Green & Lean: A Delay-Tolerant Routing Framework For Cost And Emission Optimization In Road Freight Logistics

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Abstract

Logistics networks frequently prioritize delivery speed, often selecting the fastest available route without explicitly evaluating the marginal financial and environmental cost of time savings. This study develops and evaluates a Green & Lean routing framework that quantifies the *Cost of Speed* by comparing fastest-path and shortest-path alternatives under a defined Service Level Agreement (SLA) tolerance. Using a simulation-based analysis of a synthetic Pan-India road freight network, the framework demonstrates that meaningful fuel cost and carbon emission reductions can be achieved without compromising delivery reliability. Results from 500 simulated shipments indicate substantial aggregate fuel cost savings and CO_2 reduction potential with zero SLA breaches, highlighting delay tolerance as a practical and scalable lever for sustainable logistics optimization.

Keywords: Green logistics, lean logistics, routing optimization, carbon emissions, supply chain management

1. Introduction

In road freight logistics, routing decisions are commonly guided by speed-centric heuristics that prioritize the fastest available path. While such heuristics are intuitively associated with service reliability, they often fail to account for the disproportionate increases in fuel consumption, operating cost, and carbon emissions that accompany marginal reductions in transit time. With increasing pressure on firms to reduce logistics costs and meet sustainability targets, the limitations of purely speed-driven routing decisions have become more apparent.

This paper argues that faster routes are not inherently superior and that, in many operational contexts, moderate delivery delays are acceptable without violating customer expectations or contractual SLAs. Building on this

premise, the study proposes a delay-tolerant routing framework that explicitly balances delivery time against cost and emissions. The objective is not to eliminate fast routes, but to identify conditions under which speed ceases to deliver proportional value.

2. Problem Statement

Despite advances in routing technologies, logistics networks continue to exhibit a persistent speed bias, wherein longer highway-based routes are preferred over shorter alternatives. Empirical observations and industry reports suggest that in a significant share of shipments, logistics operators incur higher fuel and emissions costs for relatively small time savings. This misalignment represents a hidden erosion of both economic efficiency and environmental performance.

The absence of a formal mechanism to quantify acceptable delivery delays contributes to conservative routing choices. As a result, potentially cost-effective and lower-emission routes are systematically ignored, even when their time penalties fall well within tolerable limits.

3. Objectives

The objectives of this study are to:

- Quantify the financial and environmental implications of speed-biased routing decisions.
- Develop a rule-based routing framework that incorporates explicit SLA tolerance.
- Evaluate whether cost and emission reductions can be achieved without increasing SLA breach risk.
- Examine the consistency and scalability of potential savings across a large shipment portfolio.

4. Literature Review

4.1 Speed–Efficiency Trade-offs in Logistics

Logistics research has long acknowledged the trade-off between delivery speed and operational efficiency. McKinnon (2018) notes that time-based competition in freight transport often encourages practices that inflate costs without delivering commensurate customer value. Similarly, Chopra (2019) highlights that excessive responsiveness can undermine supply chain profitability when time reductions are marginal.

4.2 Green Logistics and Emissions Optimization

Green logistics literature emphasizes emissions reduction through vehicle efficiency, modal shifts, and environmentally aware routing. Dekker et al. (2012) argue that sustainability objectives must be embedded directly into operational decision-making. Routing decisions, in particular, have been shown to exert a significant influence on freight-related emissions (Demir et al., 2014).

4.3 Lean Logistics and Cost Reduction

Lean logistics focuses on eliminating operational waste, including unnecessary transportation and excess distance traveled (Womack & Jones, 2003). From this perspective, distance inflation caused by speed-biased routing represents a form of structural inefficiency rather than a service necessity.

4.4 Routing with Time Constraints

Traditional routing models often rely on rigid delivery windows, limiting their applicability in real-world contexts where moderate delays are acceptable (Toth & Vigo, 2014). Recent studies suggest that introducing soft time constraints can improve overall network efficiency (Franceschetti et al., 2017). However, practical, rule-based implementations of such concepts remain limited.

4.5 Research Gap

The reviewed literature reveals a gap between sustainability-focused routing models and operationally simple decision frameworks. This study addresses that gap by proposing a delay-tolerant, rule-based approach that integrates cost, emissions, and SLA considerations into routine routing decisions.

