

Optimizing the Domestic Distribution of Packaged Tea in India: A Transportation Problem Approach to Reducing FMCG Supply Chain Costs and Emissions

Arav Gupta¹, Aryan Agarwal², Arjun Narula³, Arnav Shah⁴

^{1,2,3,4} Anil Surendra Modi School of Commerce (ASMSOC), SVKM's NMIMS, Mumbai, Maharashtra India

Abstract—Background. Freight is one of the largest controllable costs in the supply chains of fast-moving consumer goods (FMCG) companies, and in India most of it moves by road. Packaged tea is a clear example. It is one of the most widely consumed FMCG categories, yet more than 80% of the crop is grown in the north-east and North Bengal, while consumption is concentrated in the north and west of the country. This paper asks how much of the cost of moving tea from gardens to consumers could be avoided by allocating supply to markets optimally, and what the answer implies for FMCG distribution planning.

Methods. The problem is formulated as a classical transportation problem with 9 producing regions and 27 consuming states and union territories. Supplies are the Tea Board's 2023 regional production less region-wise exports. Demands are the Tea Board's 2023 estimates of state-wise consumption. Route costs combine OpenStreetMap road distances with the directional zonal freight rates per tonne-kilometre estimated by NCAER for the Department for Promotion of Industry and Internal Trade (DPIIT). The problem is solved with the north-west corner, least-cost and Vogel's approximation methods, improved to optimality with the modified distribution (MODI) method, and verified by linear programming. The plan is compared with a pooled proportional-sourcing benchmark that represents national blending. Extensions examine dual prices, unbalanced supply, alternative tariff structures, road-rail multimodal transport, sourcing-diversification constraints and the 2024 crop shortfall.

Results. The optimal plan costs INR 512.6 crore a year, or INR 4.41 per kg, against INR 630.5 crore (INR 5.43 per kg) under pooled sourcing. This is a saving of INR 117.9 crore (18.7%), with 16.9% fewer tonne-kilometres and 27.9 thousand tonnes less CO₂e. Vogel's method comes within 5.3% of the optimum, against 6.6% for the least-cost method and 13.4% for the north-west corner rule. From Vogel's starting solution, MODI

needs only 16 iterations to reach the optimum. The dual prices show that South Indian tea is worth INR 3.8–5.0 per kg more than Assam tea at the margin. Under shortages the western markets are the first left short. Allowing rail for long hauls reduces cost by a further 23.6% and emissions by 58.8%. Limiting any single origin to 60% of a market's supply raises cost by only 2.6%.

Conclusions. A textbook operations research model, built entirely from official data, identifies large and robust savings for an FMCG category with a sharply separated geography of production and consumption. The results show which origins should serve which markets, what each origin is worth, and how much resilience and modal shift would cost or save.

Index Terms—transportation problem; FMCG; supply chain optimization; Vogel's approximation method; MODI method; linear programming; tea; India; logistics cost

I. INTRODUCTION

Fast-moving consumer goods (FMCG) are low-value, high-volume products sold through millions of retail outlets, so their supply chains compete on cost per unit delivered (Fisher, 1997). In India the challenge is acute. Logistics costs were estimated at 7.97% of GDP in 2023–24. Road transport carries about 71% of the country's freight at a national average of INR 3.78 per tonne-kilometre, roughly twice the rail average of INR 1.96 (NCAER, 2025). The National Logistics Policy of 2022 aims to reduce these costs and to create data-driven support for logistics decisions (Ministry of Commerce and Industry, 2022; NCAER, 2025). For an FMCG company, the most direct lever is the allocation of supply points to

markets. Which plant or sourcing region should serve which market, and in what quantity?

This allocation is the transportation problem of Hitchcock (1941) and Koopmans (1949), one of the oldest and best understood models in operations research. It is still taught with the north-west corner, least-cost and Vogel's approximation methods and the modified distribution (MODI) method (Charnes and Cooper, 1954; Appa, 1973). Applied studies, however, often rely on small or invented numerical examples, which makes it hard for managers to see what the model is worth in practice. This paper applies the transportation problem to a real FMCG category at national scale, using only official data, and reports the savings, the dual prices and the effect of practical constraints.

