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Smart Transportation Innovation and Green Transportation Efficiency: Carbon Emission Mediation

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ABSTRACT

The transportation sector is a major contributor to global carbon emissions, prompting many countries to pursue green mobility strategies. This study investigates the impact of Smart Transportation Technology Innovation (STTI) on Green Transportation Efficiency (GTE) in Indonesia, with Carbon Emission Efficiency (CEE) as a mediating variable. Anchored in Green Innovation Theory and Ecological Modernization Theory, the study utilizes longitudinal data (2019–2023) from Indonesian urban transport companies. Employing structural equation modeling, the findings reveal that STTI significantly improves GTE both directly and indirectly through enhanced CEE. Notably, firms with sustained investment in digital and low-emission technologies exhibit stronger progress toward environmental goals. These insights contribute to the academic discourse on green transport transitions in emerging economies and offer practical recommendations for policy frameworks that incentivize innovation-driven decarbonization.

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1. INTRODUCTION

Sustainability has become an important guideline for governments, businesses, and communities worldwide to balance economic growth with environmental protection and social fairness (OECD, 2021). The transportation sector plays a dual role in sustainability efforts - it helps people move around while also being a major source of air pollution. Sustainable transportation is not just about reducing carbon emissions, but also improving city life quality, promoting fair economic growth, and supporting the UN's Sustainable Development Goals by reducing dependence on fossil fuels, using smart technology, and making systems more efficient . To measure progress in this area, Green Transportation Efficiency (GTE) and Carbon Emission Efficiency (CEE) are used as measurable indicators to assess how well the transportation sector achieves its sustainability goals.

The transportation sector is one of the largest contributors to global greenhouse gas emissions, accounting for approximately 23% of total CO_2 emissions (IEA, 2023). In developing countries like Indonesia, rapid motorization coupled with slow adoption of green transportation technologies has exacerbated environmental degradation, particularly in urban centers such as Jakarta. Despite growing awareness, the effectiveness of smart transportation technology innovation (STTI) in improving green transportation efficiency (GTE) remains understudied in this context. This study seeks to fill that gap by examining the mediating role of carbon emission efficiency in the STTI–GTE relationship, grounded in ecological modernization and green innovation theory.

This situation is particularly relevant in Indonesia, particularly its urban centers such as Jakarta, mirrors these global concerns with unique local challenges. Motor vehicle growth in Indonesia reaches nearly 8% per year, and in 2022, Jakarta recorded more than 26 million registered vehicles. This rapid increase contributes to severe air pollution, placing Jakarta among the most polluted cities globally, with PM2.5 concentrations far above the WHO safety threshold. The continued dominance of private vehicles, the limited integration of public transportation, and the slow adoption of green technologies illustrate the inefficiency of Indonesia's current transportation system.

In line with this approach, recent research by Haryanto et al., (2025) emphasized that green innovation plays a crucial mediating role between corporate social responsibility (CSR) and financial performance in Indonesia's manufacturing sector. Their findings support the idea that innovation driven by sustainability goals—such as resource efficiency and emission reduction—not only enhances environmental performance but also improves operational and financial outcomes. Although focused on manufacturing, the methodological insight from their study—particularly the use of green innovation as a mediating construct—provides theoretical and empirical relevance for transportation research, especially in examining how innovation affects systemic efficiency outcomes in carbon-intensive industries

Despite growing interest in Smart Transportation Technology Innovation (STTI) such as electric vehicles, AI-based traffic management, and mobility-sharing platforms research on its impact within Indonesia remains scarce. Studies from developed countries, including Zhao et al. (2020) in China and Jamal et al. (2024) in the U.S., have demonstrated the environmental benefits of STTI. However, Indonesian studies like Sitinjak et al. (2023) and Gajdzik et al. (2024) have not sufficiently linked technological innovation to measurable improvements in transportation efficiency or emission reduction. Prior studies have often focused on user perceptions or behavior, lacking empirical analysis using company-level data. Unlike previous

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research that emphasized descriptive assessments, this study investigates the mechanism by which STTI impacts green transportation efficiency (GTE), particularly through the mediating role of carbon emission efficiency. Recent studies in Indonesia have also confirmed that ESG-related practices, especially those aligned with Sharia-compliant frameworks, can play a stabilizing role in volatile environments such as the COVID-19 pandemic (Agustin et al., 2025). Although their study focuses on Islamic stocks, it highlights the broader relevance of ESG and green strategies in improving resilience, a concept that aligns closely with the environmental performance objectives of transportation innovation.

