular, the enclosed nature of underground spaces, where ventilation and evacuation routes are limited, accelerates the rapid spread of smoke and toxic gases upon a fire, making it highly likely to cause large-scale casualties. This environmental vulnerability is particularly fatal for vulnerable groups such as the elderly, the disabled, and pregnant women. It acts as a critical factor threatening their survival by increasing the Residual Time Set (RSET) while drastically shortening the Allowable Time Set (ASET).

Furthermore, as urban railways are critical national infrastructure, the suspension of operations due to fire results in massive social and economic losses. Therefore, it is essential to establish an emergency response system from a Business Continuity Planning (BCP) perspective to ensure human safety, including vulnerable transportation users, even in disaster situations, while simultaneously rapidly restoring and maintaining the functions of the urban railway. Accordingly, this study aims to present an effective response strategy capable of simultaneously securing human safety and material and functional business continuity by constructing a scenario for a lithium-ion battery fire in an urban railway.

1.2. Purpose of the study

This study aims to derive an integrated emergency response strategy that reflects the physical and behavioral characteristics of vulnerable transportation users from a Business Continuity Planning (BCP) perspective in the event of a lithium-ion battery fire within an urban railway station. Specifically, it seeks to comprehensively review the entire process step-by-step, ranging from the initial response and evacuation support systems immediately following a fire to the partial suspension and restoration of station and train operations, and finally, measures to ensure the continuity of transportation services. In particular by establishing physical mobility limitations experienced by vulnerable transportation users—such as the elderly, people with disabilities, and pregnant women—in environments involving flames and toxic gases as a key variable, this study quantitatively analyzes the limitations of existing evacuation systems and proposes practical supplementary measures.

Moving beyond the traditional disaster response paradigm centered on simple firefighting and evacuation, this study aims to construct an integrated model capable of simultaneously achieving "human life protection" and "operational continuity" within a single safety management system by applying a BCP framework designed to maintain and restore the core functions of urban railways even during disaster situations

1.3. Scope and Methodology of the Study

The spatial scope of this study is limited to underground subway stations and train interiors, and the disaster type is defined as fires involving portable lithium-ion batteries, including personal mobility devices (PMs), and the resulting thermal runaway phenomenon. The human scope and subjects of the study were restricted to vulnerable transportation users (such as the elderly, people with disabilities, and pregnant women) who are highly susceptible to evacuation among general passengers; the analysis focused on the physical and environmental risk factors and the necessity of emergency response that these individuals face during fire situations.

The specific methodology for conducting this study is as follows. First, qualitative and quantitative historical data were collected and analyzed, including existing railway accident databases and the Daegu subway fire case. Second, based on this, lithium-ion battery fire scenarios were directly constructed by establishing key variables such as fire scale, location of occurrence, and ventilation characteristics. Additionally, the impact of toxic gas diffusion speeds and reduced visibility after a fire on the evacuation environment of vulnerable transportation users, as well as their survival limits, were quantitatively derived. While existing studies have primarily focused on establishing uniform Standard Operating Procedures (SOPs) centered on general passengers, this study is distinguished by achieving two core values—guaranteeing the safety rights of vulnerable passengers and maintaining Business Continuity Plans (BCP) for urban railways—simultaneously within a single system. In conclusion, this study aims to propose an advanced integrated railway safety management model capable of implementing inclusive safety services without exclusion even in disaster situations by establishing step-by-step response strategies based on quantitative scenarios.

2. Theoretical Background

2.1. Fire characteristics and thermal runaway of lithium-ion batteries

Although lithium-ion batteries possess very high energy density, they contain flammable electrolytes that exhibit combustion characteristics distinctly different from ordinary flammable materials upon ignition. When the internal temperature of the battery reaches a critical point due to various causes such as external impact, overcharging, or internal short circuits, a thermal runaway phenomenon occurs, involving the thermal decomposition of the cathode material and the spontaneous release of oxygen. The chain explosions and large quantities of toxic gases generated during this process are extremely difficult to control with conventional fire extinguishers. In particular, thermal runaways in enclosed underground spaces can cause a rapid increase in smoke concentration, leading to a serious situation where visibility is instantly obstructed.

