



BALANCING CAPACITY, FLEXIBILITY AND RESILIENCE: LESSONS FROM AUTOMATED METRO SYSTEMS FOR FUTURE RAILWAYS

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Abstract – Railway and metro systems are traditionally designed to maximize capacity under normal operating conditions. However, increasing automation, reduced headways and higher infrastructure utilization make system behavior under disturbed conditions an increasingly important issue. While conventional railways and automated metro systems pursue the same objective of high capacity, degraded operating conditions manifest differently due to their different levels of operational flexibility. This paper examines the relationship between capacity, degraded operations, operational flexibility and resilience in automated rail systems, using automated metro networks as a representative example of highly optimized rail operations. Particular attention is given to infrastructure-based flexibility mechanisms, especially pocket tracks, which support service recovery and operational adaptation during disturbances. The analysis is based on a comparison of degraded operating conditions in metro and conventional railway systems and on the mechanisms used to maintain service continuity. The analysis shows that degraded operating conditions provide a new perspective for understanding the balance between capacity, operational flexibility and resilience. They further suggest that future railways may increasingly face challenges already encountered in automated metro networks, whose experiences offer valuable lessons for a future design in which balancing capacity, operational flexibility and resilience may become as important as capacity optimization itself.

Keywords – operational flexibility, degraded operations, resilience, automated metro systems, future railways.

1. INTRODUCTION

Rail transport systems are increasingly expected to provide high capacity, reliability and service quality while operating in environments characterized by growing demand and increasing levels of automation. In both conventional railways and metro systems, capacity enhancement remains one of the primary design objectives. This objective is achieved through infrastructure optimization, reduction of headways, advanced signaling systems and an increasing degree of operational automation.

Recent developments such as Communications-Based Train Control (CBTC), Grade of Automation 4 (GoA4) metro systems, Automatic Train Operation over ETCS (ATO over ETCS), Moving Block signaling, Digital Automatic Coupling (DAC) and

emerging concepts of autonomous freight trains illustrate a common trend towards highly automated and highly optimized railway systems. While these developments significantly increase capacity and infrastructure utilization, they simultaneously reduce the operational margins available for disturbance management. As a result, future railway systems may increasingly face a trade-off between maximizing capacity and maintaining resilience under disturbed operating conditions.

However, railway systems are not operated exclusively under normal operating conditions. Infrastructure failures, rolling stock malfunctions, operational incidents, maintenance activities and external events may force the system to operate under degraded operating conditions. As operational

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margins become smaller and system interdependencies increase, the ability to manage degraded operating conditions is emerging as a critical performance requirement alongside traditional capacity objectives. This evolution suggests that degraded operating conditions should no longer be regarded solely as exceptional operational situations, but increasingly as a fundamental consideration in the design of future automated railway systems.

Although conventional railways and metro systems pursue similar operational objectives, they have evolved under fundamentally different design constraints. Conventional railways traditionally rely on the inherent operational flexibility of extensive network layouts, multiple routing options and heterogeneous traffic management. Automated metro systems, by contrast, operate within closed and highly optimized networks where infrastructure redundancy is intentionally limited in order to maximize capacity and operational efficiency. Consequently, operational flexibility cannot be assumed as an inherent property of the system but must be deliberately incorporated through infrastructure design, operational concepts and traffic management strategies.

These differences become particularly evident during degraded operating conditions. While conventional railways often absorb disturbances through the inherent flexibility of the network, metro systems depend on predefined operational procedures and dedicated infrastructure solutions to maintain service continuity. Infrastructure elements such as pocket tracks, crossovers and turnback facilities therefore perform a strategic role by enabling rapid operational recovery and maintaining acceptable levels of service under disturbed operating conditions.

Against this background, degraded operating conditions provide a valuable analytical framework for understanding the evolving relationship between capacity, operational flexibility and resilience in future railway systems. Rather than treating degraded operation solely as an operational issue, the analysis presented in this study explores its broader implications for infrastructure planning and system design. Automated metro systems are adopted in this paper as the reference model because they represent the most mature operational environment in which the interaction between capacity, operational flexibility and resilience can already be observed.