The category studied is packaged tea. Tea is among the most widely penetrated FMCG products in India: about 88% of households consume it, and around 80% of urban and 75% of rural households now buy packaged rather than loose tea (Tea Board of India, n.d.). The national brands of the large FMCG companies and many regional packers draw on the same pool of production. India produced 1,393.7 million kg (M kg) of tea in 2023 (Tea Board of India, 2025a). Assam and North Bengal produced 1,121.9 M kg of this, or 80.5%, and the southern states 236.7 M kg. Consumption is concentrated elsewhere. The northern and western states account for 63% of the 1,197 M kg consumed in 2023, and Uttar Pradesh, Maharashtra, Gujarat and Madhya Pradesh alone consume 503 M kg (Tea Board of India, 2024). Most of the crop therefore travels more than 1,000 km to market, mostly by road, and the choice of origin for each market matters.

The paper addresses four research questions:

1. What is the minimum annual freight cost of meeting India's state-wise tea demand from its producing regions, and how much does it save compared with a pooled national sourcing pattern?
2. How close do the classical initial-solution heuristics come to the optimum, and how much work does the MODI method need to close the gap?
3. What do the dual prices reveal about the value of each producing region and the cost of serving each market?

4. How do the cost structure, a road-rail multimodal option, sourcing-diversification requirements and supply shortfalls change the optimal plan?

The paper makes four contributions. First, it builds a national transportation problem for an FMCG category entirely from official sources. Supply and demand come from the Tea Board of India, distances from OpenStreetMap routing, and freight rates from the 2025 DPIIT-NCAER logistics cost assessment, including its directional zonal matrix. Second, it compares the classical solution methods on this real instance and confirms the optimum by linear programming. Third, it interprets the dual prices as location rents of origins and marginal delivered costs of markets, linking the model to spatial price equilibrium (Samuelson, 1952). Fourth, it quantifies four practical extensions: unbalanced supply, tariff and mode structure, multi-sourcing for resilience, and the 2024 supply shortfall.

Section 2 reviews the literature. Section 3 describes the data, Section 4 the model and solution methods, and Section 5 the results. Section 6 discusses implications and limitations, and Section 7 concludes.

II. LITERATURE REVIEW

2.1 The transportation problem

The problem of shipping a homogeneous product from several sources with known supplies to several destinations with known demands at minimum cost was first formulated by Hitchcock (1941). Koopmans (1949) studied it independently in the context of wartime shipping. Dantzig (1951) showed that the simplex method can be specialized to its structure, and Charnes and Cooper (1954) gave the stepping-stone interpretation of the simplex iterations. Ford and Fulkerson (1956) proposed a primal-dual algorithm, and Orden (1956) extended the model to transshipment through intermediate nodes. Because the constraint matrix is totally unimodular, the problem has integral optimal solutions whenever supplies and demands are integral. Its dual has a natural economic reading as the prices that would prevail in a competitive spatial market (Samuelson, 1952; Takayama and Judge, 1964). Appa (1973) surveys its many variants, including unbalanced, capacitated and fixed-charge problems. The fixed-

charge version, in which opening a route incurs a set-up cost, remains an active topic (Adlakha and Kowalski, 2003).

2.2 Initial solutions and the MODI method

The transportation simplex starts from a basic feasible solution with $m + n - 1$ basic cells and improves it with the $u-v$ potentials of the MODI method until all reduced costs are non-negative. The quality of the starting solution therefore determines how many iterations are needed. The north-west corner rule ignores costs. The least-cost method allocates greedily to the cheapest cell. Vogel's approximation method (VAM), introduced by Reinfeld and Vogel (1958), allocates first to the row or column with the largest penalty, which is the difference between its two lowest costs. Numerous refinements have been proposed. Shimshak et al. (1981) modify the tie-breaking rules of VAM, Kirca and (1990) propose a total-opportunity-cost heuristic, Mathirajan and Meenakshi (2004) compare variants of VAM experimentally, and Juman and Hoque (2015) propose a further heuristic and test it on benchmark problems. Most such comparisons use randomly generated or small textbook instances, often produced with generators such as NETGEN (Klingman et al., 1974). Evidence on large real instances with a real cost structure is scarce.

