The role of environmental policy in promoting green transportation technologies

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Abstract. This study explores the role of environmental policy in promoting the adoption of green transportation technologies, focusing on the effects of financial incentives, regulatory frameworks, and public investment in infrastructure across key Asian urban centres. The research highlights how technological innovation acts as a crucial mediator between policy measures and the adoption of sustainable transportation options such as electric vehicles (EVs) and hydrogen-powered vehicles. Using Structural Equation Modelling (SEM), the study examines the relationships between these factors, demonstrating that higher levels of financial incentives, supportive regulations, and strategic public investment lead to significant advancements in technological innovation, which in turn drives the adoption of green transportation technologies. The findings contribute to the broader understanding of sustainable urban mobility solutions and offer important insights for policymakers and industry stakeholders in regions experiencing rapid urbanization. The study also discusses the dual role of these policy drivers, both in directly influencing adoption and in fostering technological advancement.

1 Introduction

Given that the transport sector is one of the major emitters of pollutants and one of the top contributors to environmental degradation, adopting clean transportation technology is vital for global climate change mitigation and reducing greenhouse gas emissions. The scenario outlined above has necessitated the development and use of alternative energy sources and environmentally friendly vehicles, such as electric vehicles and hydrogen-powered vehicles, and the upgrading of public transportation systems.

This research aims to evaluate and is shaped by technological innovation as a significant driver to determine the factors driving green transport technology adoption. However, it more precisely wants to align technological innovation with adopting green transport technology in countries that are part of the Asian continent system, a region of rapid urbanization and development. The investigation pertains to these locations because of the continent's rapid

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rate of urbanization and development, which, according to environmentalists, mainly translates into opportunities and challenges regarding the different solutions. While researchers have also identified financial incentives, regulation, and infrastructure, among others, as drivers of green transport technology adoption, technological innovation, on the other tool, has been considered a fundamental logical pusher of firm-based green innovation strategies.

Consequently, the natural environment of this study believes higher levels of technological innovation are expected to result in adopting this cleaner technology in the form of green transport options, originally in a context where countries are aggressively moving towards balancing economic growth and conservation of the environment.

The research aims to contribute to the broader understanding of how technological advancements influence the adoption of green technologies in a rapidly evolving context. By examining these relationships in the Asian region, this study addresses a significant gap in the existing literature, which often focuses on Western economies.

The findings of this research are expected to provide valuable insights for policymakers, industry stakeholders, and researchers interested in promoting sustainable urban mobility solutions, offering a hopeful outlook for the future of green transportation technologies.

2 Literature review

Another vital drive of green transportation technology adoption is financial incentives. This includes all forms of market intervention aiming to encourage investments in, development of, and other changes related to the widespread use of transportation infrastructure that has less impact on the environment than the existing one. Therefore, all government expenditures on charging points and infrastructure, bicycle lanes, or the promotion of electric and hybrid cars are financial incentives. Data show that the residents of EU countries each year buy more and more zero-emission cars and that, not coincidentally, all these countries were endeavoring to reduce each car's pollution.

Financial incentives for companies show their power; in Norway, for example, over 50% of new vehicles registered in recent years were electric-fed, and most of them were purchased by companies and had a related tax benefit. Financial incentives have accelerated the acceptance and expansion of electric and plug-in hybrid vehicles and considerably enhanced the charging infrastructure. Therefore, the number of EV users is increasingly determined by the density and availability of load points. Norway, for example, has one of the worlds best EV, hybrid, and efficient gasoline sales markets and one of the highest load plug-in densities.

Regulatory frameworks also include fuel efficiency standards – which are essential for promoting green transportation technology. These are vehicle requirements to meet a certain minimum of miles per gallon, which governments use to reduce overall fuel consumption and incentivize vehicle producers to design more economically. The USA's Corporate Average Fuel Economy Standards have substantially bettered the fuel efficiency of the vehicle fleet in America. Because of this, Greene et al. found a significant drop in the consumption of gasoline and CO_2 emissions and a push for automakers to design and sell hybrid or electric vehicles to produce fewer emissions and meet government regulations [1-6].

Apart from vehicle regulation, governments also have policies oriented to reduce fuel's carbon intensity–legislation requiring a switch to less carbon fuel types. The Low Carbon Fuel Standard is an example of it. It has slashed transportation emissions in California and contributed to the low-carbon fuel market. The availability and convenience of access to this are directly proportional to the customer's choice to adopt an electric vehicle because fear of being stranded without a charging location range anxiety is one of the main reasons drivers resist EV ownership. Unsurprisingly, public spending on electric vehicle charging networks contributes to the development of the EV market.

