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Time-Frequency and Causal Dynamics Between Green Logistics, Environmental Factors, and China's Transportation Sector: A Fourier Toda–Yamamoto and Cross-Wavelet Approach

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Abstract

This study examines causality relationships between the financial performance of China's transport industry and the selected green logistics, environmental, and macroeconomic indicators. Based on the monthly data spanning from January 2010 to December 2020, logarithm of Shanghai Transportation Index (LSZSE) is designated as the explanatory variable, while green logistics performance (LGRL), per capita income (LGDP), CO_2 emissions arising from transport activities (LTCO$_2$), and the percentage of renewable consumption of energy (LNREC) are employed as explanatory variables. In order to determine the properties of stationarity of the series, the unit root test with the Fourier Augmented Dickey-Fuller (Fourier ADF) that is robust to smooth structural breaks and nonlinear dynamics is employed. Based on the integration results, the Fourier Toda–Yamamoto (FTY) causality test is employed to test for causal relationships among variables of different orders of integration. The empirical test reveals a statistically significant one-way causality running from green logistics (LGRL) to sector performance of transportation (LSZSE) at the 10% level of significance. The cross-wavelet analysis demonstrated that the interactions between the series vary across long- and short-term scales, exhibiting synchronous or lagged structures depending on the period. This may be understood as that advancement in sustainability logistic activities will be able to influence investor sentiment and market worthiness within the industry.

Keywords

Green logistics, SZSE Transportation Index, Environmental Efficiency, Renewable Energy, Fourier Toda–Yamamoto, Wavelet

JEL Classification

C32, G15, L91, Q56, Q58

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Yeşil Lojistik, Çevresel Faktörler ve Çin Ulaştırma Sektörü Arasındaki Zaman-Frekans ve Nedensel Dinamikler: Fourier Toda–Yamamoto ve Çapraz Dalgacık Yaklaşımı

Özet

Bu çalışma, Çin ulaştırma sektörünün finansal performansı ile seçilmiş yeşil lojistik, çevresel ve makroekonomik göstergeler arasındaki nedensellik ilişkilerini incelemektedir. Ocak 2010–Aralık 2020 dönemine ait aylık veriler kullanılarak Shanghai Ulaştırma Endeksi'nin logaritması (LSZSE) bağımlı değişken, yeşil lojistik performansı (LGRL), kişi başına gelir (LGDP), ulaştırma kaynaklı CO_2 emisyonları ($LTCO_2$) ve yenilenebilir enerji tüketim oranı (LNREC) ise bağımsız değişkenler olarak modele dâhil edilmiştir. Serilerin durağanlık özelliklerini belirlemek amacıyla, düzgün yapısal kırılmalara ve doğrusal olmayan dinamiklere duyarlı Fourier Genişletilmiş Dickey–Fuller (Fourier ADF) birim kök testi uygulanmıştır. Bütünleşme derecelerine ilişkin bulgular temel alınarak, farklı bütünleşik mertebelerdeki değişkenler arasındaki nedensellik ilişkilerini analiz etmek için Fourier Toda–Yamamoto (FTY) nedensellik testi kullanılmıştır. Ampirik sonuçlar, %10 önem düzeyinde yeşil lojistik performansından (LGRL) ulaştırma sektörü performansına (LSZSE) tek yönlü bir nedensellik akışı olduğunu göstermektedir. Ayrıca çapraz dalgacık analizi, seriler arasındaki etkileşimlerin uzun ve kısa dönem ölçeklerinde farklılık sergilediğini; döneme bağlı olarak eşzamanlı (in-phase) ya da gecikmeli (lagged) yapılar ortaya koyduğunu kanıtlamıştır. Bu sonuçlar, sürdürülebilir lojistik faaliyetlerindeki ilerlemenin sektörün piyasa değerini ve yatırımcı duyarlılığını etkileyebileceğini göstermektedir.

Anahtar Kelimeler
Yeşil Lojistik, SZSE Taşımacılık İndeksi, Çevresel Etki, Yenilenebilir Enerji, Fourier Toda–Yamamoto, Dalgacık Analizi

JEL Kodları
C32, G15, L91, Q56, Q58

1. Introduction

According to IEA (2024), the logistics industry is responsible for nearly 11% of global greenhouse gas emissions, underscoring its pivotal role in addressing environmental and climate related challenges. Despite possessing the world's largest transportation network and committing to the "dual carbon" goals carbon peaking and neutrality by 2060, China increased its transportrelated carbon emissions by an average of 2.6% annually between 2010 and 2020 (EDGAR, 2023). This trend raises pressing questions about how carbon intensive logistics operations can be reconciled with sustained economic growth. During the same period, the Shenzhen Stock Exchange (SZSE) Transportation Index rose in real terms, driven by investments in digital supply chains and the momentum of ecommerce. This divergence between ecological constraints and financial gains has created notable strategic ambiguity for decision makers in both public and private sectors.

By incorporating environmental factors into asset pricing, capital markets can act as catalysts for sustainability oriented transformation (Friede et al., 2018). In China, the expansion of carbon sensitive portfolios by institutional investors and regulatory support for green bonds have laid the groundwork for environmental indicators to be increasingly reflected in the stock valuations of the logistics sector. In this study, the Green Logistics Ratio (GRL) defined as the ratio of economic output to transport related CO_2 emissions serves as a proxy for carbon efficiency; the share of renewable energy consumption (REC) captures the transition in the energy mix; and transport related per capita CO_2 emissions (TCO_2) represent the sector's carbon footprint. Together, these three indicators allow for the assessment of environmental sustainability from a financial perspective by capturing its distinct dimensions (Zhou, Wang & Chen, 2023).