2.3 Supply chain network design and FMCG distribution

At the strategic level, the transportation problem is the allocation core of supply chain network design, in which location decisions fix the sources and the transportation problem assigns flows (Melo et al., 2009). Fisher (1997) argues that functional products with stable, predictable demand, which describes most FMCG, need efficient supply chains that minimize physical cost, as opposed to responsive ones. For retail supply chains, Benrqa (2019) quantifies the trade-off between transport, inventory and handling costs in cross-docking. Agricultural FMCG categories such as tea add the constraint that supply is fixed by geography and season. Studies of the tea value chain in India document the dominance of Assam and the role of small growers (Das and Mishra, 2019), but they do not optimize distribution.

2.4 Multimodal, green and resilient logistics

SteadieSeifi et al. (2014) review multimodal freight planning and show that rail and water can reduce cost and emissions on long hauls, provided first- and last-mile road legs and terminal handling remain small. For India, the DPIIT–NCAER assessment finds that road–rail–road movement becomes cheaper than road beyond about 600 km (NCAER, 2025), and NITI Aayog and RMI argue for a large shift of freight to rail (NITI Aayog et al., 2021). Dekker et al. (2012) survey operations research models that add environmental objectives to logistics decisions. On resilience, Tomlin (2006) shows that sourcing from several suppliers is a valuable mitigation strategy when supply is unreliable, at the price of higher cost in normal times. Agricultural supply such as tea fluctuates from year to year, so this trade-off applies directly.

2.5 Positioning of this study

Table 1 summarizes how this study relates to the literature. Its contribution is not a new algorithm. It applies the classical theory to a real national FMCG instance built from official data and directional freight rates, interprets the dual prices for that instance, and quantifies practical extensions that the textbook formulation omits.

Table 1. Representative studies and the questions they address.

Study	Focus	Relation to this paper
Hitchcock (1941); Koopmans (1949)	Formulation of the transportation problem	Model used here
Charnes and Cooper (1954); Ford and Fulkerson (1956)	Exact solution methods	MODI/stepping stone used and verified by LP
Reinfeld and Vogel (1958); Mathirajan and Meenakshi (2004); Juman and Hoque (2015)	Initial-solution heuristics	Compared on a real national instance
Samuelson (1952)	Spatial prices and duality	Duals read as location rents and delivered costs
Melo et al.	Network	FMCG allocation

Study	Focus	Relation to this paper
(2009); Fisher (1997)	design; efficient supply chains	layer
SteadieSeifi et al. (2014); NCAER (2025)	Multimodal freight	Road–rail option with Indian cost curves
Tomlin (2006)	Disruption and multi-sourcing	Diversification constraint and 2024 shortfall
This study	Packaged tea, India, 9 origins × 27 markets	Official data; methods, duals, extensions

III. DATA

All inputs are taken from official or peer-reviewed sources and are listed in Table 3. Quantities are in million kilograms (M kg), equivalent to thousand tonnes (kt). Costs are in Indian rupees (INR); one crore is 10^7 .

3.1 Supply

Supply is the Tea Board's 2023 production by producing region (Tea Board of India, 2025a). North India comprises Assam Valley, Cachar, Dooars, Terai, Darjeeling and the other northern states, which the Tea Board reports as one group. South India comprises Tamil Nadu, Kerala and Karnataka. Part of the crop is exported. The Tea Board reports 2023 exports of 141.00 M kg from North India and 90.69 M kg from South India (Tea Board of India, 2025b). Exports are not reported by sub-region, so each region's exports are deducted from its sub-regions in proportion to their production. This leaves 87.8% of North Indian and 61.7% of South Indian output for the domestic market. Each region is represented by the town at the centre of its growing area: Jorhat, Silchar, Jalpaiguri, Siliguri, Darjeeling, Coonoor, Munnar and Chikkamagaluru. The "other North India" group is placed at Guwahati, the hub of the north-east, and Section 5.5 tests alternative locations. Table 2 lists the resulting supplies, which total 1,161.97 M kg.