Discover that the increased presence of DCFC increases Tesla sales in the USA and supplements the regional options for ownership. As with the compatibility of biofuel infrastructure, some public investment is essential. Although payback fees belong to the personal sector when fuel suppliers receive lucrative contracts for these alternatives, there is a need for critical initial expenses that support the required startup infrastructure. This led to the development of the following hypothesis:

H1: Financial incentives are positively associated with adopting green transportation technologies.

H2: Regulatory frameworks are positively associated with adopting green transportation technologies.

H3: Public investment in infrastructure is positively associated with adopting green transportation technologies.

Governments often use financial incentives to stimulate technological innovation by reducing the financial risks associated with research, development, and commercialization. In the context of green transportation technologies, economic incentives such as subsidies, grants, and tax breaks are critical in supporting research and development (R&D) efforts, enabling companies to invest in creating new technologies that contribute to reducing emissions and enhancing sustainability [7-12].

According to [11], financial incentives are pivotal in accelerating innovation in clean technologies by providing the necessary funding for R&D and early-stage deployment. In the transportation sector, subsidies for research into battery technology, for example, have led to significant improvements in the efficiency and cost-effectiveness of electric vehicle batteries. [17] found that public R&D subsidies significantly contributed to advancements in EV battery technology, which reduced costs and increased the range of EVs. These improvements, in turn, made EVs more competitive with traditional internal combustion engine vehicles, driving both technological and market advancements.

In addition to direct subsidies, financial mechanisms like tax credits for R&D activities have been shown to foster technological innovation in green transportation. For instance, tax incentives for automotive manufacturers engaged in clean technology research have encouraged investments in hybrid engines, hydrogen fuel cells, and lightweight materials. [10] these innovations have not only improved vehicle fuel efficiency but also led to the development of entirely new categories of sustainable vehicles, demonstrating the positive impact of financial incentives on technological innovation in the transportation sector.

Furthermore, venture capital and public-private partnerships fueled by government incentives also play a crucial role in driving innovation.

In the United States, the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program, funded by the Department of Energy, provides low-interest loans to automakers to develop fuel-efficient vehicles and advanced technology components. This program has catalyzed major technological breakthroughs, including the development of Tesla's battery technology.

Regulatory frameworks are a powerful driver of technological innovation, particularly in sectors where market forces alone may not be sufficient to incentivize sustainable development. In the transportation sector, regulatory policies such as emission standards, fuel economy requirements, and zero-emission vehicle (ZEV) mandates compel automakers and fuel producers to invest in the development of cleaner technologies. By creating clear targets and standards, regulatory frameworks push industries toward innovation to comply with legal requirements [13-20].

Public investment in infrastructure is essential for fostering technological innovation in green transportation technologies, particularly in areas where the private sector may be reluctant to invest due to high costs or long development timelines. Government infrastructure investments support the adoption of green technologies and spur innovation by creating the conditions for new technologies to emerge and scale.

One of the most significant areas of public investment in green transportation is the development of electric vehicle charging infrastructure. The availability of charging stations is critical for the widespread adoption of EVs, and public investment in this area has spurred technological innovation in charging technology, grid integration, and energy storage solutions. For instance, in the European Union, public investments in fast-charging networks have led to technological advancements in high-power charging systems, significantly reducing charging times and improving EVs' overall usability. These innovations have made EVs more attractive to consumers and helped alleviate range anxiety, one of the primary barriers to EV adoption.

In addition to charging infrastructure, public investment in alternative fuel infrastructure - such as hydrogen fueling stations—has driven innovation in fuel cell technology and hydrogen production. Countries like Japan and Germany have invested significantly in hydrogen infrastructure as part of their national strategies to promote green transportation. These investments have led to advancements in hydrogen production methods, such as electrolysis powered by renewable energy, which has lowered the cost of hydrogen and made it a more viable alternative fuel for transportation. Public investment in hydrogen infrastructure has also spurred innovations in fuel cell technology, leading to more efficient and longer-lasting fuel cells for vehicles. This led to the development of the following hypotheses:

H4: Financial incentives positively influence technological innovation in green transportation technologies.