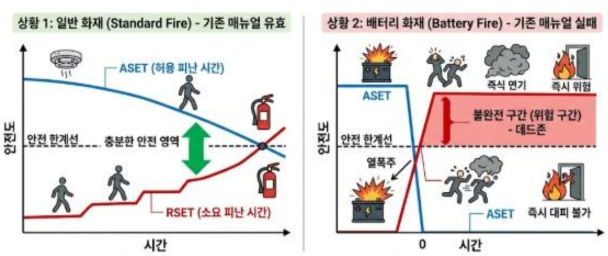

Figure 1: Conceptual diagram of dynamic changes in ASET and RSET due to thermal runaway during a battery fire

The explosive combustion characteristics of such battery fires lead to a severe imbalance between the Available Evacuation Time (ASET) and the Required Evacuation Time (RSET), which are key indicators in fire safety engineering. As shown in (fig. 1), in the case of a general fire, smoke diffusion and heat accumulation are relatively gradual, providing a sufficient safety margin where the RSET remains within the ASET. In contrast, in lithium-ion battery fires, toxic gases surge as thermal transfer between cells begins approximately 2 to 5 minutes after occurrence. Consequently, the ASET curve drops nearly vertically and intersects the RSET curve, causing the "survival threshold" where survival becomes impossible to be brought forward dramatically compared to a general fire. As a result, an unavoidable zone where the ASET becomes smaller than the RSET is formed at an extremely early stage, which acts as a key factor undermining the effectiveness of existing fire response manuals.

2.2. Analysis of Evacuation Hindering Factors through Subway Fire Cases

This study analyzed the past Daegu subway fire incident to examine the validity of lithium-ion battery fire scenarios and derive empirical implications. Although the accident was caused by intentional arson, it shares a high degree of similarity with the risks associated with battery thermal runaway fires in that flames and toxic gases rapidly spread horizontally and vertically within the enclosed underground station, drastically shortening the Available Sage Egress Time (ASET). In particular, the paralysis of lighting and the loss of guidance systems due to the power outage immediately following the accident maximized passengers' fear and caused them to lose their sense of direction. Consequently, this led to an explosive increase in the Responsible Set Time (RSET) of the vulnerable, becoming a decisive cause of large-scale casualties. This serves as strong empirical evidence supporting the necessity of the strategies proposed in this study, specifically the 'rapid transition to a manual rescue system' and the 'priority allocation of emergency power to evacuation and disaster prevention facilities,' within the BCP-based response system.

2.3. Evacuation Characteristics and Safety Indicators for the Transport Vulnerable

Among urban railway users, the transportation vulnerable are exposed to significantly higher risks than the general population in the event of a disaster due to physical and cognitive limitations. Wheelchair users and the elderly not only have walking speeds that are less than 50% of those of average adults, but they also tend to rely absolutely on specific vertical means of transportation, such as elevators, as they are unable to evacuate independently via stairs.

In the event of a battery fire, the Advancement Time to Evacuate (ASET), which is the time available for evacuation, decreases to a critical threshold due to the rapid spread of toxic gases, whereas the Restricted Time to Evacuate (RSET) for the transportation vulnerable, who have significant mobility limitations, continues to increase. Therefore, there are clear limitations to guaranteeing their safety using only uniform and general evacuation manuals, and a differentiated evacuation safety evaluation system that considers the dynamic evacuation characteristics of the transportation vulnerable is required.

2.4. Application of Business Continuity Planning (BCP) to Urban Rail and Strategic Value

A Business Continuity Plan (BCP) is a strategic management framework designed to maintain an organization's core functions without interruption in the event of a disaster, and to restore core services within a target timeframe even if operations are interrupted. When applied to urban railway safety management, this shifts the focus from simple building-centered evacuation to ensuring "Mobility Continuity" for the vulnerable. This implies that even in extreme situations like a fire, minimal evacuation and mobility services, along with customized safety guidance, must be provided without interruption for the vulnerable.

This study addresses measures to secure the Recovery Time Objective (RTO) and system resilience under the worst-case scenario of a lithium-ion battery fire. Through this, the study aims to establish an integrated safety management framework that can rapidly restore and sustain public services in the urban railway while robustly guaranteeing the safety rights of the vulnerable.

3. Emergency Response Scenarios by Situation

3.1. Scenario Setting Background and Risk Definition

This chapter aims to construct an emergency response scenario assuming a worst-case fire situation within an urban railway underground station by combining the thermal runaway characteristics of lithium-ion batteries discussed earlier with evacuation constraints for vulnerable road users. In particular, focusing on the analysis results that toxic gases rapidly spread within 2 to 5 minutes after thermal transfer between battery cells begins, a Business Continuity Plan (BCP) strategy was established to minimize the gap between the Available Evacuation Time (ASET) and the Required Evacuation Time (RSET) for Vulnerable Road Users.

The initial response phase (T+0 to 5 minutes) focused on securing the Tenability Limit by completing initial fire suppression and the operation of smoke control equipment within physical time limits. To this end, an advanced rapid initial response system was designed, which is more sophisticated than a standard fire response manual.

Each scenario was structured around the core components of BCP: Risk Analysis, Response Strategy, and Action Plan. This scenario sets the ‘30-minute golden time’ for human safety and ‘Mobility Continuity’ for the transportation vulnerable as top priorities and presents quantitative guidelines such as the step-by-step roles of the operating entity and Recovery Time Objective (RTO) to achieve this as shown in Table 1.