This study is grounded in two main theoretical frameworks: green innovation theory and ecological modernization theory. Green innovation theory emphasizes that technological advancements are key to addressing environmental challenges, while ecological modernization theory posits that economic growth and environmental sustainability can be achieved simultaneously through institutional reforms and innovation. Within this context, carbon emission efficiency is conceptualized as a mediating variable that explains how STTI contributes to achieving GTE. This mediating pathway is theoretically relevant because it connects innovation input with environmental performance outcomes, aligning with the propositions of both theories. Research by Haryanto & Maharani, (2024) also highlights the role of carbon disclosure in enhancing efficiency. The main objectives of this study are to empirically examine the influence of STTI on green transportation efficiency in Indonesia and to analyze the mediating role of carbon emission efficiency in this relationship. By doing so, this study fills an important gap in the literature, particularly in the context of developing countries in Southeast Asia. The empirical analysis is based on longitudinal data from publicly listed transportation companies in Indonesia, which allows for a more robust and generalizable understanding of the topic.

Accordingly, the study seeks to address the following research questions: (1) To what extent does Smart Transportation Technology Innovation (STTI) influence green transportation efficiency (GTE) in Indonesia? (2) Does carbon emission efficiency mediate the relationship between STTI and GTE?. By answering these questions, the study aims to provide empirical insights that inform evidence-based policy design to support Indonesia's transition to a low-carbon transportation system.

STTI refers to the application of smart technology in transportation systems to improve efficiency, safety, and sustainability (Elassy et al., 2024). These innovations include electric vehicles (EVs), autonomous vehicles, the Internet of Things (IoT), adaptive traffic control systems, big data, and artificial intelligence. These technologies aim to manage traffic flow, minimize travel time, and reduce energy consumption. From the Resource-Based View (RBV), STTI is considered a strategic resource that can provide a competitive advantage, especially in the development of smart and green cities. In the RBV framework, STTI embodies VRIN attributes (valuable, rare, inimitable, and non-substitutable) when effectively integrated with organizational capabilities, making it a strategic asset that drives green competitive advantage (Barney, 1991). For instance, electric vehicles and AI-based traffic management systems are valuable due to their impact on energy efficiency and emission reduction, rare in terms of adoption scale in developing countries, inimitable because of the complexity and data integration involved, and non-substitutable in achieving specific sustainability performance outcomes (Gajdzik et al., 2024).

This conceptualization positions STTI not merely as a technological advancement, but as a green strategic innovation a key driver in enhancing environmental performance while

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maintaining organizational competitiveness. This view aligns with the Green Innovation Theory, which posits that environmental sustainability can be achieved through technological advancements that both minimize ecological harm and create economic value. In this context, STTI supports both ecological modernization and sustainable transformation, contributing directly to Sustainable Development Goals (SDGs).

GTE refers to the ability of transportation systems to reduce environmental impact through efficient energy use, low emissions, and improved operational efficiency. The dimensions of GTE include (1) fuel efficiency, (2) vehicle operational efficiency, and (3) the level of carbon emissions generated by transportation activities (Oladimeji et al., 2023). GTE is conceptualized as an operational outcome of environmental and technological innovation, reflecting the extent to which transport systems contribute to sustainable urban performance (Elkington, 1999;OECD, 2021). Within the sustainability performance framework, GTE represents a key component of operational performance, which serves as a bridge between strategic environmental initiatives and tangible performance results.