Most existing studies exploring environmental influences on the market behavior of logistics firms tend to concentrate on company level metrics such as ESG scores or operational efficiency (Rodionova, Skhvediani & Kudryavtseva, 2022). In the context of China's logistics stock index, there is a striking lack of quantitative research that jointly examines the dynamic and potentially asymmetric effects of carbon intensity, renewable energy penetration, and green logistics efficiency. Moreover, existing studies predominantly rely on annual data and conventional threshold regressions, thereby overlooking the amplifying or dampening effects of short term shocks such as oil price fluctuations or policy announcements on the index. Thus, the dynamic and potentially nonlinear interplay between frequently updated environmental metrics and logistics stock performance remains an underexplored area in the literature.

The analysis here applies a Fourier based econometric model in an investigation into the causal linkage among the Shanghai Transportation Index (LSZSE) and the three most relevant environmental and macroeconomic measures Green Logistics Ratio (GRL), Renewable Energy Consumption share (REC), and transport related CO_2 per capita transport (TCO_2) over January 2010 to December 2020, applying the use of monthly data. To test the series for stationarity while allowing smooth structural breaks and mixed integration orders, we first apply the Fourier-augmented Dickey–Fuller (Fourier ADF) unit-root test. Building on these results, we estimate an expanded VAR that incorporates trigonometric Fourier terms and implement the Fourier Toda–Yamamoto procedure to gauge the direction and statistical significance of causal links. Finally, cross-wavelet coherence and phase-difference analysis are conducted to trace how the identified causal relationships unfold across both time and frequency domains. This approach features stable inference with respect to structural nonlinearities and avoids pre-testing cointegration or differencing, and so is especially appropriate for macro financial time series characterized by smooth regime changes.

This methodological strategy offers three primary contributions to the literature: (1) it identifies the causal impact of sector specific carbon efficiency and renewable energy intensity on the transport sector's financial performance using high frequency monthly data; (2) by incorporating Fourier terms in the causality test, it mitigates smooth structural changes in environmental variables, giving a richer understanding of how sustainability variables influence market behavior over time; and (3) it identifies dynamic adjustment processes around landmark structural changes, like the COVID-19 period, without resorting to arbitrary break dates particularly during the nine month transition period at the start of the pandemic. The results are expected to provide policy relevant results ranging from the carbon reduction strategy development in transport intensive sectors to sustainable financial instrument design and pricing under environmental uncertainty and structural change.

The remainder of the paper is structured as follows: Section 2 reviews the relevant literature. Section 3 presents the data and outlines the modeling strategy. Section 4 discusses the empirical findings, while Section 5 summarizes the main conclusions and offers policy recommendations for green logistics transformation and investment strategies.

2. Literature Review

Despite growing interest in sustainability, empirical investigations linking green logistics performance to logistics stock indices remain relatively scarce in the existing literature. Existing research predominantly focuses on the relationship between GRL and factors such as fossil fuel consumption, CO_2 emissions, foreign direct investment, transportation related CO_2 emissions, and renewable energy usage. Empirical evidence generally suggests that green logistics outcomes deteriorate with higher fossil fuel reliance and CO_2 output, whereas renewable energy adoption tends to enhance sectoral sustainability performance (Mohsin et al., 2022; Du, Cheng and Ali, 2023; Barut et al., 2023; Kirikkaleli and Ali, 2023; Zhou et al., 2023; Ouni and Abdallah, 2023).

Saboori et al. (2014) used the fully modified ordinary least squares (FMOLS) estimator to investigate whether energy consumed by the road-transport sector, CO_2 discharges, and output are mutually connected in OECD economies. Their results reveal a robust long-run bidirectional link and indicate that CO_2 emissions adjust more swiftly to a GDP shock than energy consumption does. Using the Generalized Method of Moments (GMM), Saidi and Hammami (2015) evaluated how CO_2 emissions and economic expansion influence energy demand in a panel of 58 nations. Their investigation showed that, in most world regions, higher emissions are associated with greater energy use, whereas the link between economic growth and energy consumption differs by region—displaying the strongest ties in Middle East & North Africa and in Sub-Saharan Africa. Spetan (2016), analyzed causal links between renewable energy consumption, CO_2 emissions, labor, capital, and economic growth in Jordan for the period 1986–2012. The research established that the consumption of renewable energy affects GDP and CO_2 emissions, implying that the expansion of renewable energy consumption may help to reduce emissions. Chen and Lei (2017) conducted a path analysis of Beijing's transport sector and came to the conclusion that reductions in energy consumption and transport intensity could indeed lower emissions levels, though population growth would remain the dominant cause of pressure within the sector. According to Hofmann and Prockl (2017), increasing oil prices harmed the profit position of logistics providers temporarily, although a simultaneous trend between stock prices and oil was preserved on longer horizons.

