International Journal of Transport Development and Integration
https://www.acadlore.com/journals/IJTDI

Passenger Experience in Rural Railways: A RAILQUAL-Based Evaluation for Sustainable Transport

Oranicha Buthphorm*

Department of Industrial Environmental Management, Faculty of Science and Social Sciences, Burapha University, 27160 Sakaew, Thailand

* Correspondence: Oranicha Buthphorm (oranicha@buu.ac.th)

Received: 10-18-2025 **Revised:** 11-17-2025 **Accepted:** 11-21-2025

Citation: O. Buthphorm, "Passenger experience in rural railways: A RAILQUAL-based evaluation for sustainable transport," *Int. J. Transp. Dev. Integr.*, vol. 9, no. 4, pp. 825–839, 2025. https://doi.org/10.56578/ijtdi090410.

Abstract: This study develops and validates an integrated model for evaluating passenger service quality (SQ) in Thailand's rural railway system by embedding environmental and engineering perspectives within the RAILQUAL framework. Drawing upon SERVQUAL, Grönroos's model, and Servicescape theory, it introduces the Eco-Rail Atmosphere Quality (Eco-RAQ) construct, which incorporates sustainability attributes-greenhouse-gas reduction, waste management, traction-energy efficiency, and renewable energy efficiently-into the Rail Atmosphere Quality (RAQ) dimension. Survey data from 1,013 passengers were analyzed using covariance-based structural equation modeling (CBSEM). The final model exhibits excellent fit (χ^2/df = 1.096, CFI = 1.000, RMSEA = 0.010) and explains 91.5% of variance in rail efficiency quality (REQ. RAQ demonstrates the strongest total effect on REQ (β = 0.848, $p < 0.001$), while Eco-RAQ shows a meaningful but more modest total effect (β = 0.257, $p < 0.001$), influencing REQ both directly and indirectly through rail perceived quality (RPQ). Validity diagnostics confirm discriminant validity (HTMT $<$ 0.85) and no substantive common-method bias. The findings advance service-quality theory by integrating sustainability cognition into the Stimulus-Organism-Response paradigm and by proposing Eco-RAQ as a socio-technical mechanism linking passenger perception with operational performance. The model offers actionable insights for achieving Sustainable Development Goals (SDGs) 9, 11, and 13 in rural rail contexts.

Keywords: Eco-RAQ; Passenger perception; RAILQUAL; Rural railways; SDGs; SQ; Structural equation modeling; Sustainability

1 Introduction

Service quality (SQ) has been a cornerstone of service management research since its formal conceptualization by Parasuraman et al. [1]. The core principles governing the management of SQ and the overall customer experience are thoroughly documented in foundational marketing literature [2]. Beyond marketing, SQ has gained prominence in transport studies due to its relevance to passenger satisfaction, operational efficiency, and policy design [3, 4]. In the railway sector, SQ is critical for improving user experience, operational performance, and public confidence [5].

In Thailand, rural communities depend heavily on local railways to bridge mobility gaps. The State Railway of Thailand (SRT) operates more than 2,000 km of local services, carrying approximately 26 million intercity passengers annually, which accounts for approximately 5% of the total rail ridership [6]. For many low-income and remote communities, local trains are the only reliable connection to urban centers. Despite rapid urbanization, 38.8% of the Thai population still lives in rural areas [7], and nearly 70% rely on public transport for inter-provincial travel [8]. Hence, strengthening rural railways is essential for national inclusivity and balanced development.

Rail transport aligns closely with the United Nations Sustainable Development Goals (SDGs) by promoting safe mobility (SDG 3), resilient infrastructure (SDG 9), inclusive communities (SDG 11), and climate action through low-carbon transport (SDG 13) [9]. However, prior applications of the RAILQUAL framework have predominantly addressed urban or intercity contexts [10–13], research has rarely examined how these sustainability objectives translate into measurable service-quality perceptions in rural settings. Moreover, most prior studies have overlooked the engineering dimensions, such as traction energy efficiency, rolling-stock condition, and signaling reliability—that operationalize the SDGs within the passenger experience.

This study addresses that gap by integrating environmental and technical performance factors into the RAILQUAL model through the proposed Eco-RAQ construct, providing a framework that links sustainable engineering practices with passengers' perceived efficiency. This integration not only enhances theoretical understanding of SQ in rural contexts but also aligns Thailand's rail development strategy with global standards in sustainable transport engineering.

Specifically, this research aims to: (i) adapt and validate the RAILQUAL model for Thailand's rural railway context; (ii) analyze structural relationships among service-quality dimensions using SEM; and (iii) interpret the findings within Thailand's transport strategy and the SDGs framework.

By embedding sustainability and engineering performance indicators within the RAILQUAL paradigm, the study contributes to both theoretical advancement and practical policy design. First, it empirically validates the multidimensional RAILQUAL model in a non-urban context using confirmatory factor analysis (CFA) and SEM. Second, it elucidates the mediating role of perceived quality (RPQ) in linking environmental and operational factors. Finally, it provides actionable insights for achieving sustainable railway development in developing countries.

The remainder of this paper is organized as follows: Section 2 reviews the literature. Section 3 describes the proposed methodology. Section 4 presents the results of the study. Section 5 discusses the findings. Section 6 policy and engineering implications. Section 7 conclusion, and Section 8 limitation and future research.

2 Literature Review

The following sections critically review the theoretical foundations underlying passenger experience assessment, identifying the research gap and develop a structural equation model suited to Thailand's rural railway context.

2.1 SQ Models in Transport

Research on SQ in public transport originates from seminal frameworks in the general service industry. SQ is broadly defined as the user's subjective evaluation of a service's capacity to meet expectations [1].

Parasuraman et al. [14] SERVQUAL model conceptualizes quality as the gap between customer expectations and perceived performance. Subsequent work, such as the Nordic Model [15], emphasized perceived service quality (PSQ) as a more accurate indicator, focusing on performance as experienced by passengers rather than on prior expectations. The PSQ has been consistently identified as a key predictor of satisfaction and behavioral intention [16], making it a robust approach for assessing user experience in rail transport.

In public transportation, SQ has evolved to encompass sustainability concerns [17]. Rural transport plays a vital role in promoting social equity and regional integration. This integrated view aligns with the SDGs, positioning SQ as a critical driver of inclusive and resilient mobilities.

2.2 Railway-specific Models and Research Gaps

The complexity of railway operations has prompted the development of sector-specific service-quality models that extend beyond generic frameworks. Models such as TRANQUAL [18] and RAILQUAL [19] were developed to capture the distinctive attributes of rail services.

TRANQUAL emphasizes comfort, tangibles, reliability, and service efficiency across intercity and paratransit settings [16, 20]. RAILQUAL, proposed by Cavana et al. [19], focuses on rail-specific dimensions, including safety, cleanliness, comfort, connectivity, and reservation systems [4, 10, 11].

While the literature on rail SQ is extensive, it tends to bifurcate into two primary streams: passenger-focused models (such as SERVQUAL and RAILQUAL) addressing perceived quality and satisfaction in domestic travel [1–3], and operational-focused models that use key performance indicators (KPIs) to assess efficiency, cost, and reliability in international and freight transport [21]. While studies focusing on international supply chains often utilize KPI-based frameworks to evaluate cost and reliability [22], the current research focuses exclusively on the passenger perception perspective, which is crucial for public policy and investment decisions in the rural local context.

Although both models have been widely applied in urban and intercity contexts, their adaptation to rural railways, especially in developing countries, remains limited. Rural railway systems face distinctive challenges, such as aging infrastructure, limited investment, and heightened emphasis on affordability, accessibility, and basic service equity. These contextual differences justify the extension of RAILQUAL to rural settings.

