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Current Status and Future Prospects of Driverless Train Operation (DTO): Advancing Energy-Efficient Research and Implementation in Japan

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Abstract

This paper provides an academic analysis of the evolution of Grades of Automation (GOA 1–4) in Japanese urban railways, elucidating the underlying technical and socio-economic drivers. Although Japan has long maintained the globally highly dense and punctual rail networks, the implementation of Driverless Train Operation (DTO) on existing heavy rail lines has been historically cautious, significantly influenced by a unique safety culture and stringent regulatory frameworks. Since 2019, however, the urgent social change of a rapidly shrinking working-age population has dramatically accelerated public-private Automatic Train Operation (ATO) initiatives.

This paper highlights the strategic significance of Japanese unique "GOA 2.5" (ATO with an onboard attendant at train head) and offers a comprehensive overview of recent academic advancements in Energy-Saving Train Operation (ESTO) – regarded as a primary secondary benefit of automation. Specifically, we detail the mathematical principles and implementation methodologies of experimental research on linear motor subways, as well as run-curve optimization based on the "Equivalent Gradient Rule" and fast algorithms for "Cooperative Energy Exchange" among multiple trains. Finally, the paper discusses how the Japanese philosophy of railway systems – which integrates stringent punctuality with long-term sustainability – contributes to enhancing international competitiveness in the global market.

Keywords: automatic train operation , driverless train operation , energy-saving train operation, optimisation , dynamic programming, energy-efficient train operation.

1 Introduction

Railway systems represent a critical social infrastructure, playing a vital role in enabling mass transportation and achieving decarbonization in contemporary society. According to the international standard IEC 62290-1 [1], the Grades of Automation (GOA) are categorized into four levels, ranging from GOA 1 (manual operation) with safety-backup by signalling system to GOA 4 (unattended train operation) as shown in Table 1. In major urban centres across Europe, North America, and Asia, the adoption of GOA 4 is progressing rapidly, primarily driven by the objectives of enhancing operational efficiency.

The author highlights a significant characteristic of the Japanese rail context: while Japanese railways are renowned for achieving world-class punctuality, their operations have historically relied heavily on the tacit knowledge, exceptional skills, and extensive experience of highly trained drivers. At present, however, the Japanese railway industry is confronting a structural crisis characterized by the mass retirement of veteran operators and increasing difficulties in recruiting a new generation of personnel. Japanese total population reached its peak around 2007 and has since entered a phase of rapid decline as shown in Figure 1; consequently, securing sufficient operational staff has become an acute challenge not only in rural regions but also in major metropolitan areas.