Table 2. Origins: 2023 production, domestic supply after exports and optimal dual price (location rent relative to Assam Valley).

Origin	Node	Region	Cost zone	Production (M kg)	Domestic supply (M kg)	u_i (INR/t)
Assam Valley	Jorhat	North	North-east	649.15	570.04	0
Cachar	Silchar	North	North-east	39.18	34.41	−1,192
Dooars	Jalpaiguri	North	East	237.71	208.74	−2,700
Terai	Siliguri	North	East	189.82	166.69	−2,820
Darjeeling	Darjeeling	North	East	6.01	5.28	−2,719
Other North India	Guwahati	North	North-east	35.11	30.83	−1,331
Tamil Nadu	Coonoor	South	South	167.40	103.26	−4,089
Kerala	Munnar	South	South	63.75	39.32	−3,827
Karnataka	Chikkamagaluru	South	South	5.53	3.41	−5,032
Total				1,393.66	1,161.97	

3.2 Demand

Demand is taken from the Tea Board's domestic consumption study, which surveyed 8,500 households and also covered institutions and trade channels. It estimates total consumption in 2023 at 1,197.3 M kg and reports consumption for each state and union-territory group (Tea Board of India, 2024). Each of the 27 markets is represented by its capital or principal city. The Andaman and Nicobar Islands (0.3 M kg, 0.03% of the total) have no road connection and are excluded. Demand in the 27 markets is

1,196.97 M kg, which exceeds domestic supply by 35.0 M kg (2.9%). The gap is consistent with imports and stock changes, which the official statistics do not attribute to states. In the base case, all demands are scaled by the factor 0.9708 so that the problem is balanced. Section 5.4 solves the unbalanced problem with a dummy origin instead. Table 6 in Section 5 lists the demands.

3.3 Distances

Road distances between the 9 origin nodes and the 27 market nodes were computed with the Open-Source Routing Machine on OpenStreetMap data (Luxen and Vetter, 2011). These are the shortest road routes, not straight-line approximations. The 243 distances range from 0 km (the Guwahati node, which is both an origin and a market) to 3,425 km. The demand-weighted mean distance from the largest origin, Assam Valley, is 2,063 km.

3.4 Freight rates

The DPIIT–NCAER study surveyed road transport operators across India and reports average costs per tonne-kilometre for movements between five regional zones (NCAER, 2025, Table 4.4). The matrix is directional. For example, freight from the north-east to the west costs INR 2.93 per tonne-km, while freight in the opposite direction costs INR 3.03, and movements within a zone cost INR 3.50–5.01 because they are shorter. Each origin and market is assigned to a zone: Assam and the other north-eastern states to North-east; North Bengal, Bihar, Jharkhand, Odisha and West Bengal to East; and the remaining states as in the Tea Board study. The cost of route (i, j) in INR per tonne is the road distance multiplied by the zonal rate for its direction. For the sensitivity analysis we also use the study's national average of INR 3.78 per tonne-km. We also use its distance-band costs for all-road and road–rail–road movement, in which the rail haul is preceded and followed by 50 km of road (NCAER, 2025, Figure 4.15).

3.5 Emissions

Emissions are estimated with the UK government's 2025 conversion factors (DESNZ, 2025): 0.07800 kg CO₂e per tonne-km for articulated heavy goods vehicles at average load and 0.02779 kg for freight trains. India-specific factors by vehicle class are not officially published, so these factors are used for both modes. The ratio between road and rail factors is more reliable than their absolute levels.

Table 3. Model inputs and sources.

