



Article

Ses Model and its Practical Application

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Abstract: According to market growth projections, the global digital railway market will grow from USD 82.76 billion in 2025 to USD 127.54 billion by 2030, compelling railway enterprises to shift from linear management models to data-driven governing frameworks. Meceda and Vonortas (2018) conceptualized the singular economy as the intersection of virtual and physical economies, while Brynjolfsson and McAfee (2014) recognized that economic efficiency is increasingly determined by information rather than traditional production factors. Nonetheless, these theoretical frameworks had not been integrated within a single econometric model; cross-country analysis of railway digitalization in the context of Central Asia remained rare; and linear models are often insufficient for exploring the nonlinear dynamics characteristic of the digital transformation of transport systems. Using Lagrange optimization, followed by multiple regression analysis to validate the model against data from JSC "Uzbekistan Railways", the study proposes, develops, and confirms a Singular Applied Economic Efficiency model ($SES = Y \cdot D \alpha \cdot I \beta / X(1-A)\gamma$). Applying Lagrange optimization, the equilibrium condition is derived as $D = \alpha(1-A)/\gamma$, confirming that digitalization and automation are inversely proportional. Empirical analysis reveals that the SES index is strongly correlated with the international freight share ($r = 0.8698$), while digitalized business processes and automation also demonstrate a high correlation ($r = 0.9671$). Implementation can lead to a 1.2% decrease in operational expenditure and can leverage USD 1.1 billion through PPP-based investments. The SES model represents the first empirically tested synthesis of economics sub-disciplines applied to railway transportation. The results provide railway companies in developing economies with a structured approach to measuring economic efficiency through the integration of digital, informational, and human resources, while future research should extend the model into a panel data cross-country framework and incorporate ESG dimensions.

Keywords: Singular applied economic efficiency (SES) model; railway transport; digital transformation; Lagrange optimization; nonlinear economic dynamics; Uzbekistan Railways; applied economics; digitalization elasticity.

Citation: Shokirovna B. Z. Ses Model and its Practical Application. Central Asian Journal of Innovations on Tourism Management and Finance 2026, 7(2), 414-420.

Received: 10th Jan 2026
Revised: 11th Feb 2026
Accepted: 19th Mar 2026
Published: 09th Apr 2026



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Introduction

The global railway industry is undergoing a fundamental economic and technological transformation driven by digitalization, artificial intelligence (AI), and the Internet of Things (IoT). According to MarketsandMarkets, the global digital railway market is estimated at USD 82.76 billion in 2025 and is projected to reach USD 127.54 billion by 2030, growing at a compound annual growth rate of 9.0%. The World Economic Forum has estimated that the combined value of digitalization to industry and society could exceed USD 100 trillion by 2025. Within this context, railway enterprises in developing economies, particularly in Central Asia, face the critical challenge of transitioning from conventional linear management models to data-driven, adaptive, and nonlinear

governance frameworks capable of capturing the complex interdependencies inherent in modern transport systems [1][2].

Two foundational paradigms underpin the theoretical architecture of this study: singular economy and applied economics. Meceda and Vonortas introduced the concept of a singular economy, arguing that the divide between digital and physical economic activity is becoming obsolete, with both spheres converging into a unified economic space [3][4]. Complementarily, Brynjolfsson and McAfee demonstrated that modern economic efficiency is increasingly determined by information flow and computational speed rather than by traditional production factors alone. Arthur further elaborated the notion of a "second economy" – a digital layer that governs physical processes as a parallel system. Nordhaus and Kurzweil provided the mathematical foundations for understanding exponential technological acceleration and its macroeconomic implications. However, these theoretical contributions have remained largely conceptual, with limited integration into empirical econometric models applicable to infrastructure-intensive sectors such as railway transport [5][6].

A critical review of existing literature reveals three significant knowledge gaps. First, conventional production function models (Solow, Cobb–Douglas) predominantly employ linear frameworks that fail to capture nonlinear dynamics, critical thresholds, and singular transitions characteristic of digitally transforming railway systems. Second, empirical studies on the economic efficiency of railway digitalization in Central Asian economies remain notably scarce, with the existing body of research concentrated on European, North American, and Chinese railway systems. Third, no prior study has attempted to integrate the singular and applied economics paradigms into a unified mathematical model with empirical validation. While Accinelli developed catastrophe theory methodologies for economic systems, their work did not extend to transport sector applications with econometric testing [7].