While prior studies address emissions minimization, lean efficiency, and routing with time constraints independently, they rarely translate these concepts into operationally simple decision rules. Existing models often rely on complex optimization formulations that limit managerial adoption. This study contributes by reframing delay tolerance as an explicit, actionable routing criterion.

5. Methodology and Mathematical Formulation

5.1 Research Design

The study adopts a simulation-based analytical approach to evaluate routing trade-offs under controlled and reproducible conditions. A synthetic logistics network is used to identify systemic patterns rather than route-specific predictions.

Simulation is employed to isolate systemic routing trade-offs without the confounding effects of firm-specific operational policies or proprietary datasets. The use of synthetic data enables controlled experimentation across a large number of shipments, allowing the study to identify consistent patterns rather than route-specific outcomes.

5.2 Network and Trip Generation

A set of major Indian cities is treated as logistics hubs. A total of 500 origin–destination pairs are randomly generated, with payload weights ranging from 10 to 35 tons to reflect typical heavy-duty truck operations.

5.3 Route Alternatives

For each shipment, two routing options are evaluated:

- **Fastest Path:** Baseline route minimizing travel time.
- **Shortest Path:** Alternative route minimizing distance, potentially incurring additional travel time.

Shortest-path distances are modeled as a 5–15% reduction relative to fastest-path distances, while travel times are modeled with a 10–25% penalty to reflect lower speeds and congestion.

5.4 Emissions and Cost Estimation

Carbon emissions are estimated using a standard heavy-duty truck emission factor of 0.062 kg CO_2 per ton-kilometer. Fuel cost savings are approximated using a distance-based proxy with an assumed fuel efficiency of 3 km per liter and a fuel price of ₹90 per liter. These estimates are intended for relative comparison rather than precise fuel accounting.

5.5 SLA Constraint and Decision Rule

An explicit Maximum Allowed Delay (MAD) of 5 hours is introduced. Routing decisions follow a simple rule:

- If the additional delay incurred by the shortest path is less than or equal to MAD, the shortest path is selected.
- Otherwise, the fastest path is retained.

This rule operationalizes the *Cost of Speed* concept while preserving delivery reliability.

5.6 Cost of Speed Formulation

- ΔD = Distance difference
- ΔT = Time difference
- ΔC = Cost difference
- ΔE = Emissions difference

$$\Delta E = (D\_fast - D\_short) \times W \times EF$$

6. Results and Discussion

6.1 Aggregate Results

Across 500 simulated shipments, the framework indicates a total CO_2 reduction potential of approximately 108 tons and estimated fuel cost savings of approximately ₹23 lakhs. These gains are achieved without any observed SLA breaches under the defined MAD constraint.

6.2 Distributional Effects

Most optimized shipments exhibit CO_2 savings in the range of 100–200 kg, suggesting that benefits are distributed across the network rather than concentrated in a small number of extreme cases.

6.3 Interpretation

The results highlight the inefficiency of default speed-first routing logic. In many cases, modest delivery delays unlock meaningful cost and emissions savings, challenging the assumption that fastest routes always provide superior value.

7. Managerial Implications

The Green & Lean framework can be implemented within existing transportation management systems without additional capital investment. By formalizing delay tolerance, logistics managers can systematically capture cost and sustainability benefits while maintaining service reliability.

8. Limitations and Future Scope

The analysis is based on simulated data and does not incorporate real-time traffic variability or vehicle-specific fuel consumption. Future research may extend the framework using telematics data, multimodal networks, and dynamic carbon pricing.

9. Conclusion

This study demonstrates that incorporating explicit delay tolerance into routing decisions enables logistics networks to reduce both operating costs and carbon emissions without compromising SLAs. The proposed Green & Lean framework offers a practical and scalable approach to sustainable freight routing.

Appendix A: Simulation Code (Reproducibility)

To support transparency and reproducibility, the Python-based simulation code used in this study is provided below in summarized form. The complete executable notebook is available as supplementary material.