Sustainable Service Quality (SSQ) requires a holistic framework that integrates environmental stewardship, economic viability, and social inclusion alongside traditional operational effectiveness [23]. However, traditional railway service models like RAILQUAL and TRANQUAL, have historically overlooked passengers' environmental awareness, despite ecological considerations increasingly shaping attitudes toward mobility. Recent studies confirm that quality evaluation in modern transport must account for these sustainability dimensions, positioning them as intrinsic components of SQ. For example, sustainable mass transit is highlighted as a core challenge [24], whereas tangible efforts such as greenhouse gas mitigation, waste management, and renewable energy utilization are now viewed by users as essential service attributes [25, 26]. By explicitly integrating an environment dimension into the RAQ construct, this study addresses this critical theoretical gap.

Building upon these insights, the present study extends the RAILQUAL framework by embedding an environmental attribute RAQ construct, conceptualized as Eco-RAQ. This dimension captures passengers' awareness of railway sustainability practices, such as greenhouse gas reduction, waste management, and energy efficiency, and integrates them into the cognitive–affective process of service evaluation. Incorporating this attribute bridges the gap between SQ perception and sustainable transport performance, offering a novel sustainability-integrated perspective on passenger experience in rural railways.

To capture the experiential and environmental dimensions of rail service, this study draws on Servicescape Theory [27], which explains how the physical environment influences user perception. Within the railway context, this concept is embodied in RAQ—the sensory, physical, and now ecological characteristics of the railway environment, including station cleanliness, energy efficiency, and safety cues [28].

2.3 Sustainable Railway Engineering and the Perception–Efficiency Linkage

The original RAILQUAL framework limits sustainability analysis by focusing only on passenger-centered service, neglecting engineering underpinnings like traction energy, rolling-stock reliability, and signaling coordination. This study advances the model by connecting perceptual evaluations (Eco-RAQ) with measurable infrastructure performance drivers.

2.3.1 Integrating energy usage and carbon emission metrics

Recent advances in sustainable railway engineering emphasize traction energy efficiency and carbon mitigation as quantifiable engineering drivers that ultimately influence SQ perception. These technical interventions function as "engineering cues" to passengers, influencing their evaluation of the system's modernity and overall efficiency.

The technological adoption of regenerative braking is a critical component of energy recovery across global networks. For example, China employs advanced energy feedback systems with sophisticated control (NN-MPC) to maximize kinetic energy recovery [29]. Similarly, Japan manages substation output and control thresholds to efficiently utilize brake energy [30], while Europe confirms the technical benefits of these systems in optimizing utilization efficiency on diagnostic trains [31].

Beyond braking, broader traction energy management strategies are integrated with operational and service metrics. China further studies railway photovoltaic potential as a core component of sustainable urban-rural energy transition [32]. Europe uses multi-criteria sustainability assessments that explicitly link energy consumption and carbon intensity to perceived performance [33]. Meanwhile, Japan utilizes complex optimization methods for DC substation energy storage to enhance efficiency and reliability [34].

2.3.2 Linking rolling-stock condition and passenger perception

Rolling-stock condition serves as a direct technical proxy for comfort, safety, and perceived operational efficiency. Technical metrics such as vibration, noise, and interior air quality correlate with passengers' affective responses and willingness to use the service [35]. International practices confirm that robust maintenance and design strategies are essential for managing reliability. Japan, for instance, links maintenance quality and energy-efficient design investment directly to its ESG management and customer reliability [36]. Similarly, China emphasizes intelligent digital transformation, employing real-time asset management and predictive maintenance for high service stability [37]. Furthermore, Europe utilizes proactive maintenance planning and cost allocation as strategic levers to reduce unplanned delays [38].

The Eco-RAQ construct in this study captures passengers' awareness of these underlying engineering integrity efforts through observable proxies like resource efficiency and waste management practices aboard the rolling stock.

2.3.3 Operational optimization and signaling performance

The strongest link between perceptual quality and efficiency (REQ) is reinforced by advances in signaling and operational optimization, which minimize delays and ensure high punctuality. Modern digitalized systems globally are key to this. Europe for example, emphasizes AI, cyber, and energy resilience to support reliable high-frequency operations [39]. In parallel, China focuses on mitigating electromagnetic interference (EMI) for stable signaling performance [40]. Furthermore, Japan, serves as a benchmark for accuracy, using Orthogonal Frequency Division Multiplexing (OFDM) transmission for precise train control [41].

Accordingly, REQ serves as a metric for immediate service impressions, and Eco-RAQ functions as an assessment of the long-term environmental and engineering governance.

2.3.4 Synthesis and theoretical integration

The synthesis embeds key technical indicators, traction energy, rolling-stock reliability, and signaling performance, into the perception–efficiency link, directly addressing prior RAILQUAL critiques. This approach positions Eco-RAQ as a technically grounded extension of service theory. Theoretically, the framework operationalizes the

S–O–R paradigm where sustainable engineering cues (stimulus) evoke perceptual judgments (organism), which subsequently manifest as efficiency evaluations (response). This linkage successfully bridges service science and transport engineering.

To avoid ambiguity between the constructs, this study distinguishes clearly among RAQ, the ENV items, and the newly introduced Eco-RAQ structure. In the original RAILQUAL framework, RAQ reflects passengers' sensory and atmospheric impressions, including comfort, cleanliness, and physical ambience. The four environmental items (greenhouse-gas reduction, waste management, resource efficiency, and renewable-energy use) were conceptually related to sustainability but did not fit the sensory orientation of RAQ. In the revised model, these ENV items are grouped into a separate first-order construct, Eco-RAQ, which represents passengers' perception of environmental and engineering stewardship. Thus, RAQ and Eco-RAQ operate as distinct latent variables in the structural model, each serving as an independent stimulus within the S–O–R pathway. This conceptual delineation ensures that environmental cognition is not conflated with sensory atmosphere but instead functions as a separate antecedent shaping perceived quality and operational efficiency.

2.4 Conceptual Framework and Hypotheses Development

The conceptual framework for this study is grounded in the S-O-R paradigm [42], a widely applied model in environmental psychology that provides a robust basis for explaining passenger behavior in service settings [11]. The S-O-R framework posits that environmental cues (stimuli) directly influence an individual's internal cognitive and affective state (organism), which subsequently drives an outcome behavior (response). This study integrates the RAILQUAL dimensions within this causal structure, conceptualizing the comprehensive passenger experience as follows [11, 43].

2.4.1 Stimuli (S), RAQ and Eco-RAQ

The RAQ represents the environmental stimuli encompassing physical and sensory cues of the railway system [28]. It includes attributes such as comfort, safety, lighting, and cleanliness.

The Eco-RAQ, introduced as an extension to the RAILQUAL framework, represents the sustainability-oriented stimuli. This distinct construct encapsulates passengers' perception of the railway operator's commitment to environmental and engineering practices, including attributes like greenhouse-gas reduction, waste management, and energy efficiency [30, 32]. The Eco-RAQ is conceptualized as a separate first-order construct to test its unique influence on passenger perception, independent of the traditional RAQ dimensions.

2.4.2 Organism (O), RPQ

The RPQ captures passengers' cognitive and affective evaluations of the service based on convenience (affordability and accessibility) and technological integration. This cognitive evaluation is informed by models like PSQ and the technology acceptance model [44].

2.4.3 Response (R), rail efficiency quality (REQ)

REQ represents the operational outcome of service evaluation—performance in punctuality, speed, reliability, and overall efficiency—consistent with the SERVPERF approach [45].