H5: Regulatory frameworks positively influence technological innovation in green transportation technologies.

H6: Public investment in infrastructure positively influences technological innovation in green transportation technologies.

Sustainability has emerged as a critical concern in the modern era, with transportation significantly contributing to greenhouse gas emissions. Green transportation technologies, such as electric vehicles (EVs), hydrogen-powered vehicles, and intelligent public transportation systems, have become effective solutions to reduce environmental footprints. Technological innovation is a crucial driver behind adopting these technologies, which is essential in advancing sustainable transport solutions' efficiency, availability, and attractiveness.

Technological innovation encompasses advancements in product and process technologies that contribute to developing and diffusing green transportation systems. For instance, innovations in battery technology have significantly improved the range and cost-efficiency of electric vehicles, making them more appealing to consumers and businesses. Similarly, breakthroughs in hydrogen fuel cell technology have enhanced the viability of fuel cell vehicles as an alternative to conventional internal combustion engines, demonstrating how technological advancements can effectively address the challenges previously hindered adoption.

A growing body of literature supports the notion that technological innovation is positively associated with adopting green transportation technologies. [19] suggest that increased investment in research and development (R&D) has led to a surge in green patents and innovations, which, in turn, has accelerated the availability of environmentally friendly transportation options. Governmental policies supporting R&D activities, such as subsidies and grants for green technology development, are also recognized as crucial contributors to technological innovation. These policies encourage private enterprises to invest in innovative solutions, leading to a positive feedback loop where technology advances, costs decrease, and adoption rates increase.

Moreover, the rise of digital technologies such as the Internet of Things (IoT) and artificial intelligence (AI) has further facilitated the adoption of green transportation. For example, IoT-enabled innovative city initiatives enable more efficient public transportation systems through real-time data collection and optimization, reducing energy consumption and emissions. This kind of systemic innovation—where digital technology is integrated with green transportation—exemplifies how technological progress creates synergies that enhance adoption rates across multiple levels of urban infrastructure. This led to the development of the following hypothesis:

H7: Technological innovation is positively associated with adopting green transportation technologies.

3 Methodology

This study employs a quantitative research approach to investigate the relationship between technological innovation and the adoption of green transportation technologies. SEM is the primary analytical technique due to its ability to assess multiple relationships among observed and latent variables simultaneously. SEM is particularly suited to the complexity of this study, which involves examining direct and indirect relationships between technological innovation and the adoption of green transportation technologies, considering other influencing factors such as regulatory frameworks, financial incentives, and infrastructure investment.

The data for this study was collected through a structured questionnaire administered to 430 respondents across vital urban centers in Asia. The sample includes policymakers, industry experts, and consumers directly involved in or affected by adopting green transportation technologies. The questionnaire was designed to capture respondents' perceptions of technological innovation, regulatory and financial support, and willingness to embrace green transportation technologies. Items were measured using a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

SEM allows for the simultaneous estimation of multiple regression equations, enabling a comprehensive analysis of the factors influencing the adoption of green transportation technologies. The model includes exogenous variables, such as financial incentives and regulatory frameworks, and endogenous variables, such as technological innovation and adoption. Confirmatory Factor Analysis (CFA) was conducted to validate the measurement model, ensuring the constructs were reliable and valid before proceeding with the structural model.

Given the context of Asian economies, particular attention was paid to cultural, economic, and infrastructural differences that could influence the adoption of green technologies. The analysis was conducted using AMOS. The findings from this study are expected to provide empirical support for the hypothesis that technological innovation is a significant predictor of green transportation technology adoption, with implications for policy and investment strategies across Asia.

4 Findings

The robustness tests presented in Table 1 highlight several key indicators that assess the Structural Equation Model (SEM) fit. The Comparative Fit Index (CFI), with a value of 0.95, suggests a strong fit between the proposed model and the observed data, as values above 0.90 generally indicate an acceptable fit, and values near 0.95 are considered excellent. Similarly, the Tucker-Lewis Index (TLI), also at 0.94, supports the robustness of the model, showing that the model improves substantially over a baseline model where no relationships between variables exist. The Goodness-of-Fit Index (GFI) of 0.92, alongside the Adjusted Goodness-of-Fit Index (AGFI) of 0.90, confirms that a large proportion of variance and covariance is explained by the model, reflecting a well-fitting structure.

