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Carbon Emission Reduction Strategies for the Logistics Industry in Northeast China's Three Provinces under the Carbon Peaking and Carbon Neutrality Goals

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Abstract: Using panel data from 2008 to 2022, this study assesses carbon efficiency and emission reduction potential in the logistics industry across Northeast China's three provinces. The analysis combines data envelopment analysis (DEA), the Malmquist index, and frontier projection. Liaoning has the highest carbon efficiency, followed by Jilin and Heilongjiang. Productivity across the three provinces remains broadly unchanged over the study period. Cumulative technical emission reduction potential amounts to 18.20% of actual emissions during this period. As a share of actual emissions, reduction potential is highest in Heilongjiang, followed by Jilin and Liaoning. These differences suggest province-specific priorities: low-carbon technologies and cleaner energy sources in Liaoning, closer alignment of input scale with transport service provision in Jilin, and consolidation of existing resources and improved operational efficiency in Heilongjiang.

Keywords: Northeast China; Logistics industry; Carbon efficiency; Carbon emission reduction; DEA

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1. Introduction

As China keeps pushing for high-quality economic development, and as it works toward carbon peaking and carbon neutrality, the logistics sector is facing more and more pressure; it has to improve carbon efficiency, use fewer resources, and lower environmental impacts. Northeast China has long been a major industrial and agricultural base, and logistics there helps keep the regional economy moving by distributing industrial products, sending grain to other regions, and supporting cooperation among industries. If resource inputs, logistics outputs, and carbon emissions are put into one common framework, then it becomes possible to see how carbon efficiency and emission reduction potential differ across the three northeastern provinces; the results can also help each province find its own way to cut logistics costs, improve efficiency, and support green development.

Work on green and low-carbon logistics has mainly centered on two things: one is emission characteristics, and the other is efficiency measurement. Studies of emission characteristics look at how emissions change across space and time, and at what factors drive those changes. With provincial data from 2010–2021, Zhang *et al.*, for instance, combined spatial autocorrelation analysis with geographically and temporally weighted regression; they found that logistics carbon emissions were spatially clustered, and they also found that the effects of their determinants differed from region to region and over time [1]. Efficiency studies, on the other hand, bring energy consumption and carbon emissions into an input–output framework, so that resource use and the quality of logistics development can be evaluated. Jiang *et al.* used a super-efficiency slack-based measure (SBM) model and the Malmquist index to assess static carbon emission efficiency and how it changed over time; their approach gives a methodological reference for linking relative efficiency measurement with dynamic analysis [2].

In this study, we look at how logistics efficiency and its components differ across provinces [3,4], how productivity changes from year to year, and what technical emission reduction potential exists relative to the specified sample frontier; we also look at how that potential is distributed across historical periods. Data from 2008–2022 give us a static efficiency benchmark, while dynamic indices track changes between consecutive years, and frontier projection is used to estimate target emissions and potential reductions. Taken together, these measures turn regional efficiency gaps into quantifiable technical emission reduction potential, show how it varies from province to province and from period to period, and can help shape emission reduction strategies that fit each province.

2. Methods and data sources

This study examines static efficiency, dynamic change, and frontier projections. Static efficiency measures each observation's performance relative to best practice within the sample and distinguishes between pure technical and scale inefficiencies. Dynamic indices capture productivity changes between consecutive periods. Frontier projections identify target input and output levels, which are used to estimate the scope for improvement. Emission reduction potential is calculated from the target emissions obtained through static projections; dynamic indices do not enter this calculation.

2.1. Static efficiency evaluation

Input-oriented data envelopment analysis (DEA) is used to evaluate logistics carbon efficiency under an explicit emission constraint. The CCR model assumes constant returns to scale and measures overall technical efficiency (TE). For the evaluated observation , the model is expressed as:

$$\min_{\theta,\lambda} \theta$$

$$s.t. \sum_{j=1}^{n} \lambda_j x_j \le \theta x_o, \sum_{j=1}^{n} \lambda_j y_j \ge y_o,$$

$$\sum_{j=1}^{n} \lambda_j b_j \le b_o, \lambda_j \ge 0 \quad (1)$$

Here, x_j, y_j, and b_j denote inputs, desirable outputs, and carbon emissions, respectively; λ_j represents

reference weights, and $n = 45$. The optimal value θ measures the scope for proportional input contraction while maintaining desirable outputs and keeping emissions at or below the observed level. Values closer to 1 indicate higher relative efficiency, but do not directly represent emission reduction potential.