Based on the extended RAILQUAL-Eco-RAQ framework and the established S-O-R paradigm, the hypothesized relationships among these constructs are summarized below:

H1: RAQ has a significant positive direct effect on the REQ.
H2: Eco-RAQ has a significant positive direct effect on the REQ
H3: RAQ has a significant positive direct effect on the RPQ.
H4: Eco-RAQ has significant positive direct effect on the RPQ.
H5: RPQ has a significant positive direct effect on REQ.
H6: RPQ mediates the relationship between RAQ and REQ.
H7: RPQ mediates the relationship between Eco-RAQ and REQ.

3 Methods

3.1 Research Design and Data Collection

This study employed a quantitative, cross-sectional design to assess SQ in Thailand's rural railways system, focusing on passengers of the SRT. The questionnaire was developed based on the established RAILQUAL framework and refined through expert review and a pilot test (N = 30). All items demonstrated high content validity, with an item-objective congruence (IOC) values ranging from 0.80 to 1.00 and strong internal consistency (Cronbach's alpha = 0.98).

Data were collected using the Paper-and-Pencil Interview (PAPI) method between November 2024 and April 2025, a mode well suited for rural fieldwork where digital access is limited. Prior to data collection, six interviewers completed a standardized two-day training program covering exact questions phrasing, neutral probing, and ethical procedures. A dedicated module addressed interviewer influence and social desirability mitigation. Following SEM sample size recommendations [46] for 43 observed variables, 1,021 responses were collected, of which 1,013 were valid. Surveys were conducted across three major operational corridors, covered three operational corridors, Northeastern, Northern, and Southern Lines—covering 28 provinces to ensuring representation of diverse rural contexts.

3.2 Measurements

The survey instrument measured four latent constructs—RAQ, Eco-RAQ, RPQ, and REQ—using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Items were adapted from the RAILQUAL and the broader SQ literature, with contextual adjustments for rural Thailand. Each observed indicator was assigned to its respective construct based on the SEM specification. Table 1 provides details of the constructs, variables, and measurement items.

Table 1. The constructs, variables, and items

Constructs	Variables	Examples Measurement Items	No. of Items
RAQ	COM 1–8, SAS 1–4, HAC 1–6	Train comfort, lighting, station cleanliness	18
Eco-RAQ	ENV 1–4	Greenhouse gas reduction	4
RPQ	TEC 1–5, AFF 1–4, ACC 1–5	E-ticketing, fare affordability, station location	14
REQ	EFF 1–7	On-time service, reliability, travel speed	7
Total			**43**

3.3 Measurement and Validation Procedures

To ensure cultural and statistical validity, multiple assessment procedures were applied based on the guidelines of Hair et al. [47] and Kline [48]. In the measurement model, RAQ and Eco-RAQ are specified as separate first-order constructs (Table 1). The COM, SAS, and HAC indicators loaded exclusively on RAQ, whereas the four ENV (ENV1-ENV4) loaded solely on Eco-RAQ. This specification ensures a clear conceptual distinction between sensory/perceptual ambience (RAQ) and sustainability/engineering evaluations (Eco-RAQ), and prevents conflation of environmental items with the traditional RAQ dimensions. All questionnaire items were translated and back-translated by two bilingual experts following Brislin [49]. A panel of five academic and industry specialists assessed semantic and contextual accuracy using a four-point relevance scale, resulting in an average Content Validity Index (CVI) of 0.92.

Reliability was assessed using Cronbach's alpha ($\geq$ 0.70) and Composite Reliability (CR $\geq$ 0.70), while convergent validity was confirmed by Average Variance Extracted (AVE $\geq$ 0.50). Discriminant validity was evaluated using both the Fornell–Larcker criterion [50] and the Heterotrait–Monotrait ratio (HTMT $<$ 0.85) [51].

Common-method bias (CMB) was examined using Harman's single-factor test, with the first factor explaining less than 50% of total variance [52]. Multicollinearity was assessed using the Variance Inflation Factors (VIF $<$ 3.0) [53].

Model fit and robustness were evaluated using multiple indices: χ^2/df < 3, CFI > 0.95, TLI > 0.95, RMSEA < 0.06, and SRMR < 0.08 [53]. Rival model testing—including baseline, merged, and proposed models—was performed to confirm structural stability and verify the theoretical distinctiveness of the Eco-RAQ construct, following recommended CB-SEM procedures [48, 54].

3.4 Analytical Methods

Covariance-based SEM (CB-SEM) was conducted using AMOS. This method simultaneously estimates the measurement and structural models while accounting for measurement error [46].

A three-stage process analytical strategy was adopted. First, preliminary data screening assessed factorability using the Kaiser–Meyer–Olkin (KMO) statistic and Bartlett's Test of Sphericity. Normality was examined using the Anderson–Darling and Henze–Zirkler tests; despite mid non-normality, Maximum Likelihood Estimation (MLE) was applied given the large sample size (N = 1,013) [48]. Second, exploratory factor analysis (EFA) using principal component analysis with Varimax rotation was performed to refine the initial factor structure for 43 indicators, followed by CFA to validate the measurement model. Reliability (CR $\geq$ 0.70), convergent validity using AVE $\geq$ 0.50 [46], and discriminant validity were confirmed following Fornell–Larcker criterion [50]. Overall, model fit satisfied recommended thresholds (χ^2/df < 3, CFI > 0.95, TLI > 0.95, RMSEA < 0.06, and SRMR < 0.08 [55]. Finally, structural model estimation tested the hypothesized direct and indirect effect (H1-H7). Explanatory power evaluated through coefficients of determination (R^2), while standardized path coefficients (β) and associated p-value ($p < 0.05$) established significance.

4 Results

4.1 Demographic Profiles

A total of 1,013 valid responses were collected from passengers of local trains operated by the SRT. The demographic profile indicates that 57.2% of respondents were female, and 62.4% were between 20–30 years old. In terms of regional representation, 48.4% were from the northeastern region, 30.5% from the northern region, and 21.1% from the southern region. Regarding train usage frequency, 24.6% of participants reported using local trains two to five times per month, reflecting a predominance of frequent but consistent users. The data captured adequate diversity in gender, age, region, and travel frequency.

4.2 Measurement Model Validation

The measurement model comprised four second-order latent constructs (RAQ, Eco-RAQ, RPQ, and REQ) and eight first-order dimensions. CFA was conducted using the MLE method. The data exhibited acceptable univariate normality (skewness and kurtosis within the recommended thresholds) [48] (Appendix Table A1).

All constructs demonstrated strong internal consistency and convergent validity. The CR and Cronbach's alpha exceeded the recommended level of 0.70, indicating high internal reliability (CR ranging from 0.873 to 0.950). Convergent validity was confirmed with AVE values above 0.50, and all standardized factor loadings 0.50 [46].

Sampling adequacy was further validated by the KMO measure (0.959) and Bartlett's Test of Sphericity (χ^2 = 17,103.889, df = 91, p <0.001). These results confirm the data were well-suited for factor analysis and that the measurement model demonstrated sound psychometric properties. Table 2 presents the full reliability and validity statistics.

Table 2. Reliability and convergent validity

Construct	Item	Standard Loading Range	Cronbach's Alpha	CR	AVE
RAQ	COM	0.779–1.000	0.923	0.907	0.590
	SAS	0.780–0.876	0.925	0.873	0.708
	HAC	0.724–0.919	0.945	0.924	0.734
Eco-RAQ	ENV	0.886–0.954	0.953	0.946	0.840
RPQ	TEC	0.571–0.920	0.906	0.937	0.739
	AFF	0.854–0.878	0.932	0.925	0.756
	ACC	0.765–0.913	0.954	0.940	0.761
REQ	EFF	0.816–0.886	0.946	0.950	0.733

Note: Loadings equal to 1.000 reflect AMOS scaling constraints and were verified from standardized estimates.