Lin and Wu (2022) validated the interconnections of transportation, environmental pollution, and health dynamics in China via the Bootstrap ARDL approach complemented with a Fourier function. Their tests confirmed the presence of long run cointegration relationships among variables. Karaca (2023) examined how logistics competencies both impact financial performances and market valuations among the listed companies at Borsa Istanbul's Transportation and Storage Sector between 2012 and 2021. Rodionova et al. (2022) examined whether US headquartered logistics firms actively embedding ESG factors into their activities exhibit enhanced stock performance between the years 2007 and 2022. In their research on the 2020 pandemic year, Czech et al. (2022) examined the performance of the stock within various transportation subsectors such as air freight, maritime, rail, and road transport. Jaber et al. (2025) employed the Toda–Yamamoto causality framework to explore how economic activity, energy demand, and greenhouse-gas discharges interact in Jordan. The analysis revealed that heightened energy use is a key driver of rising greenhouse-gas emissions, while economic expansion was found to be a causal force behind greater energy consumption.

3. Data and Model Specifications

This study applies a Fourier based test of causality with monthly macroeconomic time series for China spanning 2010M01–2020M12. The dependent variable is defined as Logarithm of the

Shanghai Transportation Index (LSZSE), and green logistics (LGRL), logarithm of per capita GDP (LGDP), transport induced carbon emissions ($LTCO_2$), and logarithm of share of renewable energy consumption (LNREC) as the explanatory variables. Empirical analysis was conducted with the help of R and E-Views software package. These indicators are in alignment with the United Nations' Sustainable Development Goals (SDG 7: Affordable and Clean Energy; and SDG 13: Climate Action) (Zhou et al., 2023).

The SZSE Transportation Index is constructed by calculating the monthly average of the daily closing values of the "Transportation & Logistics Industry Index" published by the Shenzhen Stock Exchange. The index represents the market capitalization weighted performance of listed land, air, maritime, and multimodal logistics firms operating in China.

The Green Logistics Ratio (GRL), following Zhou, Wang, and Chen (2023), is measured as the ratio of China's total real GDP (in constant 2015 RMB) to transport related CO_2 emissions, serving as an indicator of the sector's carbon efficiency. The Renewable Energy Consumption share is derived from the World Development Indicators (WDI) database, using the variable "Renewable energy consumption (% of total final energy consumption)." This variable reflects the percentage share of renewable energy in total final energy consumption in China. Transport related CO_2 Emissions are represented by the WDI indicator "CO_2 emissions from transport, per capita (metric tons)," which directly measures the carbon footprint of the transport sector on a per capita basis and allows for the tracking of logistics related carbon intensity over time. Since the original data for GRL, REC, and TCO_2 were available only at an annual frequency, all series were converted to monthly frequency using the Quadratic Match Sum method in EViews. This temporal disaggregation technique ensures that the original annual totals are preserved while smoothly distributing values across months. The method is suitable for capturing intra-year dynamics when no high frequency indicator is available for interpolation. Variable names and corresponding stock codes are listed in Table 1.

Table 1

Definitions of Variables

Definitions Variables	**Code**	**Source**
SZSE Transportation Index	SZSE Transp.	investing.com
Green Logistics Ratio	GRL	World Bank (calculated by the author)

Renewable Energy Consumption	REC	World Bank
CO_2 Emissions	CO_2	World Bank

3.1. Fourier ADF (FADF) Unit Root Test

To allow for possible structural breaks and nonlinearities in the time series data without prespecifying their number and nature, this paper applies the Fourier ADF (FADF) unit root test of Enders and Lee (2012). Unlike traditional unit root tests, the FADF test employs a Fourier approximation to capture smooth and gradual shifts in the deterministic components of the series. The inclusion of low frequency components through a trigonometric expansion allows the test to model structural change parsimoniously without overfitting or pre-specifying break dates. This flexibility enhances the robustness of stationarity testing when macroeconomic and financial data exhibit nonlinear periodicities. The test equation can be specified as follows:

$$\Delta Y_t = \alpha + \beta \text{t} + \Sigma[\gamma_k sin(2\pi kt/T) + \gamma_k cos(2\pi kt/T)] + \rho Y_{t-1} + \varepsilon_t \quad (1)$$

where:

- α represents the intercept,
- βt captures the linear trend component,
- γ_k and δ_k are Fourier coefficients modeling periodic fluctuations,
- k is the number of Fourier frequencies,
- T is the sample size, and
- ρY_{t-1} accounts for the presence of a unit root.

3.2. ADF Unit Root Test

To examine the stationarity properties of the time series variables, the Augmented Dickey-Fuller (ADF) unit root test developed by Dickey and Fuller (1979, 1981) is employed. The ADF test is widely used to determine whether a variable possesses a unit root, indicating non stationarity, which is a critical step in time series modeling. The ADF test equation is given in Equation 2:

$$\Delta Y_t = \alpha + \beta \text{t} + \gamma Y_{t-1} + \sum_{i=1}^{n} \delta_i \, \Delta Y_{t-i} + \varepsilon_t \quad (2)$$

where ΔY_t represents the first difference of the series, t is a deterministic trend component, and ε_t is a white noise error term.

Null Hyppthesis (H_0): γ=0, , indicating the presence of a unit root (the series is non-stationary). Alternative Hypothesis (H_a): $\gamma \neq 0$, indicating that the series is stationary.

3.3. Fourier Toda–Yamamoto (FTY)

To investigate the causal relationships between variables after accounting for likely structural breaks and smooth nonlinearities, this research uses the FTY causality test, a combination of the conventional Toda–Yamamoto (1995) approach with a Fourier approximation. The hybrid approach is very useful in empirical settings where the data generating process of the underlying data may involve gradual shifts or unspecified structural breaks.