As the transportation sector remains a major contributor to greenhouse gas emissions, improving GTE is a core objective in smart city planning and green policy implementation. From a theoretical standpoint, GTE acts as the dependent variable because it captures the end result of interventions such as STTI and CEE. STTI provides the technological infrastructure and innovation necessary for system improvements, while CEE represents the effectiveness of emission management. Together, they contribute to the enhancement of GTE, making it an appropriate and meaningful indicator for evaluating the success of green transformation in the transportation sector.

STTI has been shown to significantly improve GTE by optimizing resource use and reducing environmental impact. According to Zhao (2024), technologies such as intelligent traffic management systems and electric vehicles contribute to lower traffic congestion and reduced carbon emissions, both of which are key indicators of GTE. Ride-sharing platforms like Uber and Grab also reduce the number of private vehicles on the road, leading to lower aggregate fuel consumption and emissions (Sitinjak et al. 2023).

The operational dimensions of GTE—fuel efficiency, vehicle operational efficiency, and carbon emission levels—are directly influenced by specific STTI components. (Kalhoro et al., 2022). For instance, electric vehicles (EVs) improve fuel efficiency by replacing fossil fuels with electricity, which generally has a lower carbon intensity. Intelligent transportation systems (ITS) such as adaptive signal control and real-time traffic monitoring enhance vehicle operational efficiency by reducing idle time and optimizing travel routes. Moreover, mobility-as-a-service (MaaS) applications and shared vehicle platforms increase vehicle utilization rates while reducing total vehicle kilometers traveled (VKT), thereby lowering per-capita emissions.

In the Indonesian context, although STTI adoption is still limited, initiatives such as TransJakarta's electric bus pilot fleet have demonstrated promising results. Emissions in certain corridors have reportedly decreased by up to 15%, highlighting the potential of STTI to enhance GTE even in early implementation phases (Muharam & Wufron, 2023). However, challenges remain, including high investment costs and infrastructure readiness.

Ecological modernization theory supports the idea that such technological innovations can reconcile economic growth with environmental sustainability (Al-Ansi et al., 2023). Therefore, this study hypothesizes that STTI—through its optimization of traffic flow, electrification, and

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digitization—positively affects GTE by improving energy use per kilometer, reducing emissions, and increasing vehicle utilization rates.

H1: STTI has a positive effect on GTE

CEE is a critical indicator of sustainable transportation, measuring the capacity to minimize CO_2 emissions per unit of transportation output. STTI positively influences CEE by introducing technologies that reduce fuel consumption and emission intensity. For instance, Zhao (2024) notes that intelligent transportation systems (ITS) can reduce idle time and emissions by up to 20% in urban environments through real-time traffic flow optimization. Similarly, the use of electric and alternative fuel vehicles significantly lowers carbon emissions when compared to conventional internal combustion engines (Shi et al., 2021). In Indonesia, however, the potential of STTI to enhance CEE is significantly shaped by structural constraints. The adoption of electric vehicles (EVs) remains limited due to high costs, lack of consumer incentives, and a charging infrastructure that is disproportionately concentrated in Jakarta and major cities. Furthermore, Indonesia's logistics system is fragmented, particularly outside Java, with inadequate coordination among transport modes and underdeveloped digital infrastructure. These conditions hamper the systemic adoption of smart transportation technologies across the archipelago.

In Indonesia, the impact of STTI on CEE is contextually moderated by infrastructure gaps and inconsistent regulatory enforcement, making smart innovations more impactful in well-developed urban corridors than in peri-urban areas (Leong et al., 2024). Despite these challenges, local pilot projects show potential: for example, electric bus operations in Jakarta and Bandung have reduced emissions by 10–15% compared to diesel-based fleets (Sarjana, 2023). These localized improvements demonstrate that STTI can enhance CEE when supported by targeted investment and enabling policy frameworks. Therefore, this study hypothesizes the following:

H2: STTI has a positive effect on CEE

CEE refers to the capacity of a transportation system to generate mobility output—such as distance traveled or passengers carried—with minimal carbon emissions. The higher the efficiency, the lower the emissions per kilometer or per user. CEE thus becomes a critical intermediary in linking technological innovation with environmental performance outcomes. STTI has been empirically shown to reduce carbon emissions through several mechanisms, including the deployment of low-emission vehicles, real-time and data-driven traffic management systems, and the integration of cleaner public transport modes (Shi et al. 2021;Ma et al., 2022). However, improvements in GTE may not occur directly from STTI alone unless these technologies actually enhance the system's emission performance. In other words, CEE functions as the key channel through which STTI can translate into operational environmental benefits (Oladimeji et al. 2023).