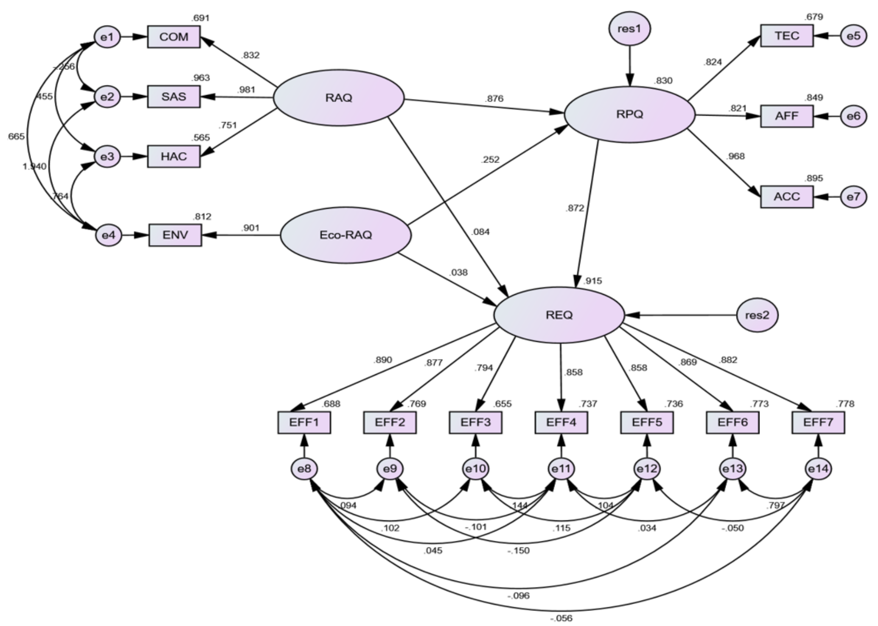

Figure 1. Path diagram of the influence of RAQ, Eco-RAQ, and RPQ on REQ

Note: Chi-square = 26.298, df = 24, p-value = .338, Chi-square/df = 1.096, CFI = 1.000, GFI = .996, AGFI = .984, IFI = 1.000, NFI = .998, TLI = .999, RMR = .008, RMSEA = .010

All parameters met or exceeded accepted threshold, conforming that the RAILQUAL measurement model was both reliable and valid.

4.3 Structural Model Testing

After validating the measurement model, the structural model was estimated using CB-SEM. The model demonstrated an excellent overall fit to the data: χ^2/df = 1.096, CFI = 1.000, TLI = 0.999, RMSEA = 0.010, and RMR = 0.008, all of which satisfy the recommended criteria [54].

The model explained 91.50 of the variance in REQ (R^2 = 0.915) and 83.0% of the variance in RPQ (R^2 = 0.830) indicating high explanatory power.

Figure 1 illustrates the structural model (CB-SEM): RAQ (comfort/safety/hygiene), Eco-RAQ (ENV1–ENV4), RPQ (perceived quality), and REQ (perceived efficiency). Path coefficients shown are standardized estimates.

All seven hypotheses (H1–H7) were thus supported. The results confirm that RAQ, Eco-RAQ significantly influences REQ both directly and indirectly through RPQ. The large total effect (β = 0.848) highlights RAQ as the most influential construct in the model, validating the integrated RAILQUAL framework for rural railway evaluations (refer to Table 3).

Table 3. Direct and indirect results

Path	β	p-value	Result
RAQ → REQ	0.084	<0.001	Supported
Eco-RAQ → REQ	0.038	<0.001	Supported
RAQ → RPQ	0.876	<0.001	Supported
Eco-RAQ → RPQ	0.252	<0.001	Supported
RPQ → REQ	0.872	<0.001	Supported
RAQ → RPQ → REQ	0.764	<0.001	Supported
Eco-RAQ → RPQ → REQ	0.219	<0.001	Supported
Total effect RAQ → REQ	0.848		Supported
Total effect Eco-RAQ → REQ	0.257		Supported

4.4 Validation Tests

4.4.1 Common-method bias (CMB) and multicollinearity

Two diagnostics were conducted to ensure data reliability. First, Harman's single-factor test was performed in SPSS 28 to assess potential common-method variance. The first unrotated factor accounted for 29.4% of the total variance, which is below the 50% threshold [52], indicating that common-method bias was not a major concern. Second, the Variance Inflation Factors (VIF) for all items were below 3.0, confirming the absence of multicollinearity among indicators and constructs [53] (Appendix Table A2 [56]).

4.4.2 Discriminant validity via HTMT criterion

The discriminant validity of the latent constructs—RAQ, Eco-RAQ, RPQ, and REQ—was evaluated using the Heterotrait–Monotrait ratio of correlations (HTMT), as recommended by Henseler et al. [51]. All HTMT values were below the conservative threshold of 0.85, indicating that each construct was conceptually distinct and free from multicollinearity concerns (Table 4). This result confirms discriminant validity beyond the Fornell–Larcker criterion [50], thereby supporting the adequacy of construct differentiation within the measurement model.

Table 4. HTMT ratios among constructs

Constructs	RAQ	Eco-RAQ	RPQ	REQ
RAQ	–	0.71	0.63	0.58
Eco-RAQ	0.71	–	0.66	0.61
RPQ	0.63	0.66	–	0.72
REQ	0.58	0.61	0.72	–

4.4.3 Rival model and robustness testing

To evaluate the robustness of the proposed model, three alternative structural specifications were compared.

Table 5, the Eco-RAQ model (M3) demonstrated superior overall fit (χ^2/df = 1.096, CFI = 1.000, TLI = 0.999, RMSEA = 0.010, SRMR = 0.008) relative to both the baseline and merged models. This supports the inclusion of Eco-RAQ as an independent latent construct representing environmental and engineering perceptions.

Table 5. The three rival model robustness

Model Specification	Description	χ^2/df	CFI	TLI	RMSEA	SRMR
M1: Baseline RAILQUAL	Traditional RAILQUAL without Eco-RAQ	2.412	0.973	0.962	0.057	0.041
M2: Merged RAQ–RPQ	Combined sensory and perceptual constructs	2.018	0.985	0.977	0.048	0.031
M3: Proposed Eco-RAQ Model	RAQ and Eco-RAQ treated as distinct constructs	1.096	1.000	0.999	0.010	0.008

Rival-model comparisons revealed highly consistent path coefficients ($\beta < 0.02$) and equivalent global fit indices (CFI < 0.01), indicating that the model relationships remained stable and theoretically coherent across estimation approaches.

This structural stability, coupled with the rigorous validation of construct distinctiveness (Discriminant Validity: HTMT ratio < 0.85) and the confirmed absence of common-method bias (CMB < 50 of total variance), collectively reinforces the methodological soundness and robustness of the proposed Eco-RAQ framework and the reliability of its structural relationships.

4.5 Summary of Extended Model Fit

The final model explained 91.50% and 83.0% of the variance in REQ and RPQ, respectively, confirming its high explanatory power. The inclusion of Eco-RAQ slightly increased both R^2 and model fit indices compared to the baseline model, signifying that passengers' awareness of environmental responsibility meaningfully enhanced perceived operational efficiency.

5 Discussion

The findings of this study advance both theoretical and empirical understanding of rural railway SQ. The validated RAILQUAL–SEM framework demonstrates strong explanatory power (R^2 = 0.915) and extends the applicability of traditional service-quality theories to non-urban and developing contexts.