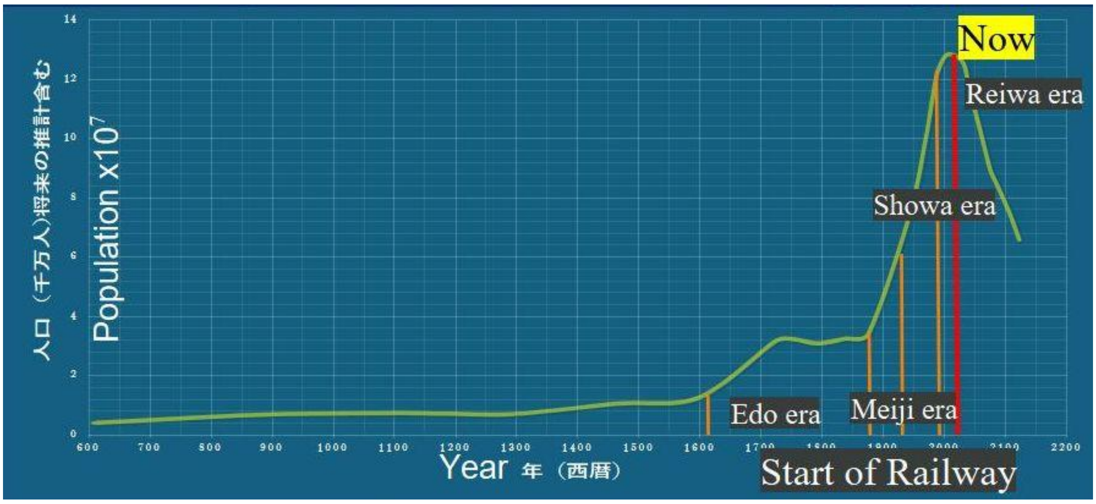


Figure1 Timeline of Longterm Japanese Population

In response to these demographic shifts, the primary motivation for automation has transitioned from traditional economic and efficient train service toward ensuring the long-term sustainability of the railway business. This paper reviews the historical background of the introduction of automatic train operation in Japan and provides a detailed discussion on the advancement of energy-efficient technologies grounded in modern control engineering.

Table 1 Grade of Automation for Train Operation in Japan

Grade of Automation (GOA)	Definition of Operation Mode	Driving and Halting	Responsibility for Door Operations	Responsibility for Emergency Response	Major Examples of Implementation and Demonstration in Japan
GOA 1	Non-automated / Manual	Driver (protected by ATP)	Driver / Conductor	Driver / Conductor	Most JR lines, private railways, and subway lines (manual sections)
GOA 2	Semi-automated (STO)	System (activated by driver)	Driver / Conductor	Driver	Tokyo Metro (Marunouchi, Namboku Lines, etc.), Toei Oedo Line, Tsukuba Express, JR Joban Line (Local)
GOA 2.5 (Japanese original level)	*Driverless with an attendant at train head*	*System*	*Attendant (no driver's licence required)*	*Attendant at train head / System*	*JR Kyushu: Kashii Line (demonstration and initial implementation), Nankai Line, JR East: Joban and Yamanote Lines, Tokyo Metro (under consideration/testing)*
GOA 3	Driverless (DTO) with attendants	System	System	Attendant onboard	Currently under study as a strategic transition from GOA 2.5 for heavy rail in Japan
GOA 4	Unattended (UTO)	System	System	System (ground monitoring)	AGT (Automated Guideway Transit):Kobe New Transit Port Island Line, Yurikamome, Nippori-Toneri Liner, Osaka Metro Nanko Port Town Line

2 The Historical Lag in Adopting DTO in Japan

Japan was a pioneering nation that achieved the globally first full-scale GOA 4 operation with the Kobe Port-Island New Transit Line in 1981. However, for approximately four decades thereafter, the introduction of DTO (Driverless Train Operation) into existing heavy rail systems, such as subways and JR (Japan Railways) lines, saw minimal progress.

The author identifies three primary socio-economic factors contributing to this delay.

Firstly, there is the pursuit of "ultimate safety" by Japanese railway operators and the existence of an exceptionally high quality of manual operation. The superior skills of professional drivers have relatively diminished the motivation for expensive investments in automation.

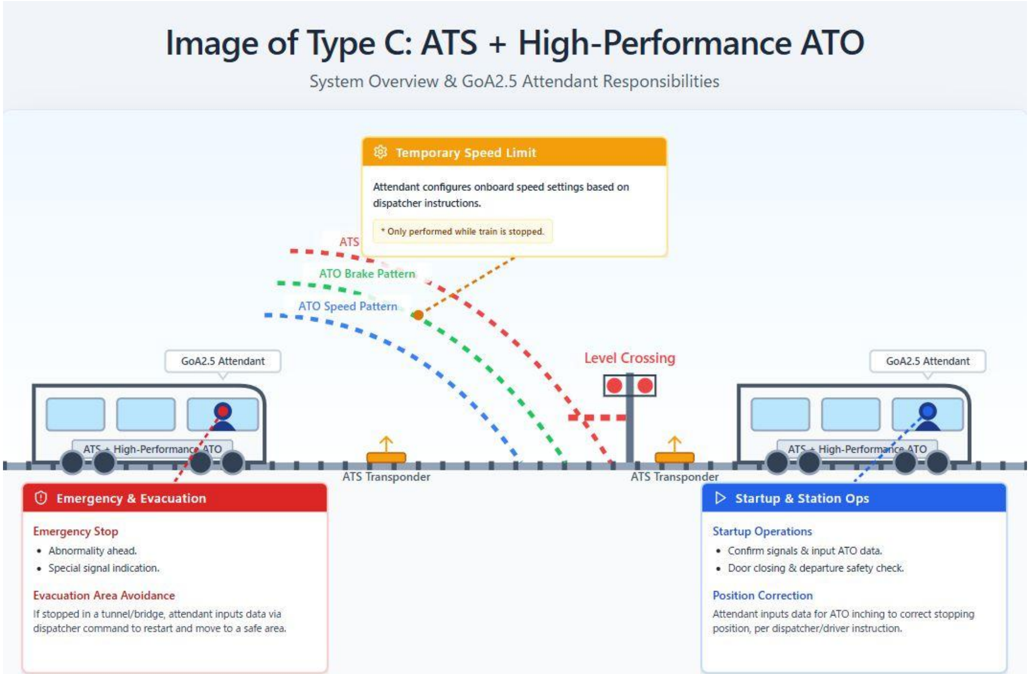
Secondly, the presence of level crossings is a characteristic unique to the Japanese rail environment. Many existing lines include level crossings, and the technical reliability of forward obstacle detection, combined with the complexities of legal liability in the event of an accident, have posed significant barriers to DTO implementation.