Table 1: BCP Implementation Plan (Example)

Time	Activities	Objecctives&RTO
T + 0-5 min (Initial Response Phase)	Ma• Detection of off-gas and activation of specialized SOP • Maximum operation of smoke control systems in the underground station	• Maximizing ASET (Available Safe Egress Time) • Ensuring visibility within 2–5 minutes before thermal runaway occurs
T + 5-15 min (Evacuation & Suppression Phase) an risk	• Activation of 1:1 guided evacuation system for transport vulnerable • Mitigation of initial fire spread using Class D fire extinguishers and fire blankets	• Zero fatalities (Completion of rescue operations before reaching **lethal concentrations** of toxic gas)
T + 30-60 min (Recovery & Continuity Phase)	• Initiation of **decontamination** and recovery of core station facilities and track sections • Connection with alternative transportation modes and announcement of operational normalization	• Securing the **30-minute golden time** and ensuring system resilience • Restoring mobility continuity for the transport vulnerable and achieving **RTO**

3.2. Analysis of detailed scenarios by situation

3.2.1. Scenario 1: PM Heat Runaway on Platform and Isolation of Vulnerable Passengers

1) Incident Situation

An explosive thermal runaway occurred within 2 minutes of off- gas being released from a Personal Mobility Device (PM) left unattended in the central waiting area for the disabled at the underground station platform.

2) BCP Risk Analysis

As dense smoke and toxic gases generated by the thermal runaway rapidly spread along the ceiling to the passageways and evacuation routes, the access route to the elevator—the only means of vertical transportation for the disabled—faced a crisis of being completely blocked.

3) BCP Response Strategy

① Immediate Action: Immediately upon detection of the fire, the smoke control system in the affected area was activated at maximum output to secure visibility within the evacuation route, thereby maximizing the Allowable Evacuation Time (ASET) for the disabled.

② Continuity Management: The elevator within the platform is blocked from stopping at the floor where the fire occurred (the relevant floor), but the system is automatically switched to remain on standby at an adjacent floor to maintain the continuity of vertical movement.

③ Human Resources: The ‘Task Force for the Transport Vulnerable (TF)’ established within the Urban Railway Operations Team is immediately deployed to activate a 1:1 matching rescue system for the transport vulnerable who are unable to evacuate on their own.

4) BCP Action Plan

Disaster prevention capabilities were concentrated on preventing the isolation of the transport vulnerable in the event of toxic gas spread caused by PM thermal runaway within the platform. The detailed timeline plan is shown in Table 2.

Table 2: BCP Implementation Plan (PM Heat Runaway and Isolation of Vulnerable Road Users)

Time	Activities	Key Activities	Objectives
1T + 0–5 min (Initial Response Phase)	Control Room & On-site Staff	• Immediate activation of Emergency Standard Operating Procedures (SOP) upon off-gas detection • Maximum operation of smoke control systems in the affected zone and broadcasting evacuation announcements • Switching elevators to dedicated evacuation mode (bypassing the fire floor and staging at adjacent floors), maintaining LMS access, situational broadcasting	Initial response and ensuring visibility
T + 5–15 min (Evacuation & Suppression)	Dedicated Rescue Task Force (TF) for the Transport Vulnerable	• Real-time tracking of the transport vulnerable using AI CCTV and beacon technology • Dispatching dedicated rescue personnel to the scene for 1:1 guided evacuation of the transport vulnerable • Mitigating initial spread of battery thermal runaway using Class D fire extinguishers and fire blankets	Life safety evacuation and preventing fire spread
T + 10–30 min (Movement Control)	Operations Team & External Agencies	• Providing digital guidance for optimal alternative routes (Secondary Routes) if primary evacuation routes are blocked • Maintaining availability of vertical transit (elevators) for wheelchair users and others • Providing guidance for tunnel evacuation links or detours to adjacent stations if necessary	Ensuring mobility continuity for the transport vulnerable
T + 10–40 min (Intermodal Transport)	Service Support Team	• Requesting dispatch of alternative transport (low-floor buses, dedicated call taxis) in preparation for station closure • Providing protection and medical services for the transport vulnerable who have completed ground evacuation	Preventing disruption of external mobility rights
T + 30–60 min (Recovery & Resumption)	Recovery Team & Safety Inspection Team	• Conducting decontamination of core facilities (elevators, air purification) within the Recovery Time Objective (RTO) • Clearing battery debris and re-inspecting the normal operation of fire protection systems • Announcing the resumption of urban railway services and normalizing operations	Prompt restoration of public services

3.2.2. Scenario 2: Battery fire in train carriage and emergency stop while in motion

1) Incident Situation

One minute prior to entering the station, toxic gases filled the enclosed passenger compartment due to a fire caused by a battery carried by a passenger inside the moving train. Passengers facing survival limits rapidly moved to adjacent cars, resulting in extreme chaos and a risk of stampede within the carriage.