To address these gaps, this study proposes the Singular Applied Economic Efficiency (SES) model, expressed as $SES = Y \cdot D^{\alpha} \cdot I^{\beta} / X(1-A)^{\gamma}$, where D represents digitalization, I denotes information intensity, A captures automation, and α, β, γ are elasticity coefficients. Lagrange optimization is employed to derive optimal equilibrium conditions, yielding $D = \alpha(1-A)/\gamma$, which mathematically demonstrates the inverse proportionality between digitalization and automation levels. The model is empirically tested using operational and financial data from JSC "Uzbekistan Railways" through paired correlation analysis, multicollinearity diagnostics (VIF/Tolerance), and multiple regression modelling [8].

The empirical findings confirm the model's validity: a strong positive correlation ($r = 0.8698$) between the SES index and the international freight share was identified, while an extremely high correlation ($r = 0.9671$) between digitalized business processes and automation necessitated the construction of a reduced regression model. The practical application of the singular transformation mechanism resulted in a 1.2% optimization of operational expenditure, a reduction of human error to 0.2%, and the attraction of USD 1.1 billion through a public–private partnership (PPP) investment strategy [9]. These results carry significant implications for both theory and practice: theoretically, the SES model extends the singular economy framework from a conceptual proposition to an empirically testable econometric tool; practically, it provides railway enterprises in developing economies with a structured methodology for evaluating and enhancing economic efficiency through the integration of digital, informational, and human capital dimensions. Future research should extend the model to cross-country panel data, incorporate ESG variables, and explore quantum computing integration for real-time SES monitoring [10].

Research Methodology

This study employs a methodological approach grounded in the integration of singular and applied economics. Singular economics interprets the railway system as a complex adaptive structure that evolves through critical points, nonlinear transitions, and

systemic instability, while applied economics provides the means to measure these processes through cost, revenue, cash flow, and operational indicators.

The central scientific apparatus of the study is the Singular Applied Economic Efficiency (SES) model proposed by the author. The core mathematical formulation of the model is expressed as follows:

$$SES = Y \cdot D^\alpha \cdot I^\beta / X(1 - A)^\gamma$$

where: Y – gross revenue; D – level of digitalization; I – information intensity; X – total costs; A – level of automation; α, β, γ – elasticity coefficients.

Lagrange optimization was applied to identify the optimal conditions of the model, yielding the optimality condition $D = \alpha(1-A)/\gamma$. This result demonstrates that the optimal level of digitalization is inversely proportional to the level of automation.

In the empirical phase of the study, paired correlation analysis, a multicollinearity test via VIF, and multivariate regression analysis were conducted using data from JSC "Uzbekistan Railways". The factors identified as influencing gross transport revenue were: the share of international freight (X_1), the share of digital channels (X_2), the SES index (X_4), and the share of digitalized business processes (X_5). Due to a high correlation of $r = 0.9671$ between X_3 (share of automation) and X_5 , a reduced regression model was constructed.

Data sources included the national statistics of the Republic of Uzbekistan, reports of JSC "Uzbekistan Railways", and analytical materials from the OECD, the World Bank, and the UIC [11].

Results and Discussion

1. Key Empirical Results of the SES Model

Application of the proposed Singular Applied Economic Efficiency (SES) model to data from JSC "Uzbekistan Railways" yielded a series of important empirical results. Paired correlation analysis revealed a strong positive relationship ($r = 0.8698$) between the SES index (X_4) and the share of international freight (X_1). In addition, an extremely high correlation ($r = 0.9671$) was recorded between digitalized business processes (X_5) and the share of automation (X_3). This result provided a scientific basis for removing X_3 from the model in order to eliminate the risk of multicollinearity.

The optimal equilibrium equation $D = \alpha(1-A)/\gamma$ derived through Lagrange optimization theoretically confirmed the inverse proportionality between digitalization and automation. This result is fully consistent with the "human-technology balance" concept advanced by Brynjolfsson and McAfee [12]. The practical application of the model showed that the structure of operational expenditure at JSC "Uzbekistan Railways" was optimized by 1.2% (Table 1).

Table 1. Key Correlation Results of the SES Model.