5.1 Theoretical Contributions and Advancement

This study reinforces the S–O–R paradigm by empirically validating how environmental stimuli, such as RAQ, influence passengers' cognitive–affective evaluations, such as RPQ, which subsequently shape perceptions of efficiency, such as REQ. By integrating SERVQUAL, Grönroos' Nordic Model, and Bitner's Servicescape Theory within the RAILQUAL structure, the research advances a unified causal framework that links tangible engineering cues, perceptual quality, and operational performance.

A key theoretical innovation lies in the development of Eco-RAQ, an extension of the RAILQUAL model that embeds environmental and engineering cognition into SQ analysis. Eco-RAQ captures passengers' awareness of sustainability-oriented operations, greenhouse-gas reduction, waste management, traction energy efficiency, and renewable-energy utilization—thereby expanding the RAILQUAL framework beyond conventional service attributes. Empirically, RAQ exerts the strongest total effect on REQ (β = 0.848, $p < 0.001$), both directly and indirectly via RPQ, confirming that ecological awareness has become a decisive determinant of perceived efficiency in rural railways.

Theoretically, this finding extends the frontier of transport service theory by reframing sustainability as both a perceptual and socio-technical construct. Passengers in rural contexts interpret environmental practices—such as clean-energy use or effective waste control—not merely as technical indicators but as moral and institutional signals of reliability, fairness, and trust. This cognitive–affective mediation enriches the S-O-R model by demonstrating how ecological responsibility functions as an antecedent of satisfaction, particularly in resource-constrained contexts.

Beyond conceptual advancement, the study also contributes to methodological rigor in service-engineering research. The application of multi-model comparison, discriminant validity testing via HTMT [51], and robustness diagnostics strengthens construct validity and model credibility. By demonstrating the consistency of structural paths across rival models, the Eco-RAQ framework achieves theoretical and empirical robustness, addressing prior gaps in sustainable transport research that relied solely on perception-based measures.

Collectively, these contributions advance the theoretical discourse by (1) extending RAILQUAL into sustainability-integrated contexts, (2) validating the S-O-R mechanism in a developing-country setting, and (3) positioning Eco-RAQ as a replicable framework that bridges service science, environmental psychology, and railway engineering—thereby defining a new paradigm for sustainable mobility research.

5.2 Conceptual Distinction between RAQ and Eco-RAQ

Although both constructs are derived from the sensory–environmental context of railway services, RAQ and Eco-RAQ represent conceptually distinct dimensions. RAQ primarily captures passengers' sensory and comfort perceptions—cleanliness, lighting, safety, and physical design—whereas Eco-RAQ integrates awareness of environmental and technical sustainability performance such as greenhouse gas reduction, waste management, and energy efficiency. Confirmatory analyses demonstrate discriminant validity (HTMT = 0.71) between the two, signifying that environmental cognition constitutes an independent evaluative process rather than a mere extension of physical comfort.

From a theoretical perspective, this distinction implies that rural passengers interpret sustainable practices not solely through direct experience but through symbolic cues of institutional responsibility. This socio-environmental cognition deepens the traditional stimulus–organism–response pathway by linking technical sustainability actions to affective trust formation, reinforcing that environmental stewardship can function as an operational signal of reliability and equity in resource-limited rail systems.

5.3 Integrating Engineering Metrics within the Eco-RAQ Framework

Integrating engineering-oriented sustainability factors into the Eco-RAQ construct bridges perceptual and technical dimensions of railway SQ. While traditional SERVQUAL and RAILQUAL models emphasize intangible service attributes, the present study redefines Eco-RAQ as a dual construct combining environmental cognition-awareness of greenhouse-gas reduction, waste management, and energy stewardship—with passengers' recognition of visible engineering efficiency. This interpretation resonates with evidence from advanced rail systems: regenerative braking adoption [29], traction energy optimization [33], intelligent signaling reliability [39], and rolling-stock modernization [36] all demonstrate that tangible efficiency improvements correspond to enhanced passenger confidence and perceived reliability.

Empirically, the modest total effect of Eco-RAQ on REQ (β = 0.257, $p < 0.001$) supports this convergence, revealing that sustainable engineering performance has become a perceptible determinant of efficiency evaluation. The partial mediation through RPQ further indicates that passengers internalize environmental and technical cues as signs of operational reliability and institutional trust. Consequently, the Eco-RAQ framework reframes SQ as a socio-technical cognition, wherein sustainable engineering initiatives simultaneously deliver ecological benefits and strengthen perceived service excellence.

5.4 Comparative Interpretation

Cross-national comparison situates these findings within the broader discourse on sustainable railway SQ. Prior studies from Malaysia [10], India [13], and South Africa [19] consistently highlight safety, cleanliness, and accessibility as key determinants of passenger satisfaction-dimensions that remain essential but largely operational. In contrast, the present study identifies an emerging paradigm in Thailand's rural railway context, where passengers increasingly assess SQ through a sustainability-oriented lens encapsulated by the Eco-RAQ construct. Environmental stewardship-manifested in awareness of waste management, energy efficiency, and greenhouse-gas reduction—has become integral to perceptions of efficiency and reliability.

Comparative insights from advanced rail systems reinforce this transition. In Europe, China, and Japan, engineering innovations such as regenerative braking, traction-energy optimization, and intelligent signaling [31, 32, 41] simultaneously enhance energy performance and passenger trust. These systems demonstrate that sustainability and efficiency function as co-evolving dimensions of quality rather than separate policy objectives. The Thai findings extend this paradigm to a developing-country setting, illustrating that visible environmental initiatives can substitute for the technological precision typical of high-income rail systems. While advanced networks rely on digital reliability and real-time control, rural passengers in Thailand interpret sustainability cues as signals of institutional reliability, care, and social equity.

Overall, this comparative interpretation underscores that railway SQ is a socio-technical construct shaped by cultural expectations, infrastructural maturity, and environmental consciousness. The integration of Eco-RAQ within the RAILQUAL–SEM framework thus demonstrates that ecological cognition operates as a universal mediator linking perceived environment, quality, and efficiency across diverse economic and technological contexts—bridging service science, environmental psychology, and railway engineering within a unified model of sustainable mobility.

6 Policy and Engineering Implications

This study offers critical insights for the strategic management of rural railway systems, particularly in developing economies, and provides guidance for achieving the SDGs 9, 11, and 13.

6.1 Strategic and Policy Implications

The finding that Eco-RAQ is the dominant driver of perceived efficiency, as operationalized by REQ (β = 0.257), necessitates a paradigm shift, SQ is now intrinsically linked to an operator's sustainability commitment. Railway management must elevate Eco-RAQ from a secondary environmental concern to a primary KPI for customer-facing operations. This provides a clear justification for public investment in green modernization, as rural passengers interpret such efforts (e.g., in energy and waste management) as a sign of institutional reliability. Consequently, policy development should actively communicate these socio-technical improvements, aligning the S-O-R model with national sustainability objective, such as the SDGs.

6.2 Engineering and Operational Implications

The operationalization of the Eco-RAQ construct points to specific, actionable engineering interventions.

First, regarding rolling stock and traction energy (SDG 9, 13), the high salience of traction-energy efficiency and GHG reduction indicates an urgent need to prioritize fleet modernization. Investment must target new rolling stock that utilizes low-carbon or fuel-efficient alternatives. This action should be viewed not just as a cost-saving measure, but as a direct enhancement of the perceived passenger experience.

Second, for station management (SDG 11), operators should implement visible "Green Station Retrofit" programs in rural areas. Focus must be on tangible elements directly observable by passengers, such as installing energy-efficient lighting, solar panels where feasible, and enhancing waste management systems with clear signage and segregated bins. These operational improvements directly address the most impactful drivers of passenger perception identified in the model.