Input	Value	Source
Production by region, 2023	9 regions, 1,393.66 M kg	Tea Board of India (2025a)
Exports by	North 141.00,	Tea Board of India

Input	Value	Source
region, 2023	South 90.69 M kg	(2025b)
Consumption by state, 2023	27 markets, 1,196.97 M kg	Tea Board of India (2024)
Road distances	OSRM shortest road route, 243 pairs	Luxen and Vetter (2011)
Road freight rates	Directional 5 × 5 zonal matrix, INR 2.32–5.01/t-km	NCAER (2025, Table 4.4)
National average road rate	INR 3.78/t-km	NCAER (2025)
Distance-band rates	All-road and road–rail–road, 200–3,100 km	NCAER (2025, Figure 4.15)
Emission factors	HGV 0.07800; rail 0.02779 kg CO ₂ e/t-km	DESNZ (2025)
Supply shock	2024 production 1,284.78 M kg; exports 256.17 M kg	Tea Board of India (2025a), Tea Board of India (2025b)

IV. MODEL AND SOLUTION METHODS

4.1 Formulation

Let I be the set of $m = 9$ origins with supplies s_i and J the set of $n = 27$ markets with demands d_j , where $\sum_i s_i = \sum_j d_j$. Let c_{ij} be the cost per tonne of the route from i to j , and let $x_{ij} \geq 0$ be the quantity shipped. The transportation problem is

$$\begin{aligned} \min \quad & Z = \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} \quad (1) \\ \text{s.t.} \quad & \sum_{j \in J} x_{ij} = s_i \quad \forall i \in I \quad (2) \\ & \sum_{i \in I} x_{ij} = d_j \quad \forall j \in J \quad (3) \\ & x_{ij} \geq 0 \quad \forall i \in I, j \in J. \end{aligned}$$

The model has 243 variables and 36 constraints, one of which is redundant, so a basic solution has $m + n - 1 = 35$ basic cells.

4.2 Dual and economic interpretation

The dual of 1–3 is

$$\max \sum_i s_i u_i + \sum_j d_j v_j \quad \text{s.t.} \quad u_i + v_j \leq c_{ij} \quad \forall i, j, \quad (4)$$

with u_i and v_j free. At the optimum, $u_i + v_j = c_{ij}$ on every route used. Because one constraint is redundant, the potentials are defined only up to a constant. We normalise $u_{\text{Assam Valley}} = 0$, so that Assam Valley, the largest origin, acts as the marginal source. Then v_j is the marginal cost of serving one more tonne in market j , and $-u_i$ is the saving from one more tonne of supply at origin i compared with Assam Valley, which is the location rent of that origin. In a competitive spatial market, these are the price differentials that would make the observed flows an equilibrium (Samuelson, 1952; Takayama and Judge, 1964).

4.3 Solution methods

Three initial basic feasible solutions are constructed: the north-west corner rule (NWCR), the least-cost method (LCM) and Vogel's approximation method (VAM) (Reinfeld and Vogel, 1958). Each is then improved with the MODI method. The potentials u_i, v_j are computed from the basic cells, the cell with the most negative reduced cost $c_{ij} - u_i - v_j$ enters the basis, and the stepping-stone cycle determines the leaving cell (Charnes and Cooper, 1954). Iterations stop when no reduced cost is negative. Degenerate bases are completed with zero-valued cells so that the basis always forms a spanning tree. The optimum is verified independently by solving the linear program with the CBC solver (Forrest and Lougee-Heimer, 2005) through PuLP (Mitchell et al., 2011), whose dual values are compared with the MODI potentials.

4.4 Benchmark

Actual flows of tea between Indian states are not published. As a benchmark we therefore use pooled proportional sourcing, $x_{ij}^p = d_j s_i / \sum_k s_k$, in which every market draws from every origin in proportion to that origin's share of national supply. This represents a supply chain in which tea is bought from a national pool, as through the auction system, and blended into national brands without regard to where each lot is sent. The comparison measures the value of allocating origins to markets deliberately. It does

not measure the inefficiency of any particular company, many of which already source regionally.