2) BCP Risk Factors (Risk Analysis)

Due to backflow and pushing phenomena caused by the chaotic evacuation crowd, the movement paths of wheelchair users and the elderly were completely blocked. Additionally, upon stopping at the station platform, the evacuation lines of general passengers overlapped with the disembarking routes of passengers with disabilities, causing severe bottlenecks and posing a very high risk of disembarkation delays.

3) BCP Response Strategy

① Core Task: The control center identified the exact location of the burning carriage in real-time and pre-positioned station rescue teams in front of the corresponding Platform Screen Doors (PSD) at the adjacent station where the train is to stop.

② Information Provision: Individual guidance is provided to passengers with disabilities via dedicated announcements and mobile app notifications to "disembark at a specific door (safety door) where a rescue team is waiting," separating them from the general evacuation crowd.

③ Service Restoration: To ensure external mobility continuity in case the station is closed for fire suppression and decontamination after disembarking, alternative means of transportation, such as low-floor buses or taxis for the disabled, are connected immediately upon evacuation to the ground level.

4) BCP Action Plan

Securing the safety of passengers with disabilities and ensuring mobility continuity in the event of a battery fire on the train has been set as the top priority. The aim is to minimize casualties by establishing a phased response system that extends from securing rapid rescue points in the initial stages of the accident to emergency evacuation and the connection of alternative transportation methods; the detailed timeline plan is shown in Table 3.

Table 3: BCP Action Plan (In-cabin Battery Fire & Emergency Stop)

Time	Activities	Key Activities	Objectives
1T + 0–5 min (Initial Response Phase)	Control Room & Train Driver	• Identify the location of the fire-affected car and standby for synchronization with the Platform Screen Doors (PSD) at the adjacent station. • Announce designated disembarking doors for mobility-impaired individuals via on-board emergency broadcasting. • Urgently pre-deploy the station rescue team to the scheduled stopping position of the fire-affected car.	Pre-securing rescue contact points
T + 5–15 min (Evacuation & Isolation)	Field Rescue Team (Station Staff)	• Guide the priority disembarkation of mobility-impaired individuals and crowd separation immediately upon train stop. • Urgently transport passengers with mobility constraints, such as wheelchair users, to safe zones within the platform. • Operate fire shutters and ventilation/smoke control systems to block the influx of toxic gas.	Rapid disembarkation and safe isolation
T + 10–30 min (Operations Control)	Operations Team & Control Room	• Decide on the suspension of the affected train's operation and control subsequent trains. • Decouple the fire-affected car and provide passenger detour route information to adjacent stations. • Activate the customized ground-level evacuation route guide for mobility-impaired individuals in the event of station closure.	Operations control and accelerated evacuation
T + 10–40 min (Connected Transport)	Service Support Team	• Link alternative transportation: Request immediate dispatch of low-floor buses, call taxis for the disabled, etc. • Provide dedicated guidance for mobility-impaired individuals to ensure continuity of movement to their destinations.	Ensuring continuity of movement
T + 30–60 min (Recovery & Resumption)	Safety Inspection Team & Recovery Team	• Decontaminate the train interior and collect fire cause debris. • Determine the Recovery Time Objective (RTO) for core services after safety inspections of platforms and tracks. • Announce the normalization of operations and verify the availability of facilities for the mobility-impaired.	Rapid service recovery

3.2.3. Scenario 2: Subway Station Power Outage and System Shutdown due to Fire Spread

1) Incident Situation

Intense heat and toxic gases from a lithium-ion battery fire spread to the station's distribution panels and communication trays, resulting in a complete shutdown of commercial power within the station and a temporary suspension of the central monitoring system.

2) BCP Risk Factors (Risk Analysis)

Due to insufficient lighting within the station, platforms and concourses are instantly plunged into total darkness, causing evacuating passengers to lose their sense of direction. In particular, vertical transit systems such as elevators and escalators come to a complete halt, maximizing the risk of mobility-impaired individuals becoming trapped deep underground. Furthermore, visually and hearing-impaired individuals face complete information isolation as public address speakers and electronic displays cease operation, making it impossible for them to grasp the emergency situation or evacuation procedures.

3) BCP Response Strategy

① Resilience: Immediately upon the interruption of commercial power, battery-powered emergency lighting and standalone voice guidance devices are activated to visually and audibly secure a minimum evacuation route that can be perceived by the vulnerable even in a blackout.