The traditional Toda–Yamamoto (TY) method estimates an augmented VAR $k + d_{max}$ model, where k is the optimal lag length determined by information criteria (AIC, SIC), and d_{max} is the maximum order of integration among the variables. The FTY approach enhances this by incorporating Fourier terms sine and cosine functions into the VAR model to flexibly capture smooth structural breaks in the deterministic component without prior knowledge of their number, timing, or form.

This approach allows for valid statistical inference regardless of the integration properties of the variables whether I(0), I(1), or I(2) and enhances the model's ability to capture complex dynamic interactions in the presence of gradual structural changes. Therefore, the FTY framework is well suited for the study's objective of uncovering causal linkages between green logistics, economic growth, environmental factors, and transport sector performance in China.

The augmented regression can be expressed as:

$$Y_t = \alpha + \sum_{i=1}^{k+d_{max}} \Phi Y_{t-i} + y_1 \sin\left(\frac{2\pi kt}{T}\right) + y_2 cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \quad (3)$$

Granger non-causality is then tested using the standard Wald test on the first k lags of the potentially causal variable, while the additional d_{max} lags ensure robustness in the presence of non-stationary variables.

3.4. Wavelet-Coherence Analysis

Wavelet-coherence analysis provides a robust framework for probing the joint time-frequency behaviour of two non-stationary series. It rests on the continuous wavelet transform (CWT), which maps a signal into time–frequency space through wavelets mathematical functions that are simultaneously localised in both time and scale.

Wavelet coherence is computed as the normalized cross wavelet transform:

$$R_{xy}^{2}(a,b)=\frac{\left|S\left(b^{-1}W_{xy}(a,b)\right)\right|^{2}}{S\left(b^{-1}W_{x}(a,b)\right)^{2}S\left(b^{-1}W_{y}(a,b)\right)^{2}} \quad (4)$$

In this framework, S signifies a two-dimensional smoothing operator acting across both time and scale domains (Torrence & Compo, 1998). The derived wavelet-coherence measure, R^2(a, b), varies from 0 to 1 and gauges the local linear association between the series at each time–frequency location. Values approaching 1 imply a pronounced correlation, whereas coefficients near 0 reflect a weak or nonexistent relationship (Grinsted et al., 2004).

The phase difference in the function as;

$$\phi_{xy}=arctan\left(\frac{Im\left[S\left(b^{-1}W_{xy}(a,b)\right)\right]}{RE\left[S\left(b^{-1}W_{xy}(a,b)\right)\right]}\right),\text{ with } \phi_{xy}\,\epsilon\,[-\pi,\pi] \quad (5)$$

Equations (4) and (5) demonstrate that the real (Re) and imaginary (Im) parts of the smoothed cross-spectrum capture distinct properties of the signals. The associated phase angle, ϕxy\phi_{xy}ϕ_{xy}, conveys both the strength of linkage and the possible direction of influence i.e., lead–lag behaviour—between the two series. On the wavelet plot, right-pointing arrows (→) signal in-phase, positive comovement, whereas left-pointing arrows (←) indicate out-of-phase, negative comovement. A diagonal arrow slanting upward to the right (↗) shows that $x(t)$x(t) leads $y(t)$y(t), while one slanting downward to the left (↙) reveals that $y(t)$y(t) leads $x(t)$x(t) (Torrence & Compo, 1998).

4. Econometric Findings

The stationarity properties of the variables were examined using both the Fourier ADF and the conventional ADF unit root tests. The results are reported in Table 2 and Table 3, respectively.

Table 2

Fourier ADF Unit Root Test Results

	Level			First Difference			Second Difference	
Variable	Constant	Constant+Trend	Variable	Constant	Constant+Trend	Variable	Constant	Constant+Trend
LSZSE k=2 p=1	-2.364	-3.361***	LSZSE k=2 p=0	-9.761***	-9.721***		-	-
LGRL k=1 p=1	-4.167***	-0.272	LGRL k=5 p=1	-1.656	-1.892	LGRL k=1 p=0	-13.595***	-13.558***
LGDP	-3.456***	0.563	LGDP	-1.439	-1.820	LGDP	-14.015***	-13.976***

k=1 p=1			k=5 p=1			k=1 p=0		
LTCO2	1.888	-0.276	LTCO2	-2.588	-2.648	LTCO2	-11.641***	-11.629***
k=3 p=12			k=2 p=12			k=3 p=11		
LNREC	0.378	-2.908	LNREC	-2.175	-2.213	LNREC	-11.333***	-11.399***
k=6 p=12			k=6 p=12			k=6 p=11		

Table 3

ADF Unit Root Test Results

	Level		First Difference		Second Difference	
Variable	Constant	Constant +Trend	Constant	Constant+ Trend	Constant	Constant+Trend
LSZSE	-1.556	-2.446	-9.528***	-9.524***	-	-
LGRL	-1.272	-1.523	-1.827	-2.139	-13.238***	-13.184***
LGDP	-1.327	-0.782	-1.862	-2.254	-13.630***	-13.576
LTCO2	1.238	-1.825	-2.411	-2.679	-93.594***	-93.316***
LNREC	-0.119	-3.183	-2.285	-2.177	-153.75***	-153.915***