Only representative excerpts are shown for brevity.

```python
# Simulation of delay-tolerant routing trade-offs
import pandas as pd
import random
import numpy as np
import matplotlib.pyplot as plt


cities = ["Delhi", "Mumbai", "Chennai", "Kolkata", "Bangalore", "Hyderabad", "Pune",
    "Ahmedabad", "Jaipur", "Surat", "Lucknow", "Kanpur", "Nagpur", "Indore",
    "Thane", "Bhopal", "Visakhapatnam", "Patna", "Vadodara", "Ghaziabad",
    "Ludhiana", "Agra", "Nashik", "Faridabad", "Meerut", "Rajkot", "Coimbatore",
    "Bhubaneswar", "Guwahati", "Chandigarh"]


NUM_TRIPS = 500
EMISSION_FACTOR = 0.062
FUEL_PRICE = 90
random.seed(42)


# Data generation loop omitted for brevity; full version available via hyperlink
```

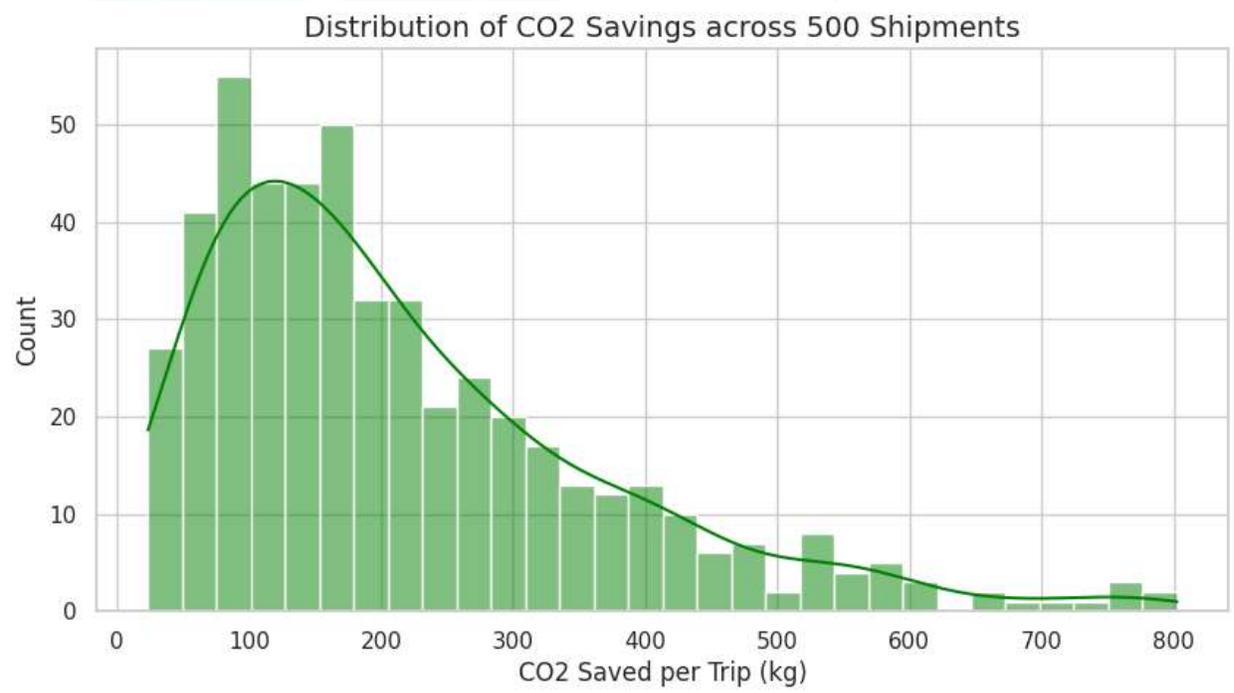Cell Output :

Simulating 500 logistics trips across India...

SIMULATION COMPLETE

Total Trips Audited: 500

Total CO2 Reduction Potential: 108,032.14 kg

Total Est. Fuel Cost Savings: ₹2,301,881.09

File 'Logistics_TradeOff_Analysis_500.csv' saved successfully!

The Cost of Speed: CO2 Savings vs. Time Penalty

Distribution of CO2 Savings across 500 Shipments

Supplementary Material:

Google Colab notebook (public):

https://colab.research.google.com/drive/1nqz8pLtN0um72y1st9IUyrPrf0ZzB-xF?usp=sharing

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