4.5 Extensions

1. Unbalanced supply. A dummy origin with zero cost supplies the 35.0 M kg deficit. Its allocation shows which markets are cheapest to leave to imports or stock.
2. Tariff and mode structure. The problem is resolved with the national flat rate, with the distance-band road tariff, and with the cheaper of road and road-rail-road for each route under the distance-band tariffs.
3. Sourcing diversification. The constraint $x_{ij} \leq \beta d_j$ limits the share of any market's demand that a single origin can supply, for β from 1 down to 0.4.
4. Supply shortfall. The problem is re-solved with the actual 2024 production (1,284.78 M kg) and exports (256.17 M kg), which reduce domestic supply by 11.5%.

V. RESULTS

5.1 Comparison of solution methods

Table 4 and Figure 1 compare the solution methods. All three starting solutions, once improved by MODI, reach the same optimum of INR 512.62 crore. CBC reaches the same value, and its duals equal the MODI potentials to within INR 0.0001 per tonne. The starting solutions differ considerably. The north-west corner rule, which ignores costs, starts 13.4% above the optimum and needs 35 MODI iterations. The least-cost method starts 6.6% above and needs 27 iterations. Vogel's method starts 5.3% above and needs only 16. This ordering matches the experimental evidence on random instances (Mathirajan and Meenakshi, 2004; Juman and Hoque, 2015), and the gap between VAM and the optimum, about INR 27 crore a year, shows that the improvement phase still matters in practice. The optimal solution is non-degenerate and uses exactly 35 of the 243 possible routes. Every instance solves in a few milliseconds.

Table 4. Solution methods on the base instance
(annual freight cost, INR crore).

Method	Initial cost	Gap to optimum	MODI iterations	Final cost
North-west corner rule	581.53	13.4%	35	512.62
Least-cost method	546.41	6.6%	27	512.62
Vogel's approximation method	539.60	5.3%	16	512.62
Linear programming (CBC)	—	—	—	512.62
Pooled proportional sourcing (benchmark)	630.50	23.0%	—	—

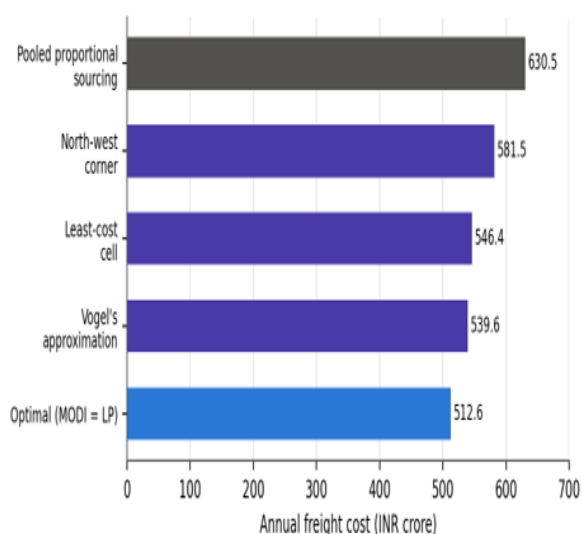


Figure 1. Annual freight cost of the benchmark, the three initial solutions and the optimum.

5.2 The optimal distribution plan

The optimal plan costs INR 512.62 crore a year, or INR 4.41 per kg delivered. Pooled proportional sourcing costs INR 630.50 crore (INR 5.43 per kg). Optimization therefore saves INR 117.88 crore a year (18.7%). Freight tonne-kilometres fall from 2.115 billion to 1.758 billion (16.9%), the average haul from 1,821 km to 1,513 km, and road emissions from 165.0 to 137.1 kt CO₂e. For comparison, the average 2023 export unit value of Indian tea was INR 265.91 per kg (Tea Board of India, 2025b), so the optimal freight cost is about 1.7% of product value. Figure 2 maps the optimal flows, and Table 5 lists the 35 routes used.