The remainder of the paper is organized as follows. Section 2 introduces the concept of degraded operating conditions and defines the theoretical framework adopted in this study. Section 3 discusses the relationship between capacity, operational flexibility, robustness and resilience. Section 4 compares conventional railway and automated metro systems under degraded operating conditions. Section

5 examines the role of infrastructure design in creating operational flexibility, while Section 6 presents pocket tracks as an example of infrastructure-based resilience. Finally, Section 7 discusses the implications of current automation trends for future railway systems, followed by concluding remarks.

2. CAPACITY-ORIENTED DESIGN PHILOSOPHY IN RAIL SYSTEMS

Capacity has traditionally been regarded as one of the most important performance indicators of both railway and metro systems. Historically, rail systems have been designed, planned and evaluated primarily under normal operating conditions. Infrastructure capacity, timetable construction, fleet sizing and signaling performance are typically determined assuming a stable operating environment in which trains run according to the planned service pattern. In other words, system performance is generally assessed for a “normal day” scenario. [1]

The continuous growth of transport demand has further strengthened this capacity-oriented design philosophy. To increase throughput and improve infrastructure utilization, rail operators and infrastructure managers have introduced a wide range of measures, including headway reduction, timetable optimization, advanced signaling systems and increasing levels of automation. On conventional railways, this trend is reflected through the implementation of ETCS, Moving Block concepts and Automatic Train Operation (ATO), while metro systems increasingly rely on CBTC technology and high Grades of Automation (GoA).

The primary objective of these developments is to maximize the utilization of existing infrastructure and increase system capacity. However, the performance achieved under normal operating conditions does not necessarily reflect system behavior under disturbed conditions. Infrastructure failures, rolling stock malfunctions, operational incidents and external events remain unavoidable regardless of the level of automation applied.

Consequently, modern automated rail systems should not be evaluated exclusively through their performance under normal operating conditions. While automation and optimization significantly increase system capacity, they may simultaneously reduce the operational margins available for disturbance management. As a result, the more a rail system is optimized for normal operation, the more sensitive it may become to disturbances and the more complex its management becomes under degraded conditions. This observation highlights that maximizing capacity alone cannot fully characterize system performance under disturbed operating conditions and points towards the need for a balanced

consideration of capacity, operational flexibility and resilience.

3. DEGRADED OPERATIONS, RESILIENCE AND OPERATIONAL FLEXIBILITY

Railway systems are traditionally assessed through indicators such as capacity, reliability, safety and interoperability. While these concepts provide valuable insights into system performance, they offer only a partial understanding of how rail systems behave under disturbed conditions. A complementary perspective can be obtained by viewing the railway as a complex socio-technical system capable of operating in different states, each characterized by specific operating conditions, constraints and performance levels.

From this perspective, understanding the relationship between capacity, degraded operations and resilience requires a clear definition of both operational states and performance-related concepts that describe system behavior in the presence of disturbances.

Three principal operational states can be distinguished. Normal operation represents the state in which all intended functions are performed within predefined performance limits and operating conditions [2, 3]. In railway systems, this corresponds to the planned realization of train services with all infrastructure, signaling and rolling stock subsystems functioning as intended.

Degraded operation refers to a state in which the system continues to perform its essential functions despite the loss, reduction or malfunction of one or more components, subsystems or operational capabilities [4, 5]. Within railway systems, degraded operation implies that safety remains preserved, while performance is reduced through capacity restrictions, speed reductions, timetable modifications, rerouting or modified operating procedures.

Emergency operation represents a state triggered by major disruptions or hazardous events requiring exceptional operating measures to protect passengers, personnel, assets or the environment [6]. Such conditions may involve service suspension, evacuation procedures, emergency traffic management or other extraordinary actions aimed at preserving system safety.

In addition to operational states, several performance-related concepts are essential for analyzing system behavior under disturbed conditions.

Capacity may be defined as the maximum number of trains, passengers or freight units that can be accommodated by a railway system within a specified period while satisfying predefined operational requirements [7, 8]. Traditionally, capacity has been one of the dominant criteria used to evaluate railway

performance.

Reliability expresses the probability that a system will perform its required functions without failure for a specified period under stated conditions [3, 4]. In the railway context, reliability reflects the consistency with which infrastructure, rolling stock and operational processes deliver planned services.