No	Factor Pair	Correlation (r)	Economic Interpretation	Relationship
1	X_4 and X_1	0.8698	The SES index grows in parallel with the expansion of the international freight segment	Strong
2	X_2 and X_1	0.8363	Digital channels are adopted more rapidly in the international segment	Strong
3	X_5 and X_3	0.9671	Digitalization and automation move along nearly identical trajectories	Very high

Source: Based on data from JSC "Uzbekistan Railways"

2. Discussion of Results in the International Context

The results of the SES model were compared with global railway industry trends. According to MarketsandMarkets, the global digital railway market amounted to USD 82.76 billion in 2025 and is projected to reach USD 127.54 billion by 2030 at an annual growth rate of 9.0% [13]. This trend is theoretically grounded in the SES model by the digitalization variable (D) having an elasticity coefficient of $\alpha > 1$, implying an exponential effect.

The digitalization outcomes of JSC "Uzbekistan Railways" are consistent with this global trend. The freight wagon ordering process was reduced from 7 days to 3 days, and processing time was cut from 72 hours to 12 hours. Train frequency around Tashkent increased by 30%, and for the first time the enterprise recorded a profit of 30 billion soum. Plans through 2030 include the construction of 151 km of new railway lines, 182 km of electrification, and the modernization of 27 stations. These outcomes confirm the practical significance of the SES model.

Table 2. Comparative analysis of SES model results and international trends.

No	Indicator	Global trend	Uzbekistan result	Source
1	Digital railway market	USD 82.76–127.54 bn (2025–2030)	USD 200 mn Hyundai rotem contract	Marketsand markets, 2025
2	Electrification level	Europe: 50–60%	Uzbekistan: 52–55%; 85% planned by 2030	Euronews, 2026; asian transport observatory, 2025
3	AI and IoT integration	Predictive maintenance, real-time monitoring	Smart Rail project; human error reduced to 0.2%	European transport research review, 2024
4	PPP investments	Global public–private partnership trend	USD 1.1 bn investment attracted	IMF, 2025; World Bank, 2025
5	CO ₂ efficiency	Rail freight 3–4 times more efficient than road transport	Emission intensity fell from 5 g/\$ to 0.6 g/\$ (2000–2023)	IEA, 2024; Asian Transport Observatory, 2025

Source: Compiled by the author from international sources

First, foreign studies of railway economics are dominated by classical linear approaches, which fail to adequately represent the nonlinear characteristics, critical points, and singular transitions of the system. The SES model was developed precisely to fill this gap.

Second, empirical studies assessing the impact of digitalization and automation on economic efficiency in the railway systems of developing countries, particularly Central Asia, are virtually non-existent. The existing literature is primarily based on European, US, and Chinese experience.

Third, no prior studies were found that present the integration of the singular and applied economics paradigms within a single mathematical model. While Meceda and Vonortas put forward the concept of the singular economy, translating it into a practical econometric model had not been accomplished. The SES model serves to bridge this theoretical–practical gap [14].

Table 3. Identified knowledge gaps and the SES model's responses.

Knowledge gap	State in existing literature	SES model's response
Assessment of nonlinear economic dynamics	Classical linear models dominant	Nonlinear effects expressed through exponential elasticity coefficients (α, β, γ)
Digitalization–automation equilibrium	Studied separately; no integration	Optimal equilibrium equation $D = \alpha(1-A)/\gamma$

Empirical base for Central Asian railway economics	Few empirical studies; focused on Europe/US/China	Tested on JSC "Uzbekistan Railways" data
Integration of singular and applied economics	Meceda and Vonortas left it at the conceptual level	Brought to the applied level with a mathematical model and econometric testing

Source: Compiled by the author based on a literature review

4. Theoretical and practical significance of the results

Theoretically, the SES model expands the concept of economic efficiency by linking it to digital intensity, information flow, and the human–technology balance. By incorporating modern variables such as digitalization (D), information intensity (I), and automation (A) into conventional production functions, the model forms a new paradigm for economic analysis. This approach is aligned with W.B. Arthur’s "second economy" concept and R. Kurzweil’s theory of exponential growth [15][16].

Practically, the research results provided a basis for developing specific management decisions for JSC "Uzbekistan Railways". The singular transformation mechanism was implemented in stages: two engineering pilot projects were carried out on the Angren–Pop route; USD 1.1 billion was attracted through a PPP investment strategy; under the Smart Rail project, human error was reduced to 0.2%; and forecast indicators up to 2031 were developed using the Temporal Fusion Transformer (TFT) model. Given that the World Bank has allocated USD 200 million for transport sector modernization in Uzbekistan and that the volume of PPP projects is expected to reach USD 30.2 billion in 2025–2030, the practical relevance of the SES model is further reinforced [17][18].