Thirdly, strict safety standards that rely on human eyes for emergency evacuation guidance and door-closing confirmation have set an extremely high hurdle for the transition to driverless automatic train operation.

3 The Rapid Acceleration of ATO Initiatives in Japan since 2019

In 2019, Japanese railway policy underwent a dramatic transformation. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) established the "Committee for the Examination of Automatic Train Operation Technology in Railways [2]" and commenced the restructuring of technical standards on the premise of labour reduction, anticipating future driver shortages.

The author emphasises that the primary motivation for this policy shift is the acute sense of crisis regarding the labour shortage. Consequently, a series of demonstration trials aimed at GOA 2.5 and GOA 3 have been launched on various lines, including the Yamanote Line of JR East, the Kashii Line of JR Kyushu, and the Daishi Line of Tobu Railway as summarized in Figure 2. Some of these projects proactively try to test Communication-Based Train Control (CBTC) systems, too—which function independently of conventional track-side equipment—as well as on-board Obstacle Detection Systems utilising high-performance cameras and millimetre-wave radars.



Schematic diagram of Japanese GOA-2.5 for local lines
(named as Type-C in the ministry document [2]).

(1) JR Kyushu: GOA 2.5 on Kashii Line (Mar 2024).
(2) Nankai: GOA 2.5 tests (Aug 2023).
(3) JR East: GOA 2 tests on Yamanote Line (2018-2022).
=> GOA-3 in 2035?
(4) JR East: Plans for Shinkansen GOA 4 (2029) and GOA 3/4.
(5) Osaka Metro GOA 2.5 tests (FY2024).
(6) Tokyo Metro: GOA 2.5 tests on Marunouchi Line (FY2025).
(7) JR Central: GOA 2 tests on Tokaido Shinkansen (from Nov 2021).
(8) JR West: GOA 2.5 tests on Osaka Loop Line.
(9) Tobu: Studying GOA 3 for Daishi Line.

Figure 2 Actual status of technical development of ATO/DTO in Japan

4 The Value of Automation

In the Japanese automatic train operation strategy, the most significant feature is the definition and implementation of an intermediate level designated as GOA 2.5.

GOA 2.5 is defined as a system in which a staff member (on-board attendant) who does not possess a driver’s licence is stationed at the train head to manage duties such as emergency stop, emergency evacuation guidance, and door closing operation while the system itself takes charge of acceleration, deceleration, and Train Automatic Stop Control (TASC). The author evaluates this approach as a unique and pragmatic solution tailored to the Japanese context, designed to lower the socio-technical barriers associated with unattended train operation (GOA 4).