Closely related to reliability is the concept of robustness, which describes the ability of a system to withstand disturbances without significant degradation of performance. While a robust railway system continues to function with limited consequences following a disturbance, a resilient railway system emphasizes the ability to adapt, maintain service and recover functionality once significant disruption has occurred.

Resilience extends beyond reliability by addressing system behavior after a disturbance has occurred. It is commonly defined as the capability of a system to anticipate, absorb, adapt to and recover from disruptive events while maintaining an acceptable level of functionality [9, 10]. In railway systems, resilience is reflected in the ability to preserve service continuity and restore operational performance following disruptions.

Unlike capacity, reliability and resilience, operational flexibility does not have a universally accepted definition within railway literature. The concept is interpreted differently across research domains, including infrastructure design, traffic management, operations planning and resilience studies. For the purposes of this paper, operational flexibility is defined as the capability of a railway system to modify train operations, service patterns or infrastructure utilization in response to disturbances while maintaining an acceptable level of service.

The concepts introduced above are closely interconnected. The manifestation of degraded operations depends largely on the inherent operational flexibility of the system, while resilience reflects its ability to maintain and recover functionality under such conditions. Operational flexibility may therefore be viewed as the mechanism through which degraded operating conditions are managed and resilience is achieved. This relationship is particularly relevant when comparing conventional railways and automated metro systems, whose structural and operational characteristics result in fundamentally different responses to disturbances.

4. DIFFERENT INTERPRETATIONS OF DEGRADED STATE IN METRO AND CONVENTIONAL RAIL SYSTEMS

Although conventional railways and metro systems pursue the same objective of maximizing capacity, degraded operating conditions do not affect them in

the same way. As discussed in the previous section, the manifestation of degraded operations depends largely on the operational flexibility available within the system. Consequently, two rail systems exposed to a similar disturbance may experience significantly different operational consequences.

This distinction becomes particularly evident when comparing automated metro systems and conventional railways. Automated metro systems operate within highly controlled and isolated environments characterized by homogeneous rolling stock, fixed service patterns, dedicated infrastructure and intensive infrastructure utilization. These characteristics enable exceptionally high levels of automation, short headways and high transport capacity. However, they simultaneously limit the range of operational responses available during disturbances.

This creates an apparent paradox of automated metro systems. The same characteristics that maximize efficiency and capacity under normal operating conditions may reduce the system's ability to adapt when disturbances occur. Metro systems generally provide limited opportunities for rerouting, overtaking, train reordering or alternative service patterns. Consequently, even relatively minor disturbances may significantly affect service continuity and rapidly lead to partial service

suspension or substantial reductions in operational performance.

Conventional railways present a different operational paradigm. They are characterized by a greater diversity of operational resources and traffic management possibilities. Multiple train categories, station tracks, overtaking facilities, alternative routes and traffic regulation measures provide a level of inherent flexibility that allows the system to adapt to disturbances without necessarily interrupting service. As a result, degraded operation in railway systems often manifests itself through capacity reductions, timetable modifications, train reordering, rerouting or other operational compromises rather than through direct service interruption.

From this perspective, the fundamental difference between metro systems and conventional railways is not the occurrence of disturbances but the ability to respond to them. Railway flexibility is largely inherent, emerging from the structure and organization of the network itself. Metro flexibility, in contrast, must be deliberately designed through dedicated operational procedures and infrastructure solutions.

Tab 1 summarizes the principal characteristics influencing the manifestation of degraded operations in both systems.

Tab 1. Comparison of metro and conventional railway characteristics affecting degraded operations

Feature	Metro	Conventional Railway	Impact on Degraded Operations
Automation level	Very high	Medium to high	Influences dependence on system functionality
Capacity utilization	Very high	High	Affects sensitivity to disturbances
Operational flexibility	Low	High	Determines adaptation capability
Alternative routing	Very Limited	Available	Influences service continuity
Traffic regulation options	Very Limited	Extensive	Affects disturbance management
Disturbance recovery	Challenging	More flexible	Influences recovery time

Consequently, degraded operation manifests differently in metro and conventional railway systems. In conventional railways, disturbances are frequently absorbed through operational adaptation. In automated metro systems, the same disturbances may produce more severe consequences because fewer adaptation options are available. Therefore, understanding degraded operations requires not only analyzing the disturbance itself but also examining the operational flexibility available within the system.