Adding $\sum_{j=1}^{n}\lambda_j = 1$ to Equation (1) yields the BCC model, which measures pure technical efficiency (PTE) under variable returns to scale. Scale efficiency is calculated as $SE = TE / PTE$. This decomposition distinguishes inefficiency associated with resource use from that associated with operating scale.

2.2. Dynamic evaluation

The adjacent-period Malmquist index is employed to measure productivity change and identify its sources. Input-oriented CCR frontiers are constructed separately for periods t and $t+1$. Let A and B denote the efficiencies of observations in these two periods evaluated against the period-t frontier. Similarly, C and D denote their efficiencies evaluated against the period-$t+1$ frontier. The decomposition is:

$$EFFCH = \frac{D}{A}, TECHCH = \sqrt{\frac{B}{D} \times \frac{A}{C}}$$

$$TFPCH = EFFCH \times TECHCH; EFFCH = PECH \times SECH \tag{2}$$

Here, TFPCH denotes total factor productivity change, EFFCH captures changes in efficiency relative to each period's frontier, and TECHCH reflects frontier shifts. EFFCH is further decomposed into pure technical efficiency change (PECH) and scale efficiency change (SECH). PECH is calculated as the ratio of period-specific BCC efficiencies, and $SECH = EFFCH / PECH$. Index values above, equal to, or below 1 indicate improvement, stability, or deterioration, respectively.

For dynamic evaluation, emissions are transformed into $y_b = M - b$, where M equals 1.01 times the maximum emission value across the full sample. This transformation treats lower emissions as more favorable, although results depend on the transformation and the selected constant. Static evaluation and emission reduction projection retain the direct emission constraint in Equation (1).

3. Empirical results

3.1. Static efficiency levels and structure

Across the full sample, mean TE, PTE, and SE were 0.8156, 0.8892, and 0.9163, respectively. TE differed clearly across provinces, averaging 0.9514 in Liaoning, 0.8331 in Jilin, and 0.6623 in Heilongjiang (**Table 1**). Liaoning was generally close to the common frontier, Jilin occupied an intermediate position, and Heilongjiang had a larger relative gap. The annual results show that Liaoning approached the frontier in most years after 2012, while Jilin reached it in 2021–2022. Heilongjiang did not show comparable convergence during the middle and later parts of the sample period.

Table 1. Mean static efficiency in the three provinces, 2008–2022

Province	Overall technical efficiency (TE)	Pure technical efficiency (PTE)	Scale efficiency (SE)
Liaoning	0.9514	0.9722	0.9765
Jilin	0.8331	0.9604	0.8685
Heilongjiang	0.6623	0.7350	0.9038

Note: Each column reports the arithmetic mean of 15 annual values. All measures are dimensionless. The means need not satisfy the multiplicative identity that holds for individual observations.

The efficiency components and their combinations reveal different sources of the gaps. Efficiency structure was classified according to whether PTE and SE each exceeded 0.9. Except in the initial years of 2008–2009, Liaoning fell into the high–high category, leaving little scope for proportional input contraction. Jilin mainly exhibited a high–low pattern during the first half of the sample period. Its PTE was close to the frontier, but SE was lower, averaging 0.8685. Its gap therefore arose mainly from an inability to fully benefit from returns to scale. Heilongjiang exhibited a persistent low–high pattern, with PTE (0.7350) markedly below SE (0.9038). Considerable resource-use inefficiency remained even after accounting for scale differences. Both components declined after 2018, placing the province in the low–low category.