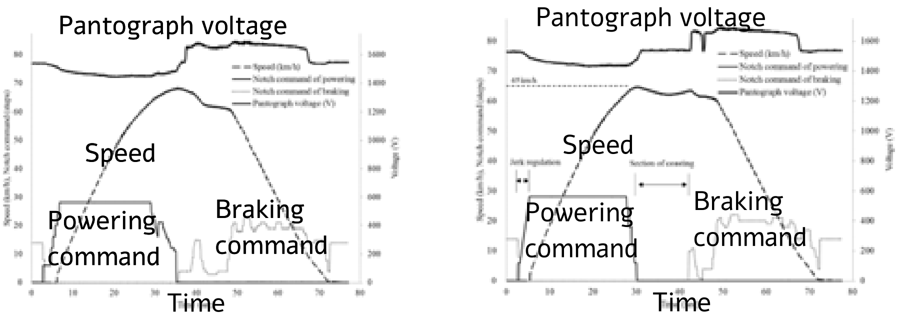
By adopting GOA 2.5, operators can mitigate the substantial time and expense required for driver training, while simultaneously providing passengers with a level of reassurance comparable to traditional manned services. Additionally, the integration of Moving Block signalling will significantly enhance the capability for highly frequent train operations and improves the system resilience in recovering from operational delays.

5 Secondary Benefits of ATO: Energy-Saving Train Operation (ESTO)

The implementation of ATO serves not only as a means for labour reduction but also as a fundamental platform for the precise execution of Energy-Saving Train Operation (ESTO), which aims to minimise energy consumption. This is because Energy-Saving Train Operation (ESTO), as discussed later, fundamentally requires strong braking down to the low-speed range, making it a difficult driving pattern for human operators. However, the introduction of Automatic Train Operation (ATO) enables this to be achieved easily, safely, and with exact reproducibility. The author highlights that ATO allows for the exact replication of theoretically derived driving patterns that are often difficult for human drivers to maintain consistently.

5.1 Dr S. Watanabe's Research: Empirical Validation of Energy-Saving Theory [3]

The author cites the research conducted by S. Watanabe [3], which demonstrates that automatic train control enables significant reductions in power consumption compared to manual operation. Through field tests on a linear motor subway (Nanakuma Line in Fukuoka and Tsurumi-Ryokuchi Line in Osaka), S. Watanabe proved that an ATO system, by precisely reproducing optimal driving patterns—such as the calculated timing for powering, coasting, and regenerative braking based on numerical optimisation—can achieve energy savings of approximately 8% to 17% compared to manual driving as shown in Figure 3. This research academically confirmed that ATO is not merely a substitute for a driver but a sophisticated tool for efficient and systematic energy management.



(a) Operation before our proposal　　(b) Energy-saving operation

Figure 3 Comparison between without and with energy-saving train operation strategy proposed by Dr S. Watanabe.
(The results of the on-track tests demonstrated that the operation method (b) on the right achieved a 12.4% reduction in energy consumption compared to the operation method (a) on the left where both traveling times are identical.)

5.2 Dr X. Meng's Research-I: Run-Curve Optimisation Based on the Equivalent Gradient Rule [4]

The author provides a detailed explanation of the fast optimisation algorithm based on the *Equivalent Gradient Rule* proposed in Dr X. Meng's research [4]. According to the fundamental theory of energy-saving train operation, the optimal run curve is achieved by the combination of the best powering effort, possibly long coasting and the best braking operation in a simple track profile. However, real-world tracks involve multiple Temporary Speed Restrictions (TSRs) and complex gradient variations as shown in Figure 4, which traditionally made the calculation of optimal solutions extremely computationally intensive.

Dr X. Meng developed a breakthrough methodology to address these complexities [4]: Segmentation of Speed Limit Zones: The algorithm divides the route into multiple segments based on speed limit boundaries. By analytically applying the equivalent gradient rule within each segment, it dramatically reduces the computational load compared to conventional purely numerical optimisations, *e.g.*, Dynamic Programming (DP).

Fast Coasting Point Search: This algorithm enables the high-speed calculation of the balance between minimum-time operation and minimum-energy operation, even on tracks with fluctuating gradients. This makes real-time run-curve generation on on-board units feasible.