This observation provides the foundation for understanding why automated metro systems have developed dedicated infrastructure-based mechanisms to support operational flexibility and resilience during degraded operating conditions. These mechanisms illustrate how operational flexibility contributes to

achieving an appropriate balance between capacity and resilience and are discussed in the following section.

5. DESIGNED FLEXIBILITY IN AUTOMATED METRO SYSTEMS

Automated metro systems may be viewed as laboratories for studying degraded operations and resilience. Their high degree of automation, intensive infrastructure utilization and strict operational requirements have led to the development of dedicated mechanisms specifically intended to support service continuity under disturbed conditions. Consequently, the management of degraded operating conditions becomes an integral part of system design rather than merely an operational issue.

In contrast to conventional railways, where many adaptation options emerge naturally from network structure and traffic management practices, metro systems must deliberately incorporate flexibility into their architecture. In other words, flexibility in metro systems is not inherited from the network structure; it is deliberately designed into the system. This flexibility is not primarily intended to improve performance under normal operating conditions. Instead, it is designed to provide alternative operational options when planned service patterns can no longer be maintained.

To achieve this objective, metro systems employ a range of infrastructure elements specifically intended to support operational adaptation and service recovery. Typical examples include crossovers, turnback facilities, storage tracks and pocket tracks. Although these elements differ in their physical configuration and operational function, they share a common purpose: enabling the system to continue operating when disturbances prevent the execution of the planned service pattern.

Tab 2 summarizes the principal infrastructure mechanisms used to support degraded operations in automated metro systems.

Tab 2. Infrastructure mechanisms supporting degraded operations in automated metro systems

Infrastructure element	Primary function in degraded operation
Crossovers	Route changes and traffic diversion
Turnback tracks	Short-turning and service regulation
Storage tracks	Temporary train holding and fleet management
Pocket tracks	Service recovery, incident isolation and partial line operation

These infrastructure elements may be interpreted as physical manifestations of resilience embedded within the network itself. Rather than increasing capacity, their primary purpose is to preserve operational functionality when normal operating conditions can no longer be sustained. In this sense, resilience is not achieved solely through operational procedures but is also incorporated into the infrastructure during the design phase.

Consequently, the solutions developed in metro systems provide valuable insights into how operational flexibility interacts with infrastructure design to support resilience under degraded operating conditions. Among these solutions, pocket tracks represent one of the most comprehensive mechanisms for restoring operational flexibility because they simultaneously support train regulation, service recovery, incident isolation and partial line operation. For this reason, they are examined in greater detail in

the following section

6. POCKET TRACKS: FROM DEGRADED OPERATIONS TO RESILIENCE

A pocket track is an additional track, typically located between the running tracks, which allows trains to reverse direction, be temporarily removed from service or be held without obstructing mainline operations. Although relatively simple from an infrastructure perspective, pocket tracks play an important role in supporting railway operations when planned service patterns can no longer be maintained.

The significance of pocket tracks cannot be fully explained through normal operating requirements. Their primary value becomes evident when disturbances occur and the system enters a degraded operating state. Under such conditions, operators are required to adapt train services to changing circumstances while preserving an acceptable level of service. Pocket tracks provide additional operational options that would otherwise not be available.

Several operational functions can be supported using pocket tracks. These include short turning of trains, temporary train storage, train regulation, incident isolation and partial line operation. By enabling trains to reverse direction before reaching a disrupted section, operators can continue serving unaffected parts of the network while minimizing the impact of disturbances on passengers and system performance.

From this perspective, pocket tracks represent an infrastructural response to an operational problem. They serve as technical tools for organizing train operations under disturbed operating conditions and provide operators with additional opportunities to modify service patterns when the planned operating concept can no longer be sustained.

Pocket tracks may therefore be viewed as mechanisms for restoring operational flexibility. Their purpose is not to improve operational flexibility during normal operation, but rather to create flexibility when disturbances reduce the range of available operational options. In this way, they help transform a rigid operating structure into a system capable of adapting to changing conditions.