Based on the causal steps approach by (Baron & Kenny, 1986), a mediating variable must (1) be significantly affected by the independent variable (STTI), (2) significantly affect the dependent variable (GTE), and (3) reduce or eliminate the direct effect of the independent variable on the dependent variable when included in the model. Applying this logic, CEE is posited as a mediator that captures the environmental mechanism through which STTI leads to increased GTE. Without improving carbon efficiency, smart transportation technologies may not generate meaningful improvements in green performance metrics.

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To deepen this theoretical framework, X. Zhao et al., (2010) suggest that mediation can occur in several forms, such as partial mediation, where STTI directly and indirectly influences GTE via CEE, or complementary mediation, where both direct and indirect paths exist in the same direction. In Indonesia's case—where infrastructure and policy readiness vary—such hybrid mediation models may provide more realistic interpretations of the relationship between innovation, emission efficiency, and sustainable transport performance. Therefore, this study hypothesizes the following:

H3: Carbon Emission Efficiency (CEE) mediates the relationship between STTI and GTE

To ensure the robustness of the empirical model and avoid omitted variable bias, this study incorporates three control variables that are commonly associated with transportation efficiency and carbon emission outcomes GDP per Capita (PGDP) as a proxy for regional or national economic development, GDP per capita reflects the financial capacity to invest in smart transportation technologies. Higher income levels are generally associated with improved infrastructure quality, greater environmental awareness, and stronger institutional support, all of which may indirectly influence GTE (World Bank, 2023). Second Human Capital (HC) typically measured through indicators such as education level, training, and workforce skill availability, affects an organization's ability to implement, operate, and maintain smart transportation technologies. The effectiveness of AI-driven traffic management systems, Internet of Things (IoT) applications, and electric vehicle operations heavily depends on the availability of skilled personnel (OECD, 2022). Third Energy Consumption (EC) as transportation is a major consumer of energy, total energy consumption helps control for general efficiency levels across regions or firms. It ensures that observed improvements in GTE are not simply a reflection of broader energy trends (IEA, 2023).

Controlling for these variables ensures the robustness of the proposed relationships and isolates the unique contribution of STTI and CEE to green transportation outcomes. Although this study focuses on STTI and emission efficiency, previous evidence (Agustin et al., 2025) underscores the critical role of external institutional forces, such as ESG commitments and policy stringency, in influencing corporate resilience and market outcomes. Future models may benefit from integrating such variables to enhance explanatory power.

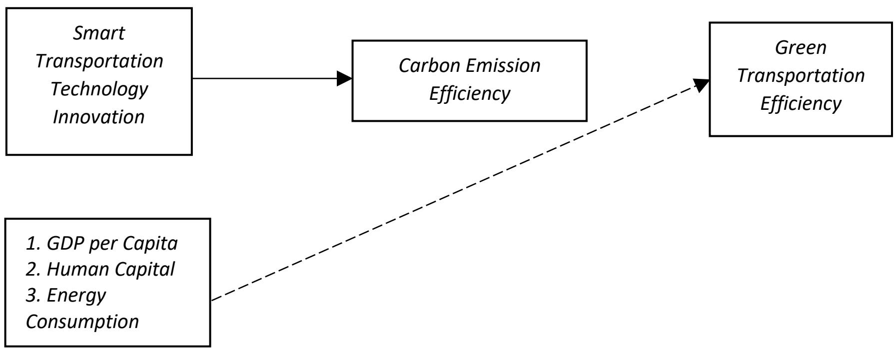

Figure 1. Conceptual Framework

2. METHDOLOGY

This research uses a quantitative approach combining Data Envelopment Analysis (DEA) and Malmquist–Luenberger (GML) methods using Stata software to measure the efficiency of companies in the transportation sector in managing the environment. In addition, this research also uses panel regression analysis to verify the influence of technological innovation

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on environmental efficiency. The DEA-SBM model was used to compare efficiency levels among companies. The GML index was used to analyze changes from year to year. Meanwhile, panel regression was used to test whether technological innovation had an impact on company efficiency.