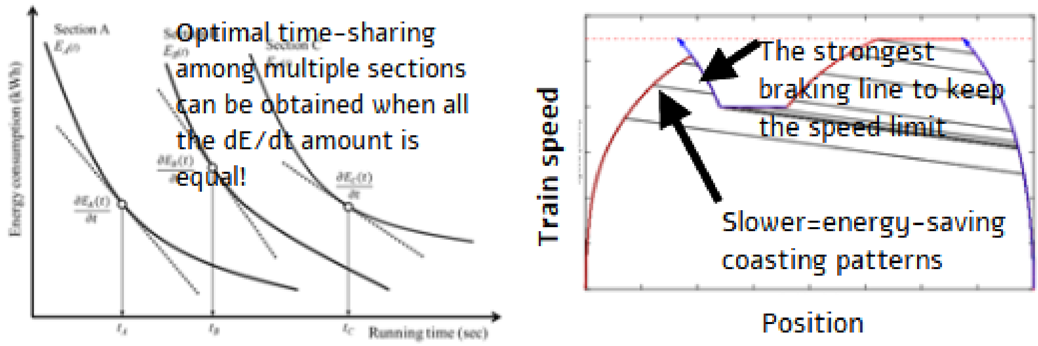


Figure 4 Mathematical principle of the *Equivalent Gradient Rule* and train speed curves with different positions of inserting coasting phase on a level track with one local speed limit section.

5.3 Dr X. Meng's Research-II: Optimisation of Cooperative Energy Exchange between Trains [5][6]

Furthermore, X. Meng's research extends the scope of optimisation from a single train to "Cooperative Energy Exchange" among multiple trains [5][6]. X. Meng proposed a fast algorithm to maximise the direct exchange of energy via the overhead contact system or third rail by synchronising the regenerative braking timing of a preceding train with the powering timing of a following train as shown in Figure 5.

Multi-Fidelity Approach: Meng adopted a two-step approach using a low-fidelity model for global search followed by a high-fidelity model for fine-tuning [5]. This enables real-time cooperative management even during operational disturbances.

Substation Load Smoothing: By coordinating multiple trains, the system minimises the energy returned to substations and improves the overall energy efficiency of the entire railway network.

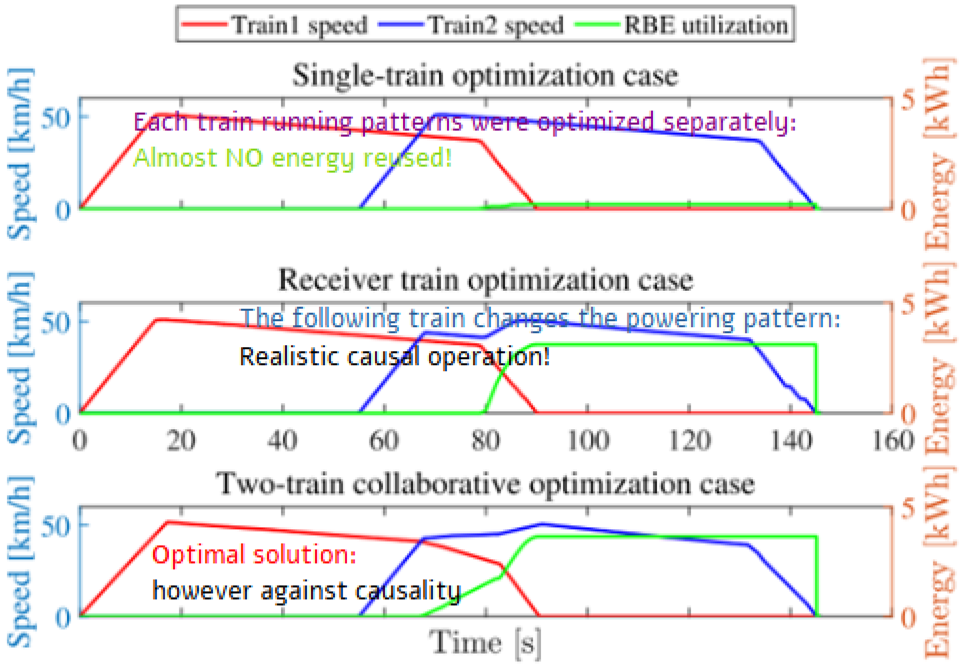


Figure 5 Train run curves and substation power curves of 3 scenarios with 55s interval