At the same time, the benefits provided by pocket tracks are not achieved without cost. Their implementation requires additional track infrastructure, turnouts, signaling equipment, control functions and maintenance activities. Consequently, the decision to incorporate pocket tracks reflects a deliberate trade-off between investment costs and the ability to maintain service during service disruptions and disturbed operating conditions.

The importance of pocket tracks extends beyond their specific operational functions. They illustrate a

broader engineering principle: the ability of a transport system to operate effectively under degraded conditions is not determined solely by operational procedures but is also influenced by infrastructure design decisions. In this sense, pocket tracks represent a tangible example of how degraded operation management and system resilience can be incorporated into the physical architecture of a rail system.

The significance of pocket tracks therefore extends beyond a single infrastructure element, illustrating a broader systems-engineering philosophy that is becoming increasingly relevant as conventional railways evolve towards higher levels of automation.

7. TOWARDS FUTURE AUTOMATED RAILWAYS: EVOLUTION, CHALLENGES AND LESSONS FROM METRO SYSTEMS

For almost two centuries, conventional railways and metro systems have followed different evolutionary paths. Conventional railways have evolved as open transport systems characterized by extensive networks, heterogeneous traffic and relatively high inherent operational flexibility. In contrast, automated metro systems have been developed as highly optimized, closed systems designed to maximize capacity within constrained urban environments. Today, however, increasing automation is gradually bringing these two evolutionary paths closer together.

This convergence is reflected in the progressive introduction of automation technologies into conventional railway systems. Concepts such as Automatic Train Operation over ETCS (ATO over ETCS), Moving Block signaling, higher Grades of Automation (GoA3 and GoA4), Digital Automatic Coupling (DAC), advanced digital traffic management systems and autonomous freight train concepts all pursue the same objective: increasing capacity, improving operational efficiency and maximizing infrastructure utilization. Recent studies indicate that automation is progressively extending beyond urban rail towards regional, mainline and freight railway applications, where ATO is increasingly integrated with ETCS-based signaling systems and digital traffic management concepts [11–13].

Several of these technologies have already progressed beyond the conceptual stage and entered operational implementation. In Germany, the Digital S-Bahn Hamburg project successfully demonstrated highly automated train operation based on ETCS, while the Digital Node Stuttgart and the ARTE programme represent the next steps towards higher Grades of Automation [12]. In Finland, Siemens Mobility successfully demonstrated ATO over ETCS

Level 2 under real mainline operating conditions, whereas in the Czech Republic AŽD Praha conducted the first autonomous train demonstrations on a regional railway line [16,17]. Outside Europe, Rio Tinto's heavy-haul railway in Western Australia became the world's first fully autonomous freight railway network, while the French National Railway (SNCF) has demonstrated autonomous passenger and freight train technologies supported by artificial intelligence [13,14, 15]. At the urban rail level, fully automated GoA4 metro systems are already operating in more than sixty cities worldwide, including Copenhagen, Paris, Milan, Vancouver and Sydney, confirming that fully automated rail operation has become an established engineering solution rather than a future concept [11,13].

Taken together, these developments demonstrate that the transition towards highly automated railway operation is no longer a future vision but an ongoing engineering reality. More importantly, they suggest that conventional railways are progressively entering a stage of technological and operational development that automated metro systems have already experienced for several decades.

Beyond technological progress, this transformation is also operational and organizational. Higher levels of automation reduce operational headways, increase infrastructure utilization and strengthen the integration between infrastructure, rolling stock and traffic management systems. At the same time, they reduce operational margins and increase the dependence of railway operation on digital communication, automated control and decision-support systems. Consequently, disturbances that could previously be managed through local operational interventions increasingly become system-level events requiring coordinated operational responses.

As a result, future railway systems will increasingly need to consider degraded operating conditions as one of the fundamental design scenarios. Infrastructure layout, operational concepts, traffic management strategies and operational flexibility mechanisms must therefore be planned not only for normal operation but also for maintaining acceptable system performance under disturbed operating conditions.

From this perspective, automated metro systems may be regarded as laboratories for the future of highly automated railways. Over several decades, they have accumulated practical experience in developing infrastructure solutions, operational procedures and traffic management concepts specifically intended to maintain service continuity under degraded operating conditions. Rather than relying on inherent operational flexibility, metro systems systematically integrate operational flexibility into the system architecture through infrastructure design, operational planning and

traffic management strategies. Consequently, they provide a unique opportunity to observe how highly automated railway systems behave under disturbed operating conditions and how resilience can be systematically incorporated into the system.