② Manual Transition: Since rescue operations based on automated systems are impossible, the system is immediately switched to a ‘human-based manual rescue system’ centered on station staff and security guards, utilizing stair-moving rescue chairs and makeshift stretchers available within the station.

③ Power Priority: When the emergency generator is activated, the limited power is not distributed to general facilities; instead, power is prioritized for allocation to air purification facilities and essential transport equipment in designated evacuation zones for the vulnerable, in accordance with the BCP resource management protocol.

4) BCP Action Plan

It was established under the assumption of a worst-case scenario involving power paralysis and system shutdown within the station due to the spread of fire. The focus was on ensuring the safety of the vulnerable by immediately switching to a manual rescue system, even in extreme environments where computer networks and automated facilities become inoperable. Through a step-by-step response ranging from the strategic distribution of emergency power to one-on-one close rescue utilizing personnel and ground-based transportation, the system was designed to prevent any system gaps from leading to life-threatening situations for the vulnerable. The detailed timeline plan is shown in Table 4.

Table 4: BCP Implementation Plan (Response to Power Outage and System Downtime)

Time	Activities	Key Activities	Objectives
1T + 0–5 min (Initial Response Phase)	On-site Safety Personnel& Integrated Control Room	• Immediately verify the activation of battery-backed emergency lighting and voice guidance systems upon commercial power failure. • Declare system downtime and issue an order to transition to the Manual Response system. •Initiate emergency generators and prioritize emergency power allocation to zones designated for the mobility-impaired.	Secure Emergency Power & Provide Guidance
T + 5–15 min (Emergency Command & Rescue)	Dedicated Rescue Task Force (TF)	• Search for and locate the mobility-impaired (visually/hearing impaired, etc.) within blackout areas. • Initiate manual rescue operations utilizing evacuation chairs for stairs and manual wheelchairs. •Form buddy systems (evacuation assistants) to provide 1:1 close-contact care.	Manual-Based Emergency Rescue
T + 10–30 min (Isolation & Recovery)	Operations Team & Recovery Team	• Isolate the area causing the power failure and attempt to restore the communication network. • Manually close fire doors to prevent fire spread and conduct safety inspections on adjacent pathways. • Establish ground-level shelters and share real-time rescue data with external emergency services.	Hazard Isolation & Initiation of Recovery

T + 10–40 min (Mobility Support)	Service Support Team	• Mitigate mobility gaps: Immediately deploy ground-linked transit (low-floor buses, etc.) if power restoration is delayed. • Assess the health status of rescued mobility-impaired individuals and support their transfer to temporary staging areas.	Minimization of Mobility Gaps
T + 30–60 min (Core Restoration)	Technical Recovery Team & Safety Assessment Team	• Prioritize power restoration for core facilities (elevators, air purification systems). • RTO Management: Normalize major facilities for the mobility-impaired and complete decontamination within target times. • Conduct system restart checks and officially declare the resumption of normal operations.	Core Service Restoration

3.2.4. Scenario 4: Passageway Fire and Severed Evacuation Route at a Complex Transfer Station

1) Incident Situation

A fire caused by a Personal Mobility (PM) device occurs in a key transfer passageway connecting subway lines. As a result, escalators, elevators, and ramps—the primary routes for the mobility-impaired—instantly enter the fire's impact zone (flames and dense smoke) and are physically blocked.

2) BCP Risk Factors (Risk Analysis)

Due to the complex organization and structure of complex transfer stations, it is extremely difficult for the mobility-impaired to independently determine alternative detour routes if the dedicated routes they are accustomed to using are blocked. Furthermore, during peak hours or periods of high traffic volume, the movement of the mobility-impaired may become entangled with that of large transfer crowds attempting to escape the fire, potentially leading to large-scale casualties (bottlenecks and the risk of crowd crush) caused by falls or being pushed.

3) BCP Response Strategy

① Route Diversion: Immediately upon the blockage of the main transfer passageway, digital signage and voice guides providing real-time dynamic detour evacuation routes (Route 2) are activated to disperse crowds and provide safe evacuation routes.

② Integrated Protection: A real-time integrated control system with adjacent lines where no fire occurred is activated. Areas free from smoke inflow, such as platforms or concourses of other lines, are designated as 'Temporary Safe Zones' to provide isolated protection for the mobility-impaired.

③ Intermodal Continuity: To minimize mobility gaps caused by the disruption of the transfer axis, ground-level hubs outside the station are utilized to secure ground-level detour routes connecting to other lines, and alternative transportation methods are prepared.