For ensuring the validity of the time series analysis, both the standard Augmented Dickey-Fuller (ADF) test and the Fourier ADF test, with allowance for any potential structural breaks, were conducted for testing stationarity properties of variables. With regard to findings in the case of the Fourier ADF test, the variable LSZSE is stationary in the first difference and hence it is integrated order one, that is, I(1). The other variables (LGRL, LGDP, LTCO2, and LNREC) were initially non-stationary at first difference but became stationary at second difference, which shows that they are integrated of order two, I(2). These findings are generally consistent with those of the standard ADF test, as it also confirms that LSZSE is I(1) and the rest of the variables are I(2). Because there are mixed integration orders of variables, normal cointegration analysis may not be suitable. The Fourier Toda-Yamamoto causality test was therefore employed as a superior tool for analysis. Although some variables in the study are integrated of order two (I(2)), the risk of spurious regression has been taken into account. Nevertheless, the Fourier Toda-Yamamoto causality test was selected due to its ability to accommodate series with different levels of integration. Moreover, the analysis covers the period from 2010M01 to 2020M12, comprising 132 monthly observations, which provides a sufficiently large sample size to ensure the validity of the model. Still, findings with marginal significance have been interpreted with appropriate caution.

Empirical findings from the Fourier Toda-Yamamoto causality test are found in Table 4, showing the direction and statistical significance of the causal relations among the variables.

Table 4

Fourier Toda-Yamamoto Causality Test Results

Variable	df	lag	Wald Test	Prob
LGRL→ LSZSE	2	2	8.9819	0.061**
LSZSE→ LGRL	2	2	1.3543	0.852
LGDP → LSZSE	2	2	3.248	0.517
LSZSE → LGDP	2	2	7.322	0.109**
LTCO2 → LSZSE	2	13	14.7453	0.4699
LSZSE → LTCO2	2	13	21.702	0.105**
LNREC → LSZSE	2	13	12.127	0.669
LSZSE → LNREC	2	13	12.862	0.613

The results of the Fourier Toda-Yamamoto causality test in Table 4 present the pairwise causality relationships between the LSZSE (Shenzhen Stock Exchange Transportation Index) and other macroeconomic and environmental variables. The number of lags used in the model was determined by summing the highest order of integration among the variables (d = 2) and their optimal lag lengths selected based on the Akaike Information Criterion (AIC). The use of AIC ensures that the lag structure minimizes information loss while balancing model fit and complexity. Additionally, applying the Fourier approximation enhances sensitivity to structural breaks or regime shifts, offering greater explanatory power than the standard Toda-Yamamoto approach.

According to Table 4, a potential one-way causality from LGRL to LSZSE is observed at the 10% significance level. This suggests that the variable LGRL, representing the scale of logistics activity, may exert a lagged influence on the financial performance of the transport sector (LSZSE). Although the result is marginally significant, it tentatively points to the possibility that real logistics mobility could act as an informative signal for movements in stock market indices.

Similarly, a potential relationship from LSZSE to LGDP is observed at the 10% significance level. This may suggest that real GDP, as a proxy for economic growth, could have a lagged and possibly positive influence on the stock performance of the transportation sector. While this finding is only marginally significant, it tentatively indicates that increased economic activity might shape investor expectations in the sector. Moreover, a possible causal relationship from LSZSE to $LTCO_2$ is also identified at the 10% significance level. This suggests that transport sector stock market performance may exert a delayed influence on environmental indicators such as carbon emissions from transportation activities. However, due to the limited level of statistical significance, these findings should be interpreted with caution and may benefit from further investigation.

The Fourier Toda-Yamamoto test was employed to reveal the overall directional relationships among the variables. In addition, to examine how these relationships evolve over time and how they behave across different frequency bands in greater detail, the cross-wavelet method was utilized. Since both analytical approaches (Fourier Toda-Yamamoto and cross-wavelet) do not require the variables to be stationary, the analyses in this study were conducted using level values. This allowed for the preservation of the long-term information within the series while enabling a coherent examination of both the causal structure and the time-frequency dynamics.