These developments may be interpreted through the conceptual framework presented in Figure 1. As railway systems evolve towards higher levels of automation, increasing capacity is likely to be accompanied by reduced operational flexibility unless appropriate resilience mechanisms are incorporated into system design. Future railway systems will therefore need to achieve an appropriate balance between capacity, operational flexibility and resilience rather than maximizing any one of these objectives independently.

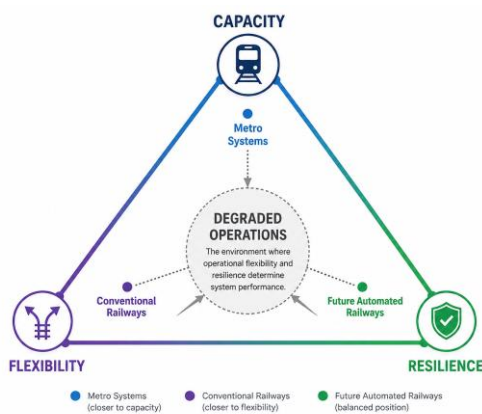


Fig 1. Conceptual framework illustrating the balance between capacity, operational flexibility and resilience under degraded operating conditions

Note: Degraded operating conditions provide the environment in which the balance between capacity, operational flexibility and resilience becomes visible

The most important lesson that future railway systems can learn from automated metro systems is therefore not a particular technology or infrastructure element, but a different design philosophy. Degraded operating conditions should no longer be regarded as exceptional operational situations to be addressed only after disturbances occur. Instead, they should become one of the fundamental design scenarios influencing infrastructure planning, operational concepts and traffic management strategies from the earliest stages of railway system development.

8. CONCLUSIONS

This paper examined the relationship between capacity, operational flexibility and resilience through the perspective of degraded operating conditions in conventional railway and automated metro systems. The analysis demonstrates that degraded operating conditions provide a valuable framework for understanding railway system behavior beyond

normal operation, revealing interactions between design objectives that often remain hidden under nominal operating conditions.

The comparison between conventional railways and automated metro systems shows that the ability to manage degraded operating conditions is fundamentally influenced by the level of operational flexibility embedded within the system. Conventional railways have traditionally relied on the inherent flexibility of their network structure to absorb disturbances through operational adaptation. Automated metro systems, by contrast, compensate for their limited inherent flexibility by deliberately incorporating operational flexibility into infrastructure design, operational concepts and traffic management strategies. Infrastructure elements such as pocket tracks illustrate how resilience can be embedded into the physical architecture of the system rather than achieved solely through operational procedures.

The ongoing evolution of railway automation suggests that this distinction will gradually become less pronounced. The introduction of technologies such as ATO over ETCS, higher Grades of Automation, Moving Block signaling and autonomous train operation is progressively increasing infrastructure utilization while simultaneously reducing operational margins. As conventional railways become operationally more similar to automated metro systems, issues of operational flexibility, degraded operating conditions and resilience are expected to become increasingly important design and operational challenges.

The principal contribution of this paper extends beyond the analysis of degraded operating conditions or individual infrastructure solutions. It argues that, as railway systems become increasingly automated, degraded operating conditions are no longer merely an operational issue but are progressively evolving into a design paradigm for future automated railway systems. The findings of this study suggest that degraded operating conditions should no longer be regarded simply as exceptional operational events requiring predefined procedures, but as fundamental design scenarios that influence infrastructure planning, operational concepts and traffic management from the earliest stages of railway system development.

From this perspective, the significance of automated metro systems extends far beyond urban transport. They are, in effect, laboratories for the future of railways. Their experience demonstrates that the long-term challenge of railway engineering is not to maximize capacity alone, nor to prioritize operational flexibility or resilience independently, but to achieve an appropriate balance between these three objectives. As conventional railways continue their

transition towards higher levels of automation, the ability to maintain acceptable performance under degraded operating conditions will increasingly depend on successfully balancing capacity, operational flexibility and resilience. Achieving this balance is likely to become one of the defining characteristics of future railway systems.

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