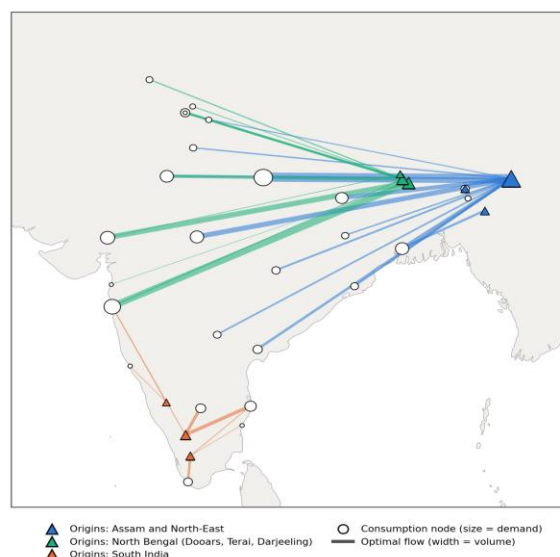


Figure 2. Optimal flows of tea from producing regions (triangles) to consuming markets (circles). Line width is proportional to volume. Coastline only; national and state boundaries are not shown.

Table 5. Routes used in the optimal plan.

Origin	Market	M kg	km	INR/t	Origin	Market	M kg	km	INR/t
Assam Valley	Delhi	18.74	2,054	6,552	Dooars	Gujarat	92.77	2,062	5,195
Assam Valley	Uttar Pradesh	170.08	1,565	4,991	Dooars	Maharashtra	115.45	2,203	5,550
Assam Valley	Rajasthan	24.34	2,140	6,825	Dooars	West (other UTs)	0.52	2,202	5,548
Assam Valley	Uttarakhand	11.61	2,119	6,760	Terai	Punjab	33.88	1,577	4,384
Assam Valley	Madhya Pradesh	86.40	2,111	6,185	Terai	Himachal Pradesh	8.99	1,680	4,671
Assam	Chhattisgarh	27.47	1,846	5,408	Terai	Rajasthan	58.37	1,441	4,005

Origin	Market	M kg	km	INR/t	Origin	Market	M kg	km	INR/t
Valley									
Assam Valley	Bihar	71.16	1,125	3,476	Terai	Haryana	36.50	1,577	4,384
Assam Valley	West Bengal	49.76	1,022	3,159	Terai	Jammu and Kashmir	16.08	1,889	5,252
Assam Valley	Jharkhand	18.81	1,295	4,000	Terai	North (other UTs)	1.40	1,577	4,384
Assam Valley	Odisha	24.37	1,454	4,493	Terai	Maharashtra	11.47	2,155	5,431
Assam Valley	North East (other)	7.32	364	1,826	Darjeeling	Gujarat	5.28	2,054	5,177
Assam Valley	Telangana	23.01	2,446	6,898	Other N. India	Assam	28.15	0	0
Assam Valley	Andhra Pradesh	36.99	2,227	6,279	Other N. India	North East (other)	2.68	99	495
Cachar	West Bengal	34.41	637	1,967	Tamil Nadu	Tamil Nadu	54.26	543	2,377
Kerala	Tamil Nadu	5.64	603	2,639	Tamil Nadu	Karnataka	43.49	319	1,396
Kerala	Kerala	32.62	261	1,143	Tamil Nadu	Maharashtra	5.51	1,213	4,162
Kerala	South (other UTs)	1.07	483	2,116	Karnataka	Maharashtra	1.25	938	3,218
					Karnataka	Goa	2.16	440	1,509

The structure of the plan is clear. Assam Valley supplies 570.0 M kg to the Gangetic plain (Uttar Pradesh, Bihar, Delhi, Uttarakhand), the east (West Bengal, Jharkhand, Odisha), central India (Madhya Pradesh, Chhattisgarh) and the Telugu states. Terai supplies the north-west (Punjab, Haryana, Himachal Pradesh, Jammu and Kashmir and most of Rajasthan). Dooars and Darjeeling supply the western coast (Gujarat and most of Maharashtra). South Indian tea stays in the south, serving Tamil Nadu, Karnataka, Kerala, Goa and Puducherry, with a small surplus to Maharashtra. Cachar's output goes to Kolkata. Geography and the directional rates together explain this pattern. Jalpaiguri is about 650 km closer to Mumbai by road than Jorhat, and westbound freight from the East zone costs INR 2.52 per tonne-km against INR 2.93 from the North-east, so North Bengal tea is best used for the long western hauls.