6 The Japanese Philosophy of Energy-Saving Train Operation: Integrating Punctuality and Efficiency

The core philosophy of energy-saving operation in the Japanese railway context lies in achieving the global minimisation of energy consumption for an entire fleet while upholding the hallmark of the system: absolute punctuality. Unlike railway systems with more flexible scheduling, Japanese urban rail operates under highly dense and extremely time-sensitive conditions, where even a minor delay can propagate rapidly throughout the network. Therefore, energy-saving strategies in Japan are not merely about reducing energy; they must be intrinsically integrated with robust, high-precision schedule-adherence control.

6.1 Dr S. Miyoshi's Research: Precise Reference Trajectory Design Considering Drive System Efficiency [7]

Dr S. Miyoshi [7] addressed the challenge of overall system optimisation by focusing on the precise control of the traction layer. He proposed a novel reference trajectory design that explicitly incorporates the detailed efficiency characteristics of the electrical drive system, including the traction motors and power inverters. Traditional ATO profiles often simplify the vehicle as a point mass with constant efficiency; however, Dr S. Miyoshi modelled the non-linear loss characteristics of the drive system to design an acceleration profile that minimises internal energy dissipation.

By employing a sophisticated feedforward control methodology, this approach allows for the precise tracking of the designed optimal trajectory. This ensures that the vehicle consumes the minimum possible electrical energy required for its mechanical motion, effectively reducing component-level losses without compromising the stringent arrival times required by the timetable [7][8]. This research highlights that the integration of power electronic traction performances into train motion control is vital for the ESTO as shown in Table 2 and Figure 6.

Table 2 Energy saving effect depending on powering acceleration: experimental results

Case	Time [s]	Energy consumption [kWh]	Energy saving [%]
$\alpha = 2.5$ Conventional	2807.5	192.5	—
$\alpha = 2.5$ Proposed I	2808.4	190.0	1.3
$\alpha = 3.0$ Proposed II	2811.2	180.9	6.0

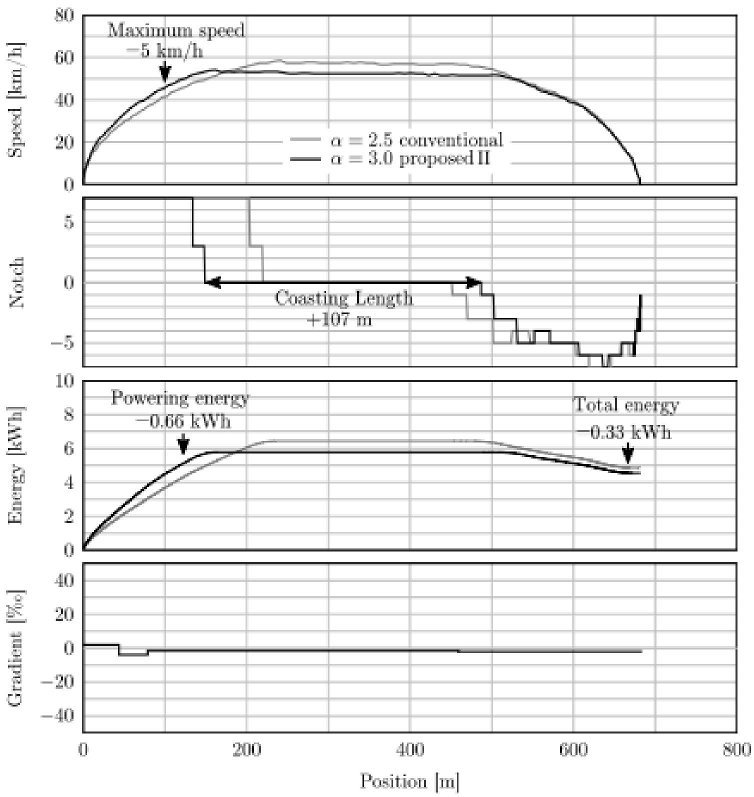
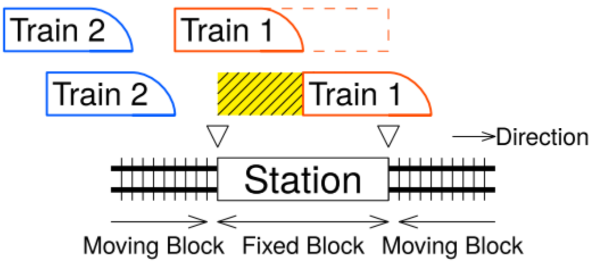