3.2. Dynamic productivity change

Across the 42 adjacent-period observations (14 per province), mean TFPCH, EFFCH, and TECHCH were 1.0014, 0.9980, and 1.0072, respectively. Mean PECH and SECH were 1.0021 and 0.9962. The mean total index was close to 1, indicating that productivity was broadly unchanged on average during the sample period. This average nevertheless masked substantial annual fluctuations. Mean TFPCH across the three provinces reached 1.1197 in 2010–2011 but fell to 0.8939 in 2013–2014.

At the provincial level (**Table 2**), TFPCH was slightly above 1 in Liaoning, close to 1 in Jilin, and slightly below 1 in Heilongjiang. Heilongjiang's TECHCH was 1.0076, whereas EFFCH was 0.9940. Frontier movement and relative efficiency catch-up therefore did not move in the same direction. Its SECH of 0.9885 also indicates that scale efficiency change weighed on overall performance and warrants attention.

Table 2. Mean Malmquist indices and decomposition components in the three provinces, 2008–2022

Province	TFPCH	EFFCH	TECHCH	PECH	SECH
Liaoning	1.0153	1.0000	1.0153	1.0000	1.0000
Jilin	0.9986	1.0000	0.9986	1.0000	1.0000
Heilongjiang	0.9903	0.9940	1.0076	1.0064	0.9885

Note: Values are arithmetic means over 14 adjacent-period comparisons per province. All indices are dimensionless and are defined in Section 2.2.

Jilin's mean SE of 0.8685 in **Table 1** is compatible with its mean SECH of 1.0000 in **Table 2**. The former measures the scale efficiency level against the common intertemporal frontier. The latter measures adjacent-period changes against annual frontiers. A mean change index of 1 does not imply an efficiency level of 1. The two models also treat emissions differently. Thus, the value of 1.0000 in **Table 2** does not imply an absence of scope for improvement.

3.3. Provincial emission reduction potential and input–output differences

Projection from the static efficiency benchmark gave total actual carbon dioxide emissions of 94723.20 × 10,000 tons and target emissions of 77479.59 × 10,000 tons for 2008–2022. Technical emission reduction potential was 17243.61 × 10,000 tons, or 18.20% of actual emissions. **Table 3** presents the provincial results. This potential is equivalent to approximately 2.7 years of carbon emissions from the three provinces' logistics

industry, representing a substantial quantity.

Table 3. Cumulative carbon dioxide emissions and technical emission reduction potential in the three provinces, 2008–2022

Province	Actual emissions (10,000 tons)	Target emissions (10,000 tons)	Potential emission reductions (10,000 tons)	Emission reduction ratio (%)
Liaoning	51293.32	48721.17	2572.15	5.01
Jilin	16528.05	12543.08	3984.97	24.11
Heilongjiang	26901.82	16215.34	10686.49	39.72
Total	94723.20	77479.59	17243.61	18.20

Note: Emissions cover only direct combustion of the seven fuels. Totals are calculated from unrounded values; displayed components may therefore differ slightly from the totals when summed.

The provincial distribution of emission reduction potential did not fully correspond to efficiency levels. Liaoning had the highest cumulative actual emissions, but its reduction potential was only 2572.15 × 10,000 tons (5.01%). Although Heilongjiang emitted less than Liaoning, its emission reduction potential reached 10686.49 × 10,000 tons (39.72%). Jilin ranked between the two, with a potential of 3984.97 × 10,000 tons (24.11%). Higher absolute emissions therefore do not necessarily correspond to greater relative scope for improvement. Liaoning faces pressure from the scale of its emissions, while Heilongjiang has a larger relative efficiency gap, calling for different responses in the two provinces.

The input–output projections show the composition of these provincial gaps. In Liaoning, mean redundancy ratios for labor, capital, and energy were 6.2%, 6.3%, and 5.2%, respectively, while the shortfall ratios for value added and freight turnover were 1.6% and 0.8%. These small input and output gaps were consistent with its position close to the frontier. Jilin showed a different pattern. Its labor, capital, and energy redundancy ratios were 22.7%, 25.6%, and 16.7%, respectively. The freight turnover shortfall ratio was 30.5%, whereas the value-added shortfall ratio was close to zero. Economic output was thus near its projected target, but physical transport services remained below the corresponding target, indicating a mismatch between input scale and freight service output. In Heilongjiang, redundancy ratios reached 48.3% for labor, 34.1% for capital, and 33.8% for energy, alongside a freight turnover shortfall ratio of 62.8%. Its projected target combines lower inputs with higher freight turnover. Closing this gap therefore involves both input savings and improved transport service output.