4) BCP Action Plan

Considering the characteristics of a complex transfer station with a complex structure and high volume of pedestrian traffic, the focus was placed on preventing cascading damage between lines and securing mobility options for the mobility-impaired. In the event of a fire paralyzing a specific transfer passage, the plan aims to prevent human isolation by immediately deciding to pass through without stopping and activating a joint rescue system between routes. In particular, it is designed to maintain mobility continuity for the mobility-impaired even within a complex transportation network by connecting ground hubs to replace severed transfer routes and dispatching wide-area shuttle buses. The detailed timeline plan is shown in Table 5.

Table 5: BCP Action Plan (Response to the Disruption of Complex Transfer Passageways)

Time	Activities	Key Activities	Objectives
1T + 0–5 min (Initial Response Phase)	Integrated Control Center & Transfer Station Management Office	• Immediately determine fire occurrence and decide whether to close the transfer passageway. • Issue orders for non-stop pass-through or slow-speed operation to trains on other lines. • Activate emergency broadcasting and evacuation guide lights dedicated to the mobility-impaired within the transfer zone.	Preventing Fire Spread & Information Dissemination

T + 5–15 min (Evacuation & Suppression Stage)	Joint Rescue Task Force (TF) across Lines	• Activate an integrated command system for rescue personnel from each line and intensively deploy them to the transfer passageway. • Conduct rescues based on real-time digital maps for the mobility-impaired isolated within the complex structure. • Operate vertical and horizontal fire shutters to prevent smoke from inflowing into other lines.	Intensive Rescue in the Transfer Zone
T + 10–30 min (Operations Control Stage)	Operations Management Team	• Secure Network Continuity: Adjust interconnected operations with other lines and establish detour routes. • Guide the mobility-impaired who planned to transfer to alternative lines via above-ground hubs outside the station. • Support movement to direct ground-level elevators in the event of transfer elevator shutdowns.	Diversification of Travel Routesy
T + 10–40 min (Intermodal Transport Stage)	Service Support Team	• Deploy shuttle buses and alternative transportation modes on a large scale to guarantee regional mobility rights. • Provide real-time mobile and signage updates on alternative routes for passengers who failed to transfer.	Maintenance of Regional Services
T + 30–60 min (Recovery & Resumption Stage)	Combined Recovery Team & Safety Inspection Team	• Precisely measure the spread of contamination between lines and prioritize decontamination of core transfer passageways • RTO Management: Decide on resuming operations after prioritizing the restoration of transfer convenience facilities (ramps, elevators). • Declare full network normalization and confirm the restoration of mobility for the mobility-impaired..	Network Recovery

3.2.5. Scenario 4: Passageway Fire and Severed Evacuation Route at a Complex Transfer Station

1) Incident Situation

This scenario assumes a fire that originates inside a train—either due to arson or the thermal runaway of a lithium-ion battery in a Personal Mobility (PM) device—and subsequently spreads throughout the entire station. Similar to the historical Daegu subway fire, within 2 to 5 minutes of ignition, explosive off-gas and high concentrations of toxic gas rapidly propagate to the upper-level concourse via horizontal and vertical passageways. Consequently, the main transit routes within the station (stairs and escalators) are engulfed in dense smoke, confronting vulnerable road users with a critical crisis where their physical evacuation routes are completely severed.

2) BCP Risk Factors (Risk Analysis)

Immediate loss of visibility due to thick smoke and off-gas. Shutdown of major systems within the station due to fire spread and power outage. Development of the risk of isolation for the vulnerable due to the paralysis of vertical transportation means (standard elevators, etc.).

3) BCP Response Strategy

Reflecting the lessons learned from the historical Daegu subway fire, a modern convergence strategy is applied to maintain operational continuity even under total system failure.

① **Integrated Control and Isolation:** Through real-time integrated control across multiple lines, the influx of additional trains and transferring passengers into the affected line is immediately blocked. Concurrently, vulnerable road users are isolated and protected within designated safe zones (fire compartments) fully equipped with smoke control systems.

② **Multi-Path Guidance:** To ensure functionality even under extreme conditions where the central control system is paralyzed, digital guide panels and voice induction devices powered by Uninterruptible Power Supplies (UPS) are activated to provide real-time, alternative evacuation routes for vulnerable road users.

Immediate loss of visibility due to thick smoke and off-

4) BCP Action Plan

The historical Daegu subway fire was heavily characterized by compounded casualties resulting from a combination of the "physical disruption of evacuation routes" and a "lack of real-time disaster information." To overcome these vulnerabilities, this study establishes a timeline-specific action plan focused on ensuring the mobility continuity of vulnerable road users until the very end, even amidst partial failures of the station systems. The detailed timeline-based plan is presented in Table 6.