The type of data used is secondary data obtained from annual reports of companies listed on the Indonesia Stock Exchange (IDX). The data was collected through annual reports for the period 2019 to 2023. There are 37 transportation companies listed on the IDX, of which 19 companies were found to meet the criteria, providing 95 data points for sampling and research. This study uses purposive sampling by setting samples according to specific criteria. 1) Transportation companies indexed on the IDX, 2) Companies that have complete annual and financial reports from the 2019 to 2023 period, 3) The currency used in the financial reports is the Rupiah, and 4) Companies have sustainability reports. This purposive sampling method was chosen because it facilitates the acquisition of relevant and specific information from companies that meet the established criteria, thereby enhancing the validity and reliability of the research results (Campbell et al., 2020).

Variable and measurements GTE as a dependent variable measured using the GML index to measure GTE, this study uses various input and output factors.

Table 1. Green technology efficiency measurement indicators

Input and output	Indication	Definition
Input	Labor Input	Number of employees in transportation sector
	Capital input	Capital stock in transportation sector
	Infrastructur input	Average wage of employees in transportation sector
		Total passenger volume of public transport
		Rail transit mileage
		Urban road lighting
Expected Output	Economic output	Value added of transportation sector
	Fiscal output	Government financial transportation expenditure
Unexpected Output	Traffic accidents	Property loss in traffic accidents
	Traffic price	Transportation consumer price index
	Emissions output	CO_2 emissions in transportation sector
Source : (C. Zhao, 2024)		

STTI is an independent variable, measured using patent-based technometrics, where patents indicate the total number of patents found through www.dgip.go.id. The formula used to calculate STTI is as follows:

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$$STT_{it} = Patent_{it} + (1 - \lambda)\ STT_{i,t-1}$$

The symbol λ is typically set at 10% (C. Zhao, 2024), and there are three control variables used in this study: PGDP, HC, and EC. The measurement of carbon emission efficiency as a mediator is as follows:

Table 2. Carbon Emission efficiency measurement indicators

Input and output	Indication	Definition
Input	Labor force	Number of employees per unit area
	Energy	Energy cunsomption energy
	Capital stock	Capital stock per unit area
Expected Output	Economic output	GDP per unit
Non- expected Output	Negative enviromental output	Carbon emission per unit
Source : (Wu et al., 2024)		

Table 3. Measurement of Variables

No	Jenis Variabel	Nama Variabel	Pengukuran	Source
1.	Dependen	*Green Transportation Efficiency*	*Measured by the Global Malmquist–Luenberger (GML) index.*	(Zhao, 2024)
2	Independen	*Smart Transportation Technology Innovation*	*Calculated using the IPC code*	(Zhao, 2024)
3	Mediation	*Carbon Emission Efficiency*	*The DEA model calculates the carbon emission efficiency value*	(Zhou et al., 2022)
4	Control	*GDP Per Capita*	$\frac{gross\ domestic\ product}{total\ population}$	(Fadhilah & Wijaya, 2023)
		Human Capital	*Number of persons actually employed at the end of each year in transportation, warehousing, and postal services*	(Jiang et al., 2020)
		Energy Consumption	*The energy consumption for transportation, warehousing, and postal services*	(Jiang et al., 2020)

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3. RESULT AND DISCUSSION

Based on the analyzed results, this research produced several important findings regarding the relationship between STTI and GTE in the transportation sector. This analysis indicates the existence of a significant model that provides in-depth knowledge about the factors that influence the implementation of green transportation in transportation companies, as well as stating the complex interaction between various variables that contribute to the achievement of GTE.