5. Directions for future research

This study has carried out the first empirical test of the SES model and identifies several promising directions for future research. **First**, it is necessary to test the model’s universality by applying it to other modes of transport (aviation, road, maritime) and to other Central Asian countries. **Second**, incorporating additional variables such as environmental sustainability (ESG), energy efficiency, and service quality could elevate the model to the level of a multidimensional index. **Third**, a large-scale econometric study based on panel data should be conducted to determine the α , β , γ elasticity coefficients of the SES model. **Fourth**, the integration of quantum computing and federated learning technologies into the SES model represents an important direction for future scientific exploration. Given that the Smart Railways market is projected to reach USD 149 billion by 2025 and grow at a CAGR of 22.4% to USD 1,124.5 billion by 2035, the need to further develop the SES model is clear [19].

Table 4. Future research directions and expected outcomes.

Research direction	Methodological approach	Expected scientific outcome
Applying the SES model to other transport modes	Comparative analysis, cross-sector analysis	Universality of the model or sector-specific features identified
Incorporating ESG and energy efficiency variables	Multidimensional index, composite assessment	SES model becomes a sustainable development indicator
Determining elasticity coefficients using panel data	Cross-country panel data, GMM estimation	A universal α , β , γ coefficient database is formed

Integration of quantum computing and federated learning	Quantum ML, edge computing, distributed AI	A real-time SES monitoring system is developed
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Source: Compiled by the author

The research results demonstrate that the SES model is of scientific and practical significance as a new methodological paradigm for evaluating economic efficiency in railway transport enterprises. The model makes it possible to identify critical points, anticipate nonlinear risks, and assess digital and physical processes as a unified system. However, the model also has limitations: data quality, precision in parameter determination, and the difficulty of modelling human cognitive behavior are among them. In future research, these limitations can be addressed and the SES model can be tested on a global scale, contributing to a new stage of economic analysis [20].

Conclusion

This study proposed the Singular Applied Economic Efficiency (SES) model as a new methodological paradigm for evaluating economic efficiency in railway transport enterprises and empirically applied it to the operations of JSC "Uzbekistan Railways". The principal findings of the study demonstrate the following:

- The SES model ($SES = Y \cdot D^\alpha \cdot I^\beta / X(1-A)^\gamma$) enables a comprehensive evaluation of economic efficiency beyond the conventional revenue–cost ratio, incorporating the level of digitalization (D), information intensity (I), and automation (A).
- The equilibrium equation $D = \alpha(1-A)/\gamma$, derived through Lagrange optimization, proved the inverse proportionality between digitalization and automation, mathematically confirming the necessity of a human–technology balance.
- Paired correlation analysis identified a strong relationship of $r = 0.8698$ between the SES index and the share of international freight, and a strong relationship of $r = 0.9671$ between digitalized business processes and automation.
- As a result of the practical application of the singular transformation mechanism, operational expenditure was optimized by 1.2%, human error was reduced to 0.2%, and USD 1.1 billion in investment was attracted through the PPP strategy.

Theoretically, the research results elevated W.B. Arthur's "second economy", E. Brynjolfsson's human–technology balance, and A.M. Meceda and N.S. Vonortas's singular economy concepts to the level of applied econometrics, and served to address three significant knowledge gaps in the existing literature: the weakness of assessing nonlinear economic dynamics, the scarcity of an empirical base in Central Asian railway economics, and the lack of integration between the singular and applied paradigms.

Practically, these results substantiated the need for JSC "Uzbekistan Railways" to deepen digital transformation, introduce the SES index as a strategic KPI, transition to a predictive maintenance model, and shape investment policy based on long-term operational efficiency criteria. However, the model's dependence on data quality, limitations in determining elasticity coefficients, and the complexity of modelling human cognitive behavior represent shortcomings that exist in the current version. In future research, there is the opportunity to contribute to a new stage of economic analysis by applying the SES model to other modes of transport and Central Asian countries, incorporating ESG and energy efficiency variables, determining universal elasticity coefficients based on panel data, and integrating quantum computing and federated learning technologies.

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