Moreover, the Root Mean Square Error of Approximation (RMSEA) is 0.05, indicating that the model approximates the population model, as values below 0.08 are typically considered acceptable, and those under 0.06 are seen as excellent. The Standardized Root Mean Square Residual (SRMR) value of 0.04 supports this, reflecting a minimal discrepancy between the predicted and observed correlations. Both the Normed Fit Index (NFI), at 0.91, and the values for the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) (350.23 and 370.45, respectively) further underline the model's suitability. Lower AIC and BIC values suggest the model is more economical while maintaining a good fit, making it robust for the data under analysis.

Table 1. Robustness Tests

Fit Index	Values
CFI	0.95
TLI	0.94
GFI	0.92
RMSEA	0.05
SRMR	0.04
NFI	0.91
AGFI	0.9
AIC	350.23
BIC	370.45

Fig. 1 illustrates the relationships between Financial Incentives, Regulatory Frameworks, and Public Investment as independent variables, Technology Innovation as a mediator, and Transportation Technologies as the dependent variable. Each independent variable exerts a significant favorable influence on Technology Innovation, with regulatory frameworks having the strongest effect, indicated by a path coefficient of 0.439 ($p < 0.01$). This suggests that regulatory measures, such as emission standards and fuel efficiency mandates, are critical in driving technological advancements. Financial incentives, with a coefficient of 0.329 ($p < 0.05$), and public investment, with 0.310 ($p < 0.05$), also have significant impacts, demonstrating that government subsidies, grants, and infrastructure investments positively contribute to the development of innovative transportation solutions.

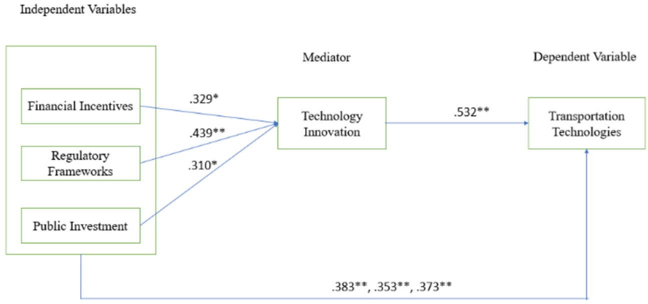

Fig. 1. Research Model

Moreover, Technology Innovationis a crucial mediator, strongly influencing the adoption of Transportation Technologies with a path coefficient of 0.532 ($p < 0.01$). This indicates that the advancement of technology is crucial for the widespread adoption of green transportation technologies such as electric vehicles and hydrogen-powered systems. In addition to these indirect effects, each independent variable has a significant direct impact on adopting transportation technologies, with coefficients of 0.383, 0.353, and 0.373, respectively.

These values indicate that financial incentives, regulatory frameworks, and public investment encourage technological innovation and independently drive the adoption of green transportation solutions. Thus, the model highlights these factors' dual role as direct influencers and contributors to technological progress in promoting sustainable transportation technologies.

5 Discussion

One of the most critical findings from this research is the strong relationship between technological innovation and the adoption of green transportation technologies. Innovations in EV battery technology, hydrogen fuel cells, and intelligent public transportation systems have significantly improved these solutions' efficiency, affordability, and convenience. Advancements in battery technologies have mainly addressed the significant challenges of range and cost, which have traditionally limited the widespread adoption of EVs. Hydrogen fuel cell advancements have similarly increased the viability of hydrogen-powered vehicles as an alternative to traditional internal combustion engines. These findings align with existing literature that underscores the importance of research and development (R&D) in fostering technological progress and making green transportation more attractive to consumers and businesses.

The study confirms that financial incentives, such as subsidies, tax credits, and grants, are vital in encouraging the development and adoption of green transportation technologies. These incentives lower the upfront costs of green technologies, making them more accessible. For example, subsidies for EVs help bridge the cost gap between EVs and conventional vehicles, encouraging consumers to opt for cleaner alternatives. Moreover, financial incentives also support R&D efforts, which are crucial for the continued advancement of green technologies. Public subsidies for R&D in areas like battery production and hydrogen fuel technology have led to innovations that reduce costs and improve the performance of green transportation systems.

The study finds that regulatory frameworks play a crucial role in accelerating the adoption of green transportation technologies. Emission standards, fuel efficiency mandates, and zero-emission vehicle (ZEV) mandates compel automakers and fuel producers to invest in cleaner technologies. These regulations not only set clear targets for reducing greenhouse gas emissions but also foster an environment of innovation as industries are forced to meet regulatory requirements. For instance, stringent CO2 emissions standards in the European Union and ZEV mandates in California have been instrumental in pushing automakers to prioritize the development of electric and hybrid vehicles. The findings show that such regulatory frameworks can be highly effective in promoting the large-scale adoption of green transportation technologies.