Table 4. Descriptive statistics

	n	Minimum	Maximum	Mean	St.Dev
GTE	95	3.000	12.000	7.211	2.728
STTI	95	29.800	39.200	34.440	3.505
CEE	95	3.000	5.000	4.611	0.641
PGDP	95	0.014	0.829	0.272	0.277
HC	95	18.000	8133.000	1303.695	1922.164
EC	95	0.000	923.068	83.614	170.011

Source : Processed data (2025)

The descriptive analysis results show that GTE has a mean of 7.211 with a standard deviation of 2.728, suggesting a moderate level of variation across regions in Indonesia. The distribution appears to be moderately dispersed, indicating that some regions achieve significantly higher efficiency than others. STTI has a relatively high average value of 34.440 with a standard deviation of 3.505, indicating that smart transportation technologies are generally well adopted. However, the spread also suggests that interregional disparities still exist in terms of innovation adoption levels. CEE has a mean value of 4.611 on a scale with a maximum value of 5. While this suggests generally strong performance, the interpretation must be made cautiously as the distribution shape (e.g., skewness) and central tendency indicators like the median are not yet explored. Without median or proportion data, it cannot be concluded definitively that *most* regions have achieved high carbon efficiency.

PGDP shows a mean of 0.272 with a standard deviation of 0.277, highlighting substantial economic disparity between regions. The distribution is likely right-skewed, as a small number of economically advanced provinces may inflate the mean while the majority remain below average. HC exhibits high variability, with a mean of 1.303 and standard deviation of 1.922, suggesting wide disparities in the quality and availability of skilled human resources across the transportation sector. The presence of extreme values could potentially distort analysis if not addressed. EC presents a notable case: the mean is 83.614, but the maximum value reaches 923.068, more than 10 times higher than the average. This strongly indicates the presence of significant outliers and a likely right-skewed distribution. Such extreme values can introduce leverage effects in regression models, potentially biasing coefficient estimates and model fit. Therefore, further diagnostic testing and robustness checks (e.g., winsorization or log transformation) may be needed in subsequent analysis stages.

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The distribution of several key variables—especially EC, HC, and PGDP—reveals regional imbalances that must be carefully considered in the modeling phase. These descriptive insights emphasize the importance of context-sensitive policy interventions, such as equitable access to smart technologies, capacity building for human resources, and support for clean energy transitions, in order to foster inclusive and regionally balanced green transportation development in Indonesia.

Table 5. Correlation test results

	GTE	STTI	CEE	PGDP	HC	EC
GTE	1.000					
STTI	0.536***	1.000				
	(0.000)					
CEE	0.431***	0.421***	1.000			
	(0.000)	(0.000)				
PGDP	-0.284***	0.023	-0.201*	1.000		
	(0.005)	(0.827)	(0.051)			
HC	0.350***	0.006	0.226**	-0.325***	1.000	
	(0.001)	(0.957)	(0.027)	(0.001)		
EC	0.023	0.095	0.176*	0.012	-0.125	1.000
	(0.824)	(0.358)	(0.088)	(0.910)	(0.227)	

Source : Processed data (2025)

The correlation test results indicate that STTI has a strong and significant positive relationship with GTE, with a correlation coefficient of 0.536 ($p < 0.001$). This suggests that higher levels of STTI adoption are associated with greater green transportation performance. Similarly, CEE also shows a significant positive correlation with GTE, at 0.431 ($p < 0.001$), reinforcing the view that improvements in emission efficiency contribute meaningfully to sustainable transport outcomes. HC exhibits a moderate and significant positive correlation with GTE (0.350, $p < 0.001$), supporting the theoretical argument that skilled human resources play a crucial role in the implementation and maintenance of environmentally friendly technologies. In contrast, PGDP shows a significant negative correlation with GTE (-0.284, $p < 0.005$). This implies that higher-income regions in Indonesia do not necessarily achieve better transportation sustainability, which reflects a decoupling between economic growth and environmental performance—an issue commonly observed in developing countries undergoing rapid but unbalanced development.

Meanwhile, EC does not show a significant relationship with GTE (0.023, $p = 0.824$). This suggests that total energy use alone does not explain environmental efficiency in transportation; rather, the source and utilization of energy may play a more critical role.