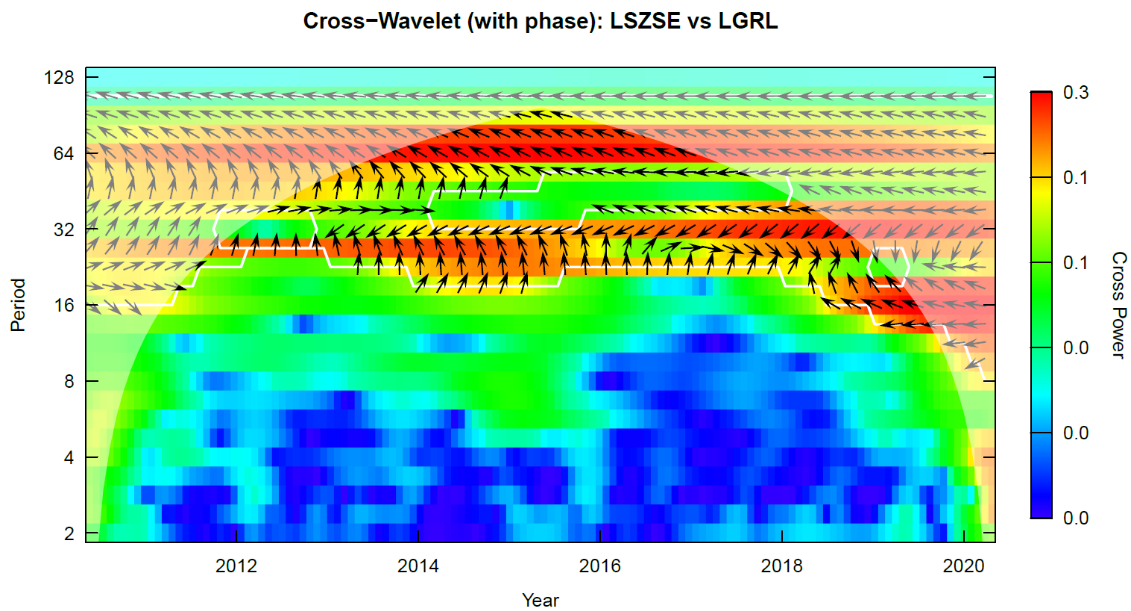

Figure 1. Cross-wavelet power spectrum between LSZSE and LGRL

Figure 1 illustrates regions of high cross-wavelet power between LSZSE and LGRL during the period 2012–2018, particularly within the 32–64 period band. The phase arrows in these regions point to the right, indicating that the two series move in the same direction and are largely synchronized. Around 2015–2016, additional short-term co-movements appear near the 8-period range, with phase arrows implying that LSZSE may follow LGRL with a slight delay. These observations point to a dynamic and positively aligned relationship across both short- and long-term frequencies.

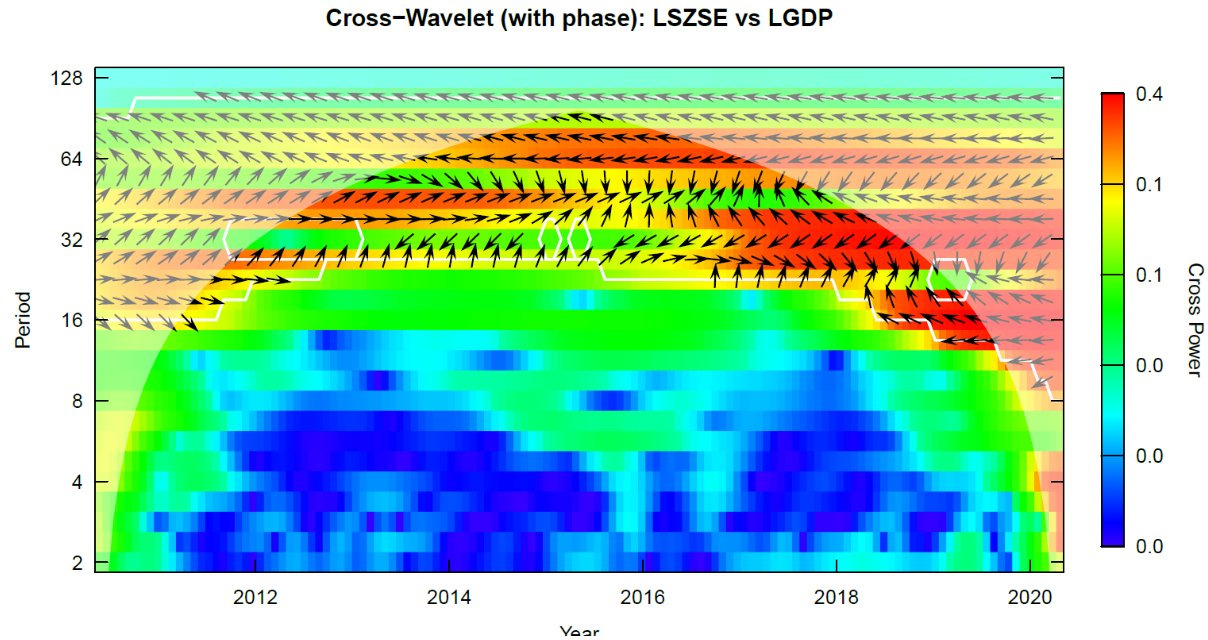

*Figure 2***.** Cross-wavelet power spectrum between LSZSE and LGDP

Figure 2 shows clear patterns of co-movement between LSZSE and LGDP over the time period from 2012 to 2019, particularly in the 32–64 interval. The phase arrows in these areas are typically downward and somewhat to the left, which suggests that LSZSE lags behind LGDP. This suggests that changes in LGDP might cause corresponding changes in LSZSE, indicative of a dynamic lag relationship at longer-term frequencies.