Figure 6 Test Results for Energy-Saving Train Operation in Short-Distance and Flat Inter-Station Sections

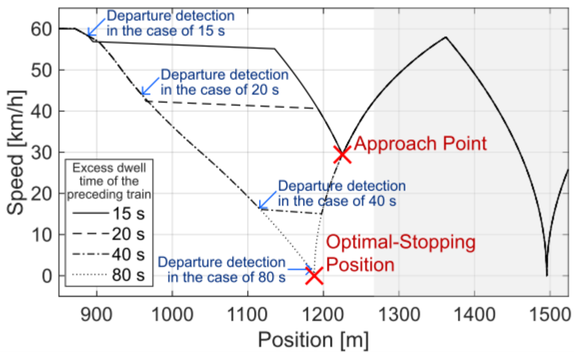
6.2 Dr K. Sakai's Research: Enhancing Robustness and Energy Management in High-Frequency Operations via realistic CBTC [9]

Dr K. Sakai [9] investigated the complex interactions within groups of trains during high-frequency operations, specifically focusing on how Communication-Based Train Control (CBTC) can enhance system robustness. In conventional fixed-block oriented signalling environments, which often remain around stations with existing interlocks in usual realistic CBTC-applications at present and in near future, a delay in a preceding train often forces following trains to undergo unplanned braking or *stops outside stations*, which results in secondary delay propagation and consequent significant energy wastage.

Dr K. Sakai proposed an optimal following control algorithm that utilises real-time information regarding the exact position and velocity of the preceding train[9][10]. By proactively adjusting the speed profile of the following train to avoid unnecessary stops and redundant acceleration cycles, the system simultaneously *mitigates the propagation of secondary delays* and minimises surplus energy consumption as illustrated in Figure 7. This research demonstrates a transition from individual train optimisation to a holistic, network-wide energy management strategy, ensuring that the railway system remains resilient and still considerably energy-efficient against daily operational disturbances in urban railways.



(a) Realistic hybrid "moving" block around a station



(b) Speed restriction curve for a following train entering a fixed-block station with a stopped preceding train

Figure 7 Examples of the following train trajectories depending on the excess dwell time of the preceding train. The trajectory to the optimal-stopping position is common regardless of the excess dwell time.

7 Conclusion

In Japan, which is currently confronting an unprecedented decline in its working-age population, the transition towards DTO/UTO (GOA 3/4) and the enhancement of environmental performance through ESTO represent two indispensable pillars for ensuring the long-term sustainability of the railway system.

The author is firmly convinced that the advanced control theories summarized in this paper—particularly the algorithms proposed by Dr X. Meng and her colleagues, such as the *Equivalent Gradient Rule* and *multi-train cooperative operation*—will serve as the core technologies for sustainable railway service. Fusing the traditional values of *punctuality* and *safety*, which Japanese railway engineers have meticulously cultivated over decades, with cutting-edge digital technology will not only enhance international competitiveness but also make a profound contribution to resolving the complex challenges faced by rail-guided public transport systems.

In this era of significant transformation, railway engineers should not merely function as implementers of specific technologies; they must assume the role of strategic leaders who redefine social infrastructure for a depopulating society. By advancing these innovations and contributing to global standardisation, the Japanese railway industry can continue to provide safe, efficient, and sustainable mobility for the global community.

Acknowledgements

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