By aligning service management with these socio-technical cues, the railway system can effectively leverage its sustainability efforts to not only improve operational performance but also to enhance passenger loyalty and contribute to broader societal goals.

7 Conclusions

This study reframes rural railway SQ through a socio-technical lens, demonstrating that environmental and engineering attributes shape how passengers perceive system performance. Integrating Eco-RAQ into the RAILQUAL framework shows that sustainability cues—whether technological, operational, or environmental—play a central role in passengers' cognitive evaluations, extending beyond traditional experiential dimensions. This conceptual shift positions sustainable engineering practices as perceptual stimuli that influence users' judgments and expectations.

From a policy perspective, the findings underscore the need for coordinated strategies that align infrastructure upgrades, environmental stewardship, and inclusive service design. Prioritizing energy-efficient rolling stock, environmentally responsive stations, transparent performance communication, and equitable accessibility can strengthen the resilience and social value of rural rail systems.

Overall, the study affirms that sustainability in rural rail transport relies on continuous alignment between technological innovation, environmental responsibility, and passenger-centered management.

8 Limitation and Future Research

While the proposed framework provides strong empirical and theoretical evidence, several limitations should be acknowledged to guide future research directions.

First, the research relied on cross-sectional, perception-based data from selected rural areas, which may limit generalizability. Future longitudinal or panel studies are recommended to capture dynamic policy and infrastructure effects on passenger perceptions over time.

Second, the sample was somewhat skewed toward younger and frequent users, reflecting the active rural commuter base but underrepresenting elderly or occasional passengers; future research should employ stratified or weighted sampling to enhance representativeness.

Third, data collection coincided with early stages of Thailand's rural railway upgrades, introducing potential temporal perception bias. Future studies could control for these effects using multi-wave or mixed-method designs.

Fourth, multi-group or multi-level SEM analyses were not conducted due to sample constraints. Extending the RAILQUAL–Eco-RAQ model across demographic and regional groups would allow testing of structural invariance and cross-cultural robustness.

Finally, future research may develop a Sustainable Rail Performance Index (SRPI) that combines perception-based constructs (RAQ, Eco-RAQ, REQ) with engineering KPIs (traction energy use, carbon intensity, punctuality) to create an integrated sustainability monitoring system. Collectively, addressing these limitations will enable future research to refine the Eco-RAQ framework into a dynamic sustainability assessment model that continually adapts to evolving engineering and environmental realities of rural rail systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Acknowledgment

The author gratefully acknowledges the support of the State Railway of Thailand (SRT) for providing access to field sites and facilitating data collection across local train routes. Appreciation is also extended to the survey participants whose valuable responses contributed to the development of the RAILQUAL model.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] A. Parasuraman, V. A. Zeithaml, and L. L. Berry, "A conceptual model of service quality and its implications for future research," *J. Mark.*, vol. 49, no. 4, pp. 41–50, 1985. https://doi.org/10.2307/1251430

[2] V. A. Zeithaml, M. J. Bitner, and D. D. Gremler, *Services Marketing: Integrating Customer Focus across the Firm*. Boston: McGraw-Hill Irwin, 2009.

[3] M. L. C. Franz, N. F. Ayala, and A. M. Larranaga, "Industry 4.0 for passenger railway companies: A maturity model proposal for technology management," *J. Rail Transp. Plann. Manag.*, vol. 32, p. 100480, 2024. https://doi.org/10.1016/j.jrtpm.2024.100480

[4] T. Vanniarajan and A. Stephen, "Railqual and passengers satisfaction: An empirical study in southern railways," *Asia Pac. Bus. Rev.*, vol. 4, no. 1, pp. 64–75, 2008. https://doi.org/10.1177/097324700800400107

[5] D. P. Maruvada and R. S. Bellamkonda, "The effects of individual dimensions of railway service quality: Findings from indian railway passenger services through developing RAILQUAL," *Int. J. Innov. Technol. Manag.*, vol. 3, no. 1, pp. 42–45, 2012.

[6] Department of Rail Transport, "Number of rail passengers," 2025. https://drt.gdcatalog.go.th/dataset/drt2565_03

[7] Institute for Population and Social Research, "Population of Thailand," 2025. https://ipsr.mahidol.ac.th/population-gazette/

[8] Department of Land Transport, "Transport Statistics," 2025. https://web.dlt.go.th/statistics/plugins/UploadiFive/uploads/6f6897ce35cd1d6a488eab4c29a548a0b5d0973421176078322eff0d7d61b5a5.pdf

[9] United Nations Development Programme, "Sustainable Urbanization Strategy," 2016. https://www.undp.org/publications/sustainable-urbanization-strategy

[10] N. M. Ali, R. M. Nor, S. F. M. Hamzah, S. M. Salleh, R. D. H. Setia, R. S. A. Rashid, H. M. Nor, and R. I. Borhanuddin, "Service quality and its impact on usage intention in Malaysian rail transportation," *Int. J. Acad. Res. Econ. Manag. Sci.*, vol. 13, no. 4, pp. 175–189, 2024. https://doi.org/10.6007/ijarems/v13-i4/23187

[11] P. Thanaraju, P. A. M. Khan, S. Sivanathan, and N. H. Juhari, "Passengers' satisfaction towards railway facilities (RAILQUAL in Central Region)," *Int. J. Recent Technol. Eng.*, vol. 8, no. 2, pp. 561–572, 2019.

[12] K. B. W. Junardy and S. R. H. Hati, "Influence of railqual on passenger satisfaction: Study of indonesian intercity trains," in *30th International Business Information Management Association Conference—Vision 2020: Sustainable Economic development, Innovation Management, and Global Growth, IBIMA 2017, Madrid, Spain*, 2017.

[13] D. P. Maruvada and R. S. Bellamkonda, "RAILQUAL: A multiple item scale for evaluating railway passenger service quality and satisfaction," *Int. J. Serv. Oper. Manag.*, vol. 27, no. 2, pp. 145–166, 2017. https://doi.org/10.1504/ijsom.2017.083761

[14] A. Parasuraman, V. A. Zeithaml, and L. L. Berry, "Servqual: A multiple-item scale for measuring consumer perceptions of service quality," *J. Retail.*, vol. 64, no. 1, pp. 12–40, 1988.

[15] C. Grönroos, "A service quality model and its marketing implications," *Eur. J. Mark.*, vol. 18, no. 4, pp. 36–44, 1984.

[16] S. Jomnonkwao, T. Champahom, and V. Ratanavaraha, "Methodologies for determining the service quality of the intercity rail service based on users' perceptions and expectations in Thailand," *Sustainability*, vol. 12, no. 10, p. 4259, 2020. https://doi.org/10.3390/su12104259

[17] N. Ngcobo, O. Akinradewo, and P. Mokoena, "Evaluating the measures to promote sustainable transport infrastructure: A case of city of Johannesburg, South Africa," *J. Eng.*, vol. 2024, no. 1, p. 6372226, 2024. https://doi.org/10.1155/je/6372226

[18] I. G. M. Y. Bakti and S. Sumaedi, "P-TRANSQUAL: A service quality model of public land transport services," *Int. J. Qual. Reliab. Manag.*, vol. 32, no. 6, pp. 534–558, Jun. 2015. https://doi.org/10.1108/ijqrm-06-2013-0094

[19] R. Y. Cavana, L. M. Corbett, and Y. L. Lo, "Developing zones of tolerance for managing passenger rail service quality," *Int. J. Qual. Reliab. Manag.*, vol. 24, no. 1, pp. 7–31, 2007. https://doi.org/10.1108/02656710710720303