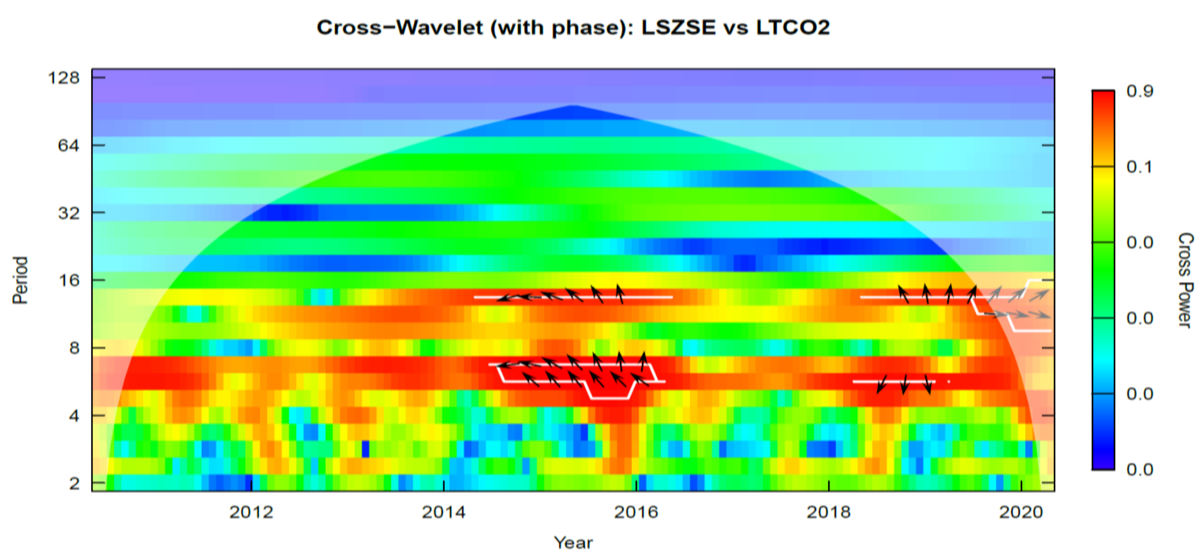

Figure 3. Cross-wavelet power spectrum between LSZSE and LTCO2

The cross-wavelet plot in Figure 3 reveals short-term frequency interactions primarily between 4 and 16 periods during two distinct intervals: 2014–2016 and 2018–2020. In the earlier phase, arrows pointing downward and to the left imply that LSZSE trails behind LTCO2. In the later interval, arrows shift upward and to the right, suggesting that LTCO2 may begin to follow LSZSE. The changing arrow orientations across time reflect an evolving, directionally varying relationship between the variables.

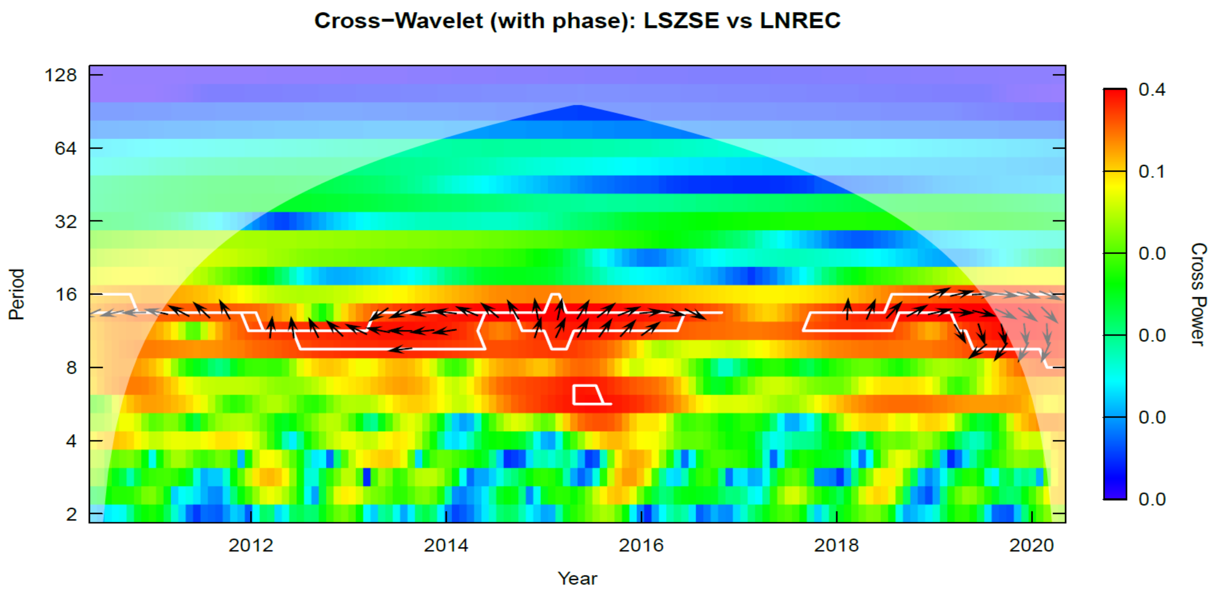

Figure 4. Cross-wavelet power spectrum between LSZSE and LNREC

As shown in Figure 4, LSZSE and LNREC exhibit co-movements within the 10–16 period band, especially during 2012–2016 and again from 2018 to 2020. In the earlier period, rightward phase arrows indicate synchronized movement in the same direction. In contrast, the later period begins with upward arrows hinting at a lagged response followed by rightward arrows that reflect resynchronization. This progression suggests a time-varying interaction pattern in the short-to-medium frequency domain.

5. Conclusion & Implications

In this study, the dynamic relationships between LSZSE and various macroeconomic and environmental indicators were examined through a multi-method time series analysis framework. Initially, the stationarity properties of the series were tested using both the traditional ADF test and the Fourier ADF test, which accounts for potential structural breaks. This provided a statistically robust foundation for the subsequent modeling process.