Table 6: BCP Action Plan (Evacuation Route Disruption and System Paralysis)

Time	Activities	Key Activities	Objectives
1T + 0–5 min (Initial Response Phase)	Integrated Control Center & Transfer Station Management Office	• Implement non-stop bypass operations for trains on the fire-affected line. • Block new entries into the fire zone and transfer passageways, and broadcast emergency evacuation announcements. • Verify the operational status of independent power-based emergency lighting and voice induction devices.	Containment of damage spread & securing baseline visibility
T + 5–15 min (Evacuation & Suppression Phase)	Vulnerable Road Users (VRU) Rescue Team	• Track the real-time locations of vulnerable road users within dense smoke zones using Uninterruptible Power Supply (UPS)-linked AI and CCTV systems. • Execute vertical evacuation utilizing manual wheelchairs and evacuation chairs through 1:1 matching.	Lifesaving within the shortest possible time

T + 10–30 min (Operations Control Phase)	Operations Management Team	• Open emergency direct-connect elevators and evacuation exits to substitute for the disrupted transfer routes. • Provide alternative evacuation route guidance and diversify transit paths by adjusting interconnected operations with other lines.	Diversification of movement routes
T + 10–40 min (Intermodal Transport Phase)	Service Support Team	• Establish connections to ground transportation hubs due to station closure (emergency dispatch of low-floor buses and specialized taxis for the disabled). • Provide emergency medical support and alternative transportation information for the rescued vulnerable road users.	Ensuring Mobility Continuity for vulnerable road users
T + 30–60 min (Recovery & Resumption Phase)	Combined Recovery Team & Safety Diagnostics Team	• Decontaminate core transfer pathways and restore power systems to achieve recovery within the Recovery Time Objective (RTO). • Announce final normal operations after conducting facility safety diagnostics and system restart inspections.	Restoration of core services

4. Strategies for Enhancing BCP-based Res ponse for Vulnerable Road Users

BCP (Business Continuity Plan)-based response strategies go beyond the technical limitations of merely suppressing disasters; instead, they focus on simultaneously guaranteeing both the safety and mobility rights of vulnerable road users even under extreme disaster conditions. This will serve as a concrete approach to substantially enhancing the disaster resilience of urban railway infrastructure in response to emerging disasters such as lithium-ion battery thermal runaway.

4.1. Advancement of Technical Infrastructure: E arly Detection and Initial Suppression

In order to secure the golden time for lithium-ion b attery fires, improvements to the physical disaster prev ention environment must be prioritized

1) Introduction of an Early Off-Gas Detection System:
A system will be implemented to detect trace gases (off-gas) emitted during the pre-thermal runaway stage of batteries. By triggering emergency alarms earlier than standard smoke detectors, this system pre-secures additional evacuation time (safety margin) for vulnerable road users with limited mobility.

2) Expansion and Deployment of Specialized Fire Suppression Equipment:
Considering that battery fires cannot be extinguished with standard fire extinguishers, dedicated Class D fire extinguishers and fire blankets for initial suffocation will be preferentially deployed in waiting areas for vulnerable road users and personal mobility (PM) storage/charging zones to block the spread of fire at an early stage.

3) Strengthening Specialized Emergency Guidance Facilities for Vulnerable Road Users:
To prepare for the complete loss of visibility caused by dense smoke and blackouts during a fire, independent wireless power-based voice induction devices and floor-level flashing guide lights will be reinforced. In addition, high-intensity visual alarm systems for the hearing-impaired will be expanded to eliminate blind spots in disaster information dissemination.

4.2. Strengthening Systemic Response Capability : Ensuring Mobility Continuity

The core of an urban railway BCP is to ensure that "Mobility", a critical service, is not completely suspended even during a disaster

1) Optimization of Evacuation Elevator Operation Algorithms:

This steps away from the rigid conventional disaster prevention method of forcibly anchoring elevators to floors below the fire level. Instead, it activates a "Vulnerable Road User (VRU)-exclusive evacuation mode" algorithm that interfaces real-time smoke propagation path analysis with the hoistway pressurization smoke control system to safely transport vulnerable road users to the ground level.

2) Real-Time Location-Based Dynamic Control:

The locations of vulnerable road users are tracked in real time by linking AI CCTVs installed inside the station with beacon technology. Based on this data, optimal, dynamic evacuation routes that bypass the propagation paths of toxic fire gases are provided via smart digital guide panels and mobile devices.

3) Establishing an Intermodal Transport Linkage System (Mobility Partnership):

In the event that a specific station is inevitably closed due to fire and dense smoke, an interconnected system is activated to immediately dispatch low-floor buses and specialized call taxis (e.g., taxis for the disabled). This ensures that vulnerable road users who rely on the affected station can travel to their final destinations without disruption, thereby realizing mobility continuity.

4.3. Improving Personnel Response Framework: Field Response and Recovery Strategies

A personnel-centered emergency response guideline is established to function even in extreme situations where systems and physical infrastructure are paralyzed.