[20] N. C. C. Tiglao, J. M. D. Veyra, N. J. Y. Tolentino, and M. A. Y. Tacderas, "The perception of service quality among paratransit users in Metro Manila using structural equations modelling (SEM) approach," *Res. Transp. Econ.*, vol. 83, p. 100955, Nov. 2020. https://doi.org/10.1016/j.retrec.2020.100955

[21] A. G. Gallego, M. P. Lambán, J. R. Sánchez, J. C. S. Catalán, and P. M. Avinzano, "Study and characterization of new KPIs for measuring efficiency in urban loading and unloading zones using the OEE (Overall Equipment Effectiveness) model," *Appl. Sci.*, vol. 15, no. 14, p. 7652, 2025. https://doi.org/10.3390/app15147652

[22] J. Shan, N. Bešinović, and J. Schönberger, "Service quality assessment of international rail transport with multiple border crossings: Eurasian rail transport as an example," *J. Rail Transp. Plan. Manag.*, vol. 29, p. 100432, 2024. https://doi.org/10.1016/j.jrtpm.2024.100432

[23] M. Giunta, "Trends and challenges in railway sustainability: The state of the art regarding measures, strategies, and assessment tools," *Sustainability*, vol. 15, no. 24, p. 16632, 2023. https://doi.org/10.3390/su152416632

[24] T. Abdallah, *Sustainable Mass Transit: Challenges and Opportunities in Urban Public Transportation*. Elsevier, 2023.

[25] D. da Fonseca-Soares, S. A. Eliziário, J. D. Galvincio, and A. F. Ramos-Ridao, "Greenhouse gas emissions in railways: Systematic review of research progress," *Buildings*, vol. 14, no. 2, p. 539, 2024. https://doi.org/10.3390/buildings14020539

[26] K. S. Gad, F. Tonini, G. Agati, D. Borello, and E. Colombo, "Energy demand prediction and scenario analysis for vehicle traction: A bottom-up approach applied to the italian railway system," *Energy Rep.*, vol. 13, pp. 4196–4208, 2025. https://doi.org/10.1016/j.egyr.2025.03.061

[27] M. J. Bitner, "Servicescapes: The impact of physical surroundings on customers and employees," *J. Mark.*, vol. 56, no. 2, pp. 57–71, 1992. https://doi.org/10.2307/1252042

[28] L. Eboli, Y. Fu, and G. Mazzulla, "Multilevel comprehensive evaluation of the railway service quality," *Procedia Eng.*, vol. 137, pp. 21–30, 2016. https://doi.org/10.1016/j.proeng.2016.01.230

[29] H. Pan, J. Yao, H. Zhang, P. Cao, and H. Zhu, "Modular multilevel railway regenerative braking energy feedback device based on NN-MPC," *Int. J. Dynam. Control*, vol. 13, no. 11, p. 387, 2025. https://doi.org/10.1007/s40435-025-01881-6

[30] I. Wakayama, K. Kondo, H. Kobayashi, and T. Nagashima, "Substation output voltage design based on threshold voltage for light-load regenerative brake control," *IEEJ J. Ind. Appl.*, vol. 14, no. 6, pp. 1016–1027, 2025. https://doi.org/10.1541/ieejjia.24013134

[31] F. Cutrignelli, G. Saponaro, M. Stefanizzi, M. Torresi, and S. M. Camporeale, "Study of the effects of regenerative braking system on a hybrid diagnostic train," *Energies*, vol. 16, no. 2, p. 874, 2023. https://doi.org/10.3390/en16020874

[32] H. Wang, B. Chen, J. An, C. Lin, and P. Gong, "China's railway photovoltaic potential for sustainable urban–rural energy transition," *Environ. Res. Lett.*, vol. 20, no. 10, p. 104039, 2025. https://doi.org/10.1088/1748-9326/adff95

[33] N. Petrović, V. Jovanović, S. Marković, D. Marinković, and M. Petrović, "Multicriteria sustainability assessment of transport modes: A European Union case study for 2020," *J. Green Econ. Low-Carbon Dev.*, vol. 3, no. 1, pp. 36–44, 2024. https://doi.org/10.56578/jgelcd030104

[34] S. Nakamura, T. Fukuda, Y. Kodama, Y. Hayashi, and H. Hayashiya, "Multipurpose optimization method for energy storage system specification using measurement data of DC traction substations," *IEEJ Trans. Electr. Electron. Eng.*, vol. 19, no. 4, pp. 553–566, 2024. https://doi.org/10.1002/tee.23998

[35] A. Mohammadi, L. Amador-Jimenez, and F. Nasiri, "A multi-criteria assessment of the passengers' level of comfort in urban railway rolling stock," *Sustain. Cities Soc.*, vol. 53, p. 101892, 2020. https://doi.org/10.1016/j.scs.2019.101892

[36] Central Japan Railway Company, "Integrated report 2024: ESG management and carbon neutrality—JESG management," 2024. https://global.jr-central.co.jp/en/company/ir/annualreport/_pdf/annualreport2024-06.pdf

[37] L. Ping, R. Xue, S. Shao, Y. Zhu, and Y. Liu, "Current state and predicted technological trends in global railway intelligent digital transformation," *Railw. Sci.*, vol. 2, no. 4, pp. 397–412, 2023. https://doi.org/10.1108/rs-10-2023-0036

[38] A. S. J. Smith and M. O. Cabral, "Is higher quality always costly? Marginal costs of quality: Theory and application to railway punctuality," *Transp. Res. A Policy Pract.*, vol. 157, pp. 258–273, 2022. https://doi.org/10.1016/j.tra.2022.01.007

[39] P. Holoborodko, D. Bazaras, and N. Batarlienė, "Future rail signaling: Cyber and energy resilience through AI interoperability," *Sustainability*, vol. 17, no. 10, p. 4643, 2025. https://doi.org/10.3390/su17104643

[40] Y. Fan, L. Zhang, and K. Li, "EMI and IEMI impacts on the radio communication network of electrified railway systems: A critical review," *IEEE Trans. Veh. Technol.*, vol. 72, no. 8, pp. 10 409–10 424, 2023. https://doi.org/10.1109/tvt.2023.3260582

[41] R. Higuchi, H. Mochizuki, H. Nakamura, R. Ishikawa, M. Sano, and S. Nishida, "Application of OFDM transmission method for railway signalling system via track circuit," *J. Phys. Conf. Ser.*, vol. 1780, no. 1, p. 012037, 2021. https://doi.org/10.1088/1742-6596/1780/1/012037

[42] A. Mehrabian and J. A. Russell, *An Approach to Environmental Psychology*. Cambridge: M.I.T. Press, 1974.

[43] E. Nathanail, "Measuring the quality of service for passengers on the hellenic railways," *Transp. Res. A Policy Pract.*, vol. 42, no. 1, pp. 48–66, 2008. https://doi.org/10.1016/j.tra.2007.06.006

[44] F. D. Davis, "Perceived usefulness, perceived ease of use, and user acceptance of information technology," *MIS Q.*, vol. 13, no. 3, pp. 319–340, 1989. https://doi.org/10.2307/249008

[45] J. J. Cronin and S. A. Taylor, "Measuring service quality: A reexamination and extension," *J. Mark.*, vol. 56, no. 3, pp. 55–68, 1992. https://doi.org/10.2307/1252296

[46] K. A. Bollen, *Structural Equations with Latent Variables*. New York: John Wiley & Sons, 1989.

[47] J. F. Hair, G. T. M. Hult, C. M. Ringle, and M. Sarstedt, *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*. Los Angeles: Sage, 2014.

[48] R. B. Kline, *Principles and Practice of Structural Equation Modeling (4th ed)*. New York: Guilford Publications, 2016.