The stationarity diagnostics, conducted using conventional ADF and Fourier ADF tests, show that LSZSE is integrated of order one, I(1), whereas the explanatory variables green logistics performance (LGRL), per capita income (LGDP), transport-induced carbon emissions ($LTCO_2$), and renewable energy consumption share (LNREC) are integrated of order two, I(2). This framework of mixed integration necessitates the use of the FTY approach, which can capture variables with different integration properties by estimating an augmented VAR in levels with higher lags and Fourier terms. The use of trigonometric Fourier terms allows the model to flexibly and smoothly capture gradual structural breaks that may be generated by policy shifts, market realignments, or overall macro environmental trends.

The results of the Fourier Toda–Yamamoto causality test reveal the presence of strong unidirectional causality from LGRL to LSZSE at the 10% level, which suggests that green logistics improvements serve as a leading indicator for China's transportation sector financial performance. This finding supports the hypothesis that sustainable logistics enhancement can positively influence investor sentiment and industry-specific stock pricing. On the other hand, there is no statistically significant causality from LGDP to LSZSE, implying that macroeconomic expansion has no causal influence on the performance of the transport stock on the sample interval. Importantly, the reverse direction from LSZSE to LGDP exhibits marginal significance at the 10% level, implying that changes in the transport sector's fiscal performance contain latent weak informational content for forecasting macroeconomic activity. For environmental variables, the results show that there is no statistically significant causal relationship from transport sector carbon emissions ($LTCO_2$) or proportion of renewable energy consumption (LNREC) to LSZSE. However, a marginally significant causality from LSZSE to $LTCO_2$ exists, indicating that transportation sector performance improvement may precede emission increases, possibly reflecting activity-driven environmental spillovers.

The cross-wavelet analysis added information regarding the way these relationships evolve over time and across different frequency bands. The analysis depicted that the relationships among the series differ at long- and short-term horizons, and that synchronous or lagged patterns are dependent on the duration. Precisely, the relationship with LGRL indicated long-run and positively correlated co-movements, while the relationship with LGDP manifested as a lagled response in some durations. The coupling with LTCO2 manifested as a dynamic structure that reverses direction on short-term frequencies.

Additionally, the wavelet analysis picked up on low-level yet identifiable patterns of co-movements even for the variables for which the Toda-Yamamoto test had not established causality. This speaks to the sensitivity and flexibility of wavelet techniques to identify time- and frequency-dependent dynamics.

In conclusion, LSZSE appears to be responsive not only to immediate market conditions but also to broader, long-term economic and environmental developments. The application of multiple analytical approaches enabled a comprehensive assessment of the relationships between variables in terms of their direction, timing, and frequency characteristics, thus providing a deeper and more integrated understanding of their interactions.

Overall, these findings point to the critical significance of green logistics in determining transportation sector dynamics and to the comparatively weaker causal role of broader macroeconomic and environmental determinants during the period under observation. The asymmetry of such relationships underscores the necessity for sectoral sustainability measures and targeted interventions.

While the Fourier Toda–Yamamoto method delivers enhanced robustness for causality inference amidst nonlinearity and structural breaks, future studies can build on the results here by applying frequency-domain analysis (e.g., wavelet coherence or spectral Granger causality) to uncover time-varying relationships. Including additional more recent data points or other structural indicators would further sharpen the empirical analysis of the dynamic and time-evolving causal processes involved in the nexus of green growth and financial market performance.

Despite the strength of this study, there are some limitations to be mentioned. Firstly, the research relies only on monthly data from 01.2010 to 12.2020 that may not fully capture long-term structural change or more recent dynamics in China's transport and sustainability sectors. Second, the model does not account for any potential nonlinearities or threshold effects beyond those approximated by the Fourier terms that may be applicable in the case of abrupt policy changes or regime changes. Third, the analysis is limited to a specific set of macroeconomic and environmental variables, which, although theoretically sound, may well be omitting other important determinants such as foreign direct investment, technological change, or sectoral policy interventions.

Subsequent studies can overcome the above constraints by expanding the temporal and cross-sectional coverage of the dataset, for example, by incorporating panel data from multiple regions or cities in China. The application of other econometric techniques such as time-varying parameter VAR models, Markov-switching models, or machine learning-based causality models can also facilitate a deeper understanding of complex dynamic relationships. Additionally, using qualitative policy analysis or stakeholder opinion might add corroborating information regarding the mechanisms through which green logistics and environmental factors influence financial performance in the transport industry.

From a policy perspective, the findings underscore the importance of giving higher priority to green logistics initiatives as a strategic catalyst for enhancing the financial performance of the transport sector. Policymakers should enact pinpoint incentives such as subsidies for environmentally efficient logistics technologies, mechanisms for carbon pricing, and regulatory frameworks supporting low-emission transport systems. These interventions not only align with sustainable development goals but also positively contribute to investor confidence through improved sectoral efficiency and long-term profitability. Also, the exposure of the transport sector to green logistics innovation implies that institutional investors and private investors need to consider environmental logistics performance as a key consideration in evaluating sectoral investment opportunities. Facilitating the integration of green logistics metrics into infrastructure planning, funding decisions, and ESG systems can amplify the industry's resilience against environmental and market shocks.

Declaration of Research and Publication Ethics

This study which does not require ethics committee approval and/or legal/specific permission complies with the research and publication ethics.

Researcher's Contribution Rate Statement

Since the author is the sole author of the article, his contribution rate is 100%.

Declaration of Researcher's Conflict of Interest

There are no potential conflicts of interest in this study.

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