1) Operation of a Dedicated Rescue Team for Vulnerable Road Users (Vulnerable Support Team):

Customized rescue techniques for different types of vulnerable road users (e.g., individuals with physical, visual, or hearing impairments, and the elderly) and training on the utilization of manual evacuation chairs are institutionalized for station staff and transit police, ensuring their immediate deployment upon fire outbreak.

2) Upgrading Step-by-Step Standard Operating Procedures (SOPs):

The response entities and their respective roles are explicitly defined for each accident stage. Moving away from traditional fire-suppression-centered metrics, BCP-specific indicators are applied to comprehensively evaluate and manage both "lifesaving efficiency" and "continuity of urban railway operations."

3) Infrastructure Resilience via Recovery Time Objective (RTO) Management:

Immediately after fire suppression, priority is given to measuring toxic substance contamination levels and executing decontamination on facilities essential for the movement of vulnerable road users (e.g., elevators, wheelchair lifts, and ramps), thereby minimizing the Recovery Time Objective (RTO) for services targeting vulnerable road users.

4.4. BCP-Based Urban Railway Framework

The BCP-based urban railway framework proposed in this study is a cyclical system that integrates and manages three stages—technology, system, personnel, and recovery—by combining the specific characteristics of lithium-ion battery fires with the evacuation constraints of vulnerable road users.

Stage 1: Technical Infrastructure Advancement (Early Detection & Initial Response)
This stage involves activating early Standard Operating Procedures (SOPs) through the off-gas detection system and blocking the spread of fire at an early stage utilizing specialized fire suppression equipment (Class D fire extinguishers, fire blankets).

Stage 2: Systemic Response Capability Enhancement (Evacuation & Mobility Continuity)
This stage guarantees the mobility continuity of vulnerable road users through the operation of evacuation elevators based on pressurized smoke control facilities, the provision of AI and beacon-linked dynamic evacuation guidance, and connections to ground-level alternative transport such as low-floor buses and specialized call taxis for the disabled.

Stage 3: Personnel Response System & Recovery Strategy (Recovery & Service Resumption)
This stage focuses on minimizing casualties under system paralysis conditions through specialized rescue personnel, and achieving resilience by prioritizing the restoration of essential mobility facilities (elevators, air purification systems, etc.) within the Recovery Time Objective (RTO) to transition back to normal operations.

Figure 2: BCP-Based Subway Fire Response Framework

5. Conclusion

Based on a novel disaster scenario of lithium-ion battery fires within urban railway stations, this study examined response strategies from a Business Continuity Plan (BCP) perspective to simultaneously ensure the safety of the mobility-impaired and the business continuity of urban railway services. The main findings and academic/practical implications of this study are as follows

First, the study identified the evacuation limitations of the mobility-impaired inherent to the characteristics of lithium-ion battery fires. The battery thermal runaway phenomenon causes a rapid diffusion of toxic gases (off gases) and a sharp decline in visibility within approximately 2 to 5 minutes of fire onset. This serves as a critical factor that causes the Required Safe Egress Time (SET for the mobility-impaired—who face significant movement restrictions—to exceed the Available Safe Egress Time (SET. Consequently, this confirms that existing building-centric fire response manuals possess fundamental limitations in guaranteeing their safety

Second, a three-stage integrated response framework based on BCP was proposed to ensure 'Mobility Continuity' for the mobility-impaired. Moving beyond fragmented, reactive responses centered solely on firefighting and evacuation, this study established a system that seamlessly guarantees the mobility rights of vulnerable populations even during disasters. This was achieved by optimizing evacuation elevator operation algorithms linked to positive-pressure smoke control systems and integrating them with alternative ground transportation (e.g., low-floor buses, specialized call taxis for the disabled). This framework is highly significant as it lays a systemic foundation to practically maintain the 'right to mobility' for vulnerable groups during emergencies.

Third, technological advancement measures and quantitative management indicators were presented to minimize casualties. The off-gas early detection system and battery-specific firefighting equipment (Class D fire extinguishers, fire blankets), implemented to secure the '30-minute golden time' for rescue operations, will serve as core infrastructure providing the essential additional safety margin for the mobility-impaired. In addition, by managing the Recovery Time Objective (RTO) during the recovery phase, a concrete pathway for the rapid normalization of essential facilities for the mobility-impaired following an accident was specified.

In conclusion, the BCP-based framework presented in this study prioritizes securing human safety and mobility continuity, aiming for the integrated management of technology, systems, and human resources. This model holds substantial academic and practical value as an 'Inclusive Safety Management Model' that effectively protects the rights of the mobility-impaired and enhances the disaster resilience of public infrastructure, even in extreme disaster situations.

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