[49] R. W. Brislin, "Back-translation for cross-cultural research," *J. Cross-Cult. Psychol.*, vol. 1, no. 3, pp. 185–216, 1970. https://doi.org/10.1177/135910457000100301

[50] C. Fornell and D. F. Larcker, "Evaluating structural equation models with unobservable variables and measurement error," *J. Mark. Res.*, vol. 18, no. 1, pp. 39–50, 1981. https://doi.org/10.1177/002224378101800104

[51] J. Henseler, C. M. Ringle, and M. Sarstedt, "A new criterion for assessing discriminant validity in variance-based structural equation modeling," *J. Acad. Mark. Sci.*, vol. 43, pp. 115–135, 2015. https://doi.org/10.1007/s11747-014-0403-8

[52] P. M. Podsakoff, S. B. MacKenzie, J. Y. Lee, and N. P. Podsakoff, "Common method biases in behavioral research: A critical review of the literature and recommended remedies," *J. Appl. Psychol.*, vol. 88, no. 5, pp. 879–903, 2003.

[53] J. F. Hair, W. C. Black, B. J. Babin, and R. E. Anderson, *Multivariate Data Analysis (8th ed)*. Andover, Hampshire, United Kingdom: Cengage Learning Emea, 2019.

[54] R. P. Bagozzi and Y. Yi, "Specification, evaluation, and interpretation of structural equation models," *J. Acad. Mark. Sci.*, vol. 40, no. 1, pp. 8–34, 2011. https://doi.org/10.1007/s11747-011-0278-x

[55] P. M. Bentler, "Comparative fit indexes in structural models," *Psychol. Bull.*, vol. 107, no. 2, pp. 238–246, 1990. https://doi.org/10.1037/0033-2909.107.2.238

[56] R. B. Kline, *Principles and Practice of Structural Equation Modeling (5th ed)*. New York: Guilford Publications, 2023.

Appendix

Table A1. Questionnaire items and statistical summary

Item	Questionnaire Item	M	SD	SK	KU
COM1	It is convenience in transporting luggage or belongings and there are enough luggage racks on the train	3.36	1.199	-0.344	-0.691
COM2	The train has comfortable seats and space	3.28	1.093	-0.211	-0.453
COM3	Appropriate passenger density	3.27	1.064	-0.165	-0.446
COM4	The train is quiet and relaxing	3.28	1.101	-0.233	-0.471
COM5	The train has a suitable interior design	3.31	1.042	-0.229	-0.292
COM6	The facilities inside the train are adequate and appropriate	3.29	1.079	-0.231	-0.428
COM7	There are sufficient and appropriate facilities for the disabled, the elderly, groups with special needs and other vulnerable groups	3.27	1.123	-0.200	-0.594
COM8	There are adequate toilets, waiting rooms and breastfeeding rooms	3.20	1.133	-0.180	-0.605
SAS1	There are adequate safety measures in trains and stations such as CCTV and security guards	3.38	1.138	-0.351	-0.518
SAS2	During your journey, you feel safe from accidents	3.50	1.268	-0.535	-0.736
SAS3	Effective emergency management	3.41	1.147	-0.427	-0.517
SAS4	Appropriate preparedness for natural disasters	3.42	1.136	-0.364	-0.570
HAC1	The train is clean and hygienic inside	3.19	1.092	-0.195	-0.472
HAC2	The toilets and facilities are clean	3.15	1.090	-0.134	-0.457
HAC3	There are appropriate preventive and cleaning measures from the railway transport service providers	3.28	1.069	-0.230	-0.379
HAC4	Appropriateness of disease prevention and infectious disease control	3.23	1.064	-0.193	-0.361
HAC5	The service provider has proper waste management	3.30	1.132	-0.334	-0.506
HAC6	Appropriate control of air quality inside trains	3.31	1.105	-0.247	-0.479
ENV1	Traveling by train reduces greenhouse gas emissions	3.39	1.226	-0.435	-0.709
ENV2	Waste and garbage management on trains is up to standard	3.34	1.173	-0.316	-0.676
ENV3	Energy conservation and efficient use of railway resources	3.40	1.208	-0.430	-0.654
ENV4	Rail transport uses renewable energy efficiently	3.40	1.227	-0.414	-0.721
TEC1	The online ticket booking is convenient and user-friendly	3.46	1.308	-0.467	-0.899
TEC2	Trains are equipped with modern technology such as station alerts, waiting times and modern systems	3.41	1.263	-0.410	-0.826
TEC3	The data collection system for train routes and times is accurate and up to date	3.38	1.166	-0.338	-0.669
TEC4	Good technology management such as ticketing system is always up to date	3.42	1.190	-0.355	-0.755
TEC5	Stability of internet signal service system at train stations and on trains	3.15	1.100	-0.039	-0.525
AFF1	Train fares are reasonable	3.54	1.411	-0.663	-0.884
AFF2	Discounts on train fares or marketing campaigns can make train services more accessible to passengers	3.43	1.247	-0.488	-0.718
AFF3	Train ticket prices reflect the quality-of-service passengers receive	3.52	1.305	-0.611	-0.736
AFF4	Train users receive good value for money and reasonable parking fees	3.39	1.167	-0.370	-0.605
ACC1	In rural areas, train stations are easily accessible	3.53	1.295	-0.589	-0.749
ACC2	The railway station is well connected to other public transport systems	3.49	1.209	-0.510	-0.646
ACC3	There are a variety of transportation options to access the train station	3.50	1.246	-0.531	-0.706
ACC4	Rail transportation covers access to all groups of people, such as the disabled, the elderly, people with special needs, and other groups	3.51	1.271	-0.600	-0.661
ACC5	Users can access information about bus schedules and routes	3.52	1.247	-0.597	-0.638
EFF1	The train arrived at its destination on time	3.28	1.143	-0.305	-0.599
EFF2	Efficient time management between stations	3.36	1.129	-0.476	-0.482
EFF3	One can buy train tickets and check tickets quickly	3.49	1.248	-0.588	-0.656
EFF4	Trains have appropriate service frequencies	3.41	1.094	-0.406	-0.510
EFF5	Problems or obstacles along the way are properly addressed	3.36	1.145	-0.406	-0.607
EFF6	The railway station is well connected to other public transport systems	3.40	1.118	-0.405	-0.530
EFF7	Railway staff provide appropriate and adequate service	3.47	1.219	-0.521	-0.680

Note: 1. M denotes average. 2. SD denotes standard deviation. 3. SK denotes skewness. 4. KU denotes kurtosis

Table A2. Factor loadings and multicollinearity diagnostics

Construct	Indicator	Standardized Loading (λ)	VIF	Decision / Comment
RAQ	RAQ1—Cleanliness	0.912	2.41	Retained
RAQ	RAQ2—Comfort	0.948	2.63	Retained (conceptually distinct)
RAQ	RAQ3—Temperature comfort	0.965	2.84	Retained (distinct from RAQ2)
Eco-RAQ	ERAQ1—Green signage visibility	0.923	2.55	Retained
Eco-RAQ	ERAQ2—Energy-saving awareness	0.954	2.66	Retained
Eco-RAQ	ERAQ3—Waste management perception	0.901	2.17	Retained
RPQ	RPQ1—Perceived reliability	0.939	2.43	Retained
RPQ	RPQ2—Service punctuality	0.951	2.59	Retained
REQ	REQ1—Operational efficiency	0.961	2.78	Retained
REQ	REQ2—Energy performance perception	0.949	2.73	Retained

Note: No VIF exceeded 3.0, indicating acceptable multicollinearity levels [56]. Items with loadings >0.95 were theoretically justified due to distinct conceptual definitions (e.g., "thermal comfort" vs. "seat comfort").