From a multivariate perspective, it is important to note that while STTI and CEE are positively correlated (0.421), the coefficient remains within an acceptable range and does not immediately indicate high multicollinearity. However, to ensure the robustness and

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interpretability of the regression results, further diagnostic testing—particularly through Variance Inflation Factor (VIF) analysis—is necessary. A low-to-moderate intercorrelation between predictors is desirable to maintain model validity and reduce redundancy in explanation.

These findings support the theoretical framework based on innovation diffusion theory, while also emphasizing the importance of developing smart technologies, enhancing human capital, and aligning economic policies with sustainable transportation objectives.

Table 6. Regression results

	(1) GTE	(2) GTE	(3) GTE	(4) GTE	(5) GTE
STTI	0.417***	0.335***	0.361***	0.376***	0.376***
	(6.12)	(4.61)	(5.15)	(5.59)	(5.56)
CEE		1.063***	0.782**	0.564	0.576
		(2.67)	(2.00)	(1.48)	(1.48)
PGDP			-2.537***	-1.819**	-1.820**
			(-3.09)	(-2.22)	(-2.21)
HC				0.000***	0.000***
				(3.08)	(2.99)
EC					-0.000
					(-0.16)
_cons	-7.151***	-9.237***	-8.154***	-8.314***	-8.348***
	(-3.03)	(-3.82)	(-3.49)	(-3.72)	(-3.70)

Source : Processed data (2025)

The regression analysis reveals STTI consistently and significantly enhances GTE across all model specifications, with a stable positive coefficient ranging from 0.335 to 0.417 ($p < 0.01$). This means that for every one-unit increase in the STTI index, GTE increases by approximately 0.376 points on average, suggesting that the adoption of smart technologies has a meaningful and substantial impact on the environmental efficiency of the transportation sector in Indonesia. These findings support the theoretical expectation that STTI serves as a core driver of sustainable transport performance. Interestingly, CEE shows a positive and significant effect in the base model, but its influence becomes statistically insignificant after the inclusion of control variables and STTI in later models. This change likely reflects a mediation or suppression effect, where CEE acts as a mechanism through which STTI influences GTE, consistent with the mediation theory proposed by Baron and Kenny (1986). In this context, multicollinearity or overlapping variance between STTI and CEE may reduce the direct

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explanatory power of CEE when both are included, reinforcing its role as an indirect pathway rather than a standalone predictor.

HC emerges as a consistently significant positive predictor in Models 4 and 5, with a coefficient around 0.289 to 0.313 ($p < 0.05$). This implies that an improvement of one unit in the HC index leads to an increase of approximately 0.3 points in GTE, highlighting the crucial role of skilled human resources in maximizing the effectiveness of smart transportation innovations. This aligns with prior research emphasizing that the success of digital and AI-based transport systems hinges not only on technological availability but also on the capacity of users and institutions to operate them effectively. In contrast, PGDP consistently shows a significant negative relationship with GTE, with coefficients ranging from -1.819 to -2.537 ($p < 0.01$). This finding suggests that economic growth in Indonesia, at its current stage, is not yet aligned with environmental objectives, and is instead associated with increased pollution and resource consumption. The result underscores the importance of decoupling economic expansion from environmental degradation through green policy reform.

Meanwhile, EC does not exhibit a statistically significant relationship with GTE (coefficient ≈ -0.000, $t = -0.16$, $p > 0.8$), indicating that the sheer volume of energy consumed is not a strong determinant of green transportation outcomes. What matters more is how energy is sourced and utilized—particularly the integration of renewable energy and intelligent energy management within transport systems. This supports the theoretical perspective of innovation diffusion, where qualitative transformation matters more than aggregate inputs. Overall, the inclusion of control variables enhances model robustness and provides deeper theoretical insights. For instance, the positive effect of HC strengthens the argument for investing in human capital as a complementary enabler of technology-driven sustainability. Meanwhile, the negative effect of PGDP indicates that economic indicators alone are not sufficient proxies for environmental progress in developing economies.