4. Carbon emission reduction strategies

4.1. Analysis of efficiency structure

Emission reduction priorities in the three provinces' logistics industry depend on resource allocation efficiency and its alignment with transport service provision. Liaoning has a large emission volume, but its TE is close to the sample frontier, with little input redundancy or output shortfall. Under existing production practices, resource reallocation alone therefore offers limited relative scope for emission reductions. Jilin's main weakness is scale efficiency. Although its PTE is high, redundant capital input coexists with a freight turnover shortfall. Better alignment between input scale and transport service output is needed. Heilongjiang has relatively low PTE, substantial labor, capital, and energy redundancies, and a pronounced freight turnover shortfall. Resource

conservation and service capacity improvement therefore need to proceed together.

4.2. Provincial priorities for improvement

Liaoning should build on its advantage in resource-use efficiency and gradually direct emission reduction efforts toward facility and equipment upgrades and more efficient energy use. Energy-saving retrofits should follow vehicle and warehouse replacement cycles, with priority given to energy-intensive equipment. Clean energy substitution should reflect transport distances, operating frequency, and access to refueling or recharging facilities. Monitoring energy use in transport and warehousing can guide route optimization, load planning, and equipment operation, helping reduce energy consumption and emissions while maintaining logistics service capacity.

Jilin, by contrast, needs to bring input scale closer to transport service output. Redundant capital and other inputs sit alongside a freight turnover shortfall, which suggests reviewing how existing logistics parks, warehouses, and transport equipment are used. New project planning should look for ways to use existing resources more fully, and it should avoid duplicating functions or building facilities when freight demand is not enough. Freight information exchange, capacity sharing, joint delivery, and return-load matching can improve facility and vehicle utilization. Service provision should follow actual freight demand, while the freight turnover gap can inform changes in transport organization and in the capacity needed to serve that demand.

Heilongjiang, for its part, can consolidate existing resources and improve their operational use. Shared warehousing and coordinated transport dispatch, supported by closer coordination across operations, can reduce idle resources and duplication tied to redundant labor, capital, and energy inputs. Job reassignment and skills training can help match labor inputs to operational needs. Transport services also need to reflect actual freight availability and seasonal demand; coordinating freight collection, trunk transport, and last-mile delivery can expand the service capacity of existing facilities and equipment. Daily energy management and targeted retrofits of identified energy-intensive processes can conserve resources while still supporting effective service provision.

Interprovincial cooperation can help support these improvements. The three provinces should strengthen links among logistics corridors, hubs, and information platforms so that transport resources can be shared and operations coordinated, which would reduce duplicate construction and ineffective transport activity. Evaluation should consider total emissions together with resource-use efficiency and transport service output. Changes in provincial efficiency and emission reduction outcomes should guide later adjustments in priorities, linking logistics cost reduction and efficiency gains with the green transition.

5. Conclusion

Liaoning can consolidate its efficiency advantage through energy-saving retrofits and clean energy substitution; Jilin needs to align input scale with transport service demand and make fuller use of existing resources; and Heilongjiang can consolidate resources and improve operations, so that inefficient inputs are reduced, and effective service provision is strengthened. These provincial priorities point in three directions: one is equipment and energy upgrades in Liaoning; another is better scale configuration in Jilin; and a third is more efficient resource use in Heilongjiang.

The estimated technical emission reduction potential is, in a sense, the historical scope for improvement relative to the sample frontier under the specified model conditions; but turning these estimates into future

reduction targets would also require assessing technological conditions, transport demand, and implementation costs, and none of these are included in the current estimates. With only three provinces observed each year, the sample also limits how well the dynamic evaluation can discriminate. Future research could extend the analysis to cities or firms, and bring in transport structure, technological conditions, and emission reduction costs, so that the feasibility and actual effects of specific strategies can be assessed.

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Disclosure statement

The authors declare no conflict of interest.

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