The research highlights the importance of public investment in infrastructure, particularly in building the necessary support systems for green transportation technologies. The availability of EV charging stations and hydrogen fueling infrastructure is directly linked to consumer adoption of these technologies.

The study points out that investments in fast-charging networks and alternative fuel infrastructure have facilitated the adoption of green technologies and spurred further technological innovation in areas like grid integration, energy storage, and fuel cell efficiency.

Public investment, therefore, supports the adoption of existing green technologies and encourages the development of new solutions by creating the necessary infrastructure for these technologies to thrive.

A significant aspect of the findings pertains to the influence of cultural, economic, and infrastructural differences in Asia on adopting green transportation technologies. Rapid urbanization and economic growth in key urban centers across Asia have created opportunities and challenges for implementing sustainable transportation solutions. The findings suggest that while financial incentives and regulatory frameworks are essential, their effectiveness can be enhanced by tailoring them to the specific socio-economic and cultural contexts of Asian countries. The study's data indicate consumer attitudes toward green technologies, infrastructure development, and government policy vary across Asian countries, highlighting the need for localized policy approaches.

6 Limitations, contributions, and further research

While the study provides valuable insights into the role of environmental policy in promoting green transportation technologies, several limitations must be considered. First, the study focuses predominantly on Asian urban centers, which limits the generalizability of the findings to other regions with different economic, infrastructural, and cultural contexts. The conditions influencing green technology adoption in Asia, such as rapid urbanization and governmental support, may not apply equally to regions with slower economic growth or more established transportation systems.

Second, the study employs a cross-sectional design, which captures data at a single point in time. This approach limits the ability to assess the long-term effects of financial incentives, regulatory frameworks, and infrastructure investments on adopting green technologies. A longitudinal approach would provide a more dynamic understanding of how these factors influence adoption over time, especially as technological innovation evolves rapidly in this sector.

Another limitation is the reliance on self-reported data from respondents, which may be subject to biases such as social desirability or misinterpretation of questions. Although the sample includes a broad range of stakeholders, including policymakers, industry experts, and consumers, the subjective nature of the responses may affect the accuracy of the findings. Additionally, the study's focus on technological innovation may overlook other equally important factors, such as social behavior, economic incentives at the local level, or the influence of non-governmental organizations, which could also play a role in the adoption of green transportation technologies.

Despite these limitations, the study makes several significant contributions to the literature on green transportation technologies. First, it provides empirical evidence of technological innovation's considerable role in advancing the adoption of these technologies in the context of Asian economies. By examining the interplay between innovation, financial incentives, regulatory frameworks, and infrastructure investment, this study highlights how these elements influence the uptake of sustainable transportation solutions.

The study's focus on Asian countries is precious, as much of the existing literature centers on Western economies. By addressing this gap, the study offers insights into how rapidly urbanizing and economically growing regions can balance environmental sustainability with development goals. Furthermore, the study contributes to the broader discourse on ecological policy by demonstrating the effectiveness of regulatory and financial measures in accelerating the transition to green transportation.

Future research could build on this study by expanding the geographic scope to include other regions, such as Latin America, Africa, or Eastern Europe, to determine whether the same factors driving green transportation technologies adoption in Asia apply elsewhere. Comparative studies could reveal how different socio-economic and regulatory environments influence the success of environmental policies promoting sustainable transportation.

Longitudinal studies would also be beneficial in examining the long-term effects of innovation, incentives, and regulations on green technology adoption. Such research could explore how technological shifts, such as the evolution of battery or fuel cell technologies, affect consumer attitudes and the market viability of green transportation over time.

Moreover, future studies should consider the role of emerging technologies like artificial intelligence, machine learning, and smart city initiatives in facilitating green transportation. These technologies have the potential to revolutionize urban mobility and enhance the efficiency of transportation networks, but their impact on the adoption of green transportation technologies remains underexplored.

Finally, more qualitative research, such as case studies of specific cities or countries, could provide deeper insights into the challenges and successes of implementing green transportation solutions at the local level. This would help contextualize the findings and offer more practical recommendations for policymakers.

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