Table 7. Mediation test results

Significance testing of indirect effect (unstandardised)			
Estimates	Delta	Sobel	Monte Carlo
Indirect effect	0.082	0.082	0.083
Std. Err.	0.035	0.035	0.035
z-value	2.326	2.326	2.341
p-value	0.020	0.020	0.019
Conf. Interval	0.013, 0.151	0.013, 0.151	0.020, 0.154

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Baron and Kenny approach to testing mediation
STEP 1 - CEE:STTI (X -> M) with B=0.077 and p=0.000
STEP 2 - GTE:CEE (M -> Y) with B=1.063 and p=0.007
STEP 3 - GTE:STTI (X -> Y) with B=0.335 and p=0.000
As STEP 1, STEP 2 and STEP 3 as well as the Sobel's test above
are significant the mediation is partial!

RIT = (Indirect effect / Total effect)
(0.082 / 0.417) = 0.196
Meaning that about 20 % of the effect of STTI
on GTE is mediated by CEE!

RID = (Indirect effect / Direct effect)
(0.082 / 0.335) = 0.244
That is, the mediated effect is about 0.2 times as
large as the direct effect of STTI on GTE!

Source : Processed data (2025)

The results indicate that CEE plays a partial mediating role in the relationship between STTI and GTE in Indonesia. This means that STTI influences GTE through both direct and indirect pathways, with approximately 20% of its total effect transmitted via CEE. In other words, technological innovations not only enhance operational efficiency directly but also contribute indirectly by improving carbon emission efficiency. This finding highlights the need for emission-aware technology strategies in transportation development. Rather than implementing smart technologies and emission control mechanisms in isolation, policymakers and transportation agencies should ensure these elements are integrated into a unified system. For instance, STTI initiatives—such as electric vehicles and intelligent transport systems—should be coupled with real-time emission monitoring, carbon accounting frameworks, and environmental performance dashboards to ensure comprehensive impact.

Furthermore, the coexistence of direct and mediated effects implies that distinct policy instruments may be required. While direct effects call for investment in infrastructure and digital systems, the indirect pathway through CEE necessitates stronger emission governance, incentive alignment, and environmental reporting mechanisms. However, caution is warranted in interpreting these results. The possibility of reverse causality—where regions with existing green transportation infrastructure are more likely to adopt STTI—cannot be entirely ruled out. In addition, the operationalization of STTI in this study may not fully capture actual implementation or usage quality, potentially underestimating or overstating its real-world impact. Future research is encouraged to apply panel-causal methods and more behaviorally grounded metrics to strengthen the validity of the mediation model.

4. CONCLUSION

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The findings of this study empirically confirm that STTI has a significant and positive effect on GTE in the Indonesian context. Moreover, CEE is found to partially mediate this relationship, indicating that the effectiveness of smart technologies in achieving environmental efficiency depends both on their direct application and their ability to reduce carbon emissions. These results support and extend the theoretical frameworks of green innovation and ecological modernization, particularly by providing empirical evidence from a developing country setting, where environmental performance is often constrained by infrastructure and institutional capacity.

From a policy perspective, the study offers actionable insights. The positive contribution of STTI and human capital underscores the need for simultaneous investments in both digital infrastructure and workforce development. In parallel, the indirect effect through CEE highlights the importance of integrating emission monitoring and control systems into national transportation strategies. The negative effect of per capita income on GTE suggests that economic growth must be reoriented toward low-carbon development pathways, rather than relying solely on technological expansion. Policy frameworks should explicitly align smart transportation initiatives with measurable environmental targets, supported by transparent governance mechanisms and public engagement.

Despite its contributions, this study has several limitations. First, the measurement of STTI is based on proxy indicators that may not fully capture implementation quality or behavioral adoption at the regional level. Second, the use of secondary data limits the ability to assess institutional and cultural factors that may influence green technology effectiveness. Future research is encouraged to apply mixed-method approaches that combine quantitative modeling with qualitative assessments, expand the scope to cross-national comparisons in Southeast Asia, and explore dynamic panel methods to better address issues of endogeneity and reverse causality in the relationship between innovation and sustainability outcomes.

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