The saving comes mostly from the south and the north-west. Under pooled sourcing, Kerala's market receives 49% of its tea from Assam Valley, 3,425 km away. In the optimal plan its delivered freight cost falls from INR 7.68 to INR 1.14 per kg. Figure 3 shows that the plan is system-optimal rather than optimal for every market. Eight markets, including Telangana, Andhra Pradesh, Madhya Pradesh and Delhi, pay more freight per kg than under pooling.

Their tea now comes entirely from Assam Valley, because the closer southern and North Bengal supplies are worth more elsewhere.

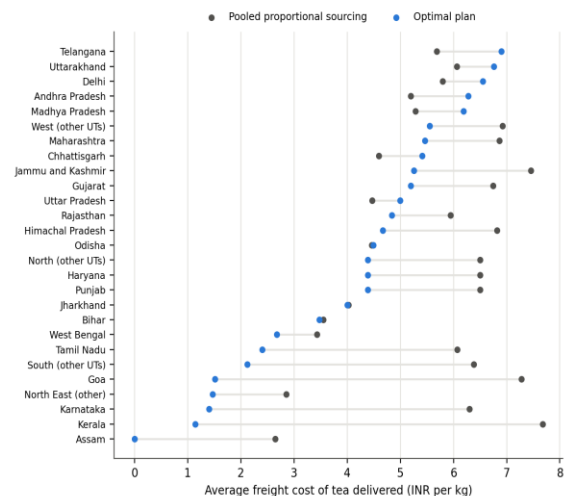


Figure 3. Average freight cost per kg of tea delivered to each market, under pooled sourcing and the optimal plan.

5.3 Dual prices

The origin potentials in Table 2 measure the location rent of each producing region relative to Assam Valley. One additional tonne of tea available in Karnataka would reduce national freight cost by INR 5,032 more than one additional tonne in Assam

Valley. The corresponding figures are INR 4,089 for Tamil Nadu, INR 3,827 for Kerala and INR 2,700–2,820 for the North Bengal regions. Per kilogram, South Indian tea is therefore worth INR 3.8–5.0 more than Assam tea at the margin purely because of location. This figure is comparable to the total freight cost of INR 4.41 per kg. Origins with a high location rent are the ones for which raising domestic availability saves the most freight, for instance by exporting less from them or by increasing their output.

The market potentials v_j in Table 6 give the marginal cost of serving one more tonne in each market. They are highest in the west, at INR 8,250 per tonne for Maharashtra, INR 8,248 for Daman and INR 7,895 for Gujarat, and in Jammu and Kashmir (INR 8,071). They are lowest in Assam (INR 1,331) and the other north-eastern states (INR 1,826). An FMCG company that sets uniform national prices therefore cross-subsidises its western and north-western markets. Any additional demand in those markets costs nearly twice the national average freight per kg to serve.

v_j Table 6. Markets: 2023 consumption, balanced demand, marginal delivered cost () and average freight cost per kg under pooled sourcing and the optimal plan.

Market	Node	Consumption (M kg)	Demand (M kg)	v_j (INR/t)	Freight (INR/kg)		Main origin
					Pooled	Optimal	
Delhi	New Delhi	19.30	18.74	6,552	5.80	6.55	Assam Valley
Uttar Pradesh	Lucknow	175.20	170.08	4,991	4.47	4.99	Assam Valley
Punjab	Chandigarh	34.90	33.88	7,203	6.50	4.38	Terai
Himachal Pradesh	Shimla	9.26	8.99	7,491	6.82	4.67	Terai
Rajasthan	Jaipur	85.20	82.71	6,825	5.94	4.84	Terai
Haryana	Chandigarh	37.60	36.50	7,203	6.50	4.38	Terai
Jammu and Kashmir	Jammu	16.56	16.08	8,071	7.46	5.25	Terai
Uttarakhand	Dehradun	11.96	11.61	6,760	6.06	6.76	Assam Valley
North (other UTs)	Chandigarh	1.44	1.40	7,203	6.50	4.38	Terai
Gujarat	Gandhinagar	101.00	98.05	7,895	6.74	5.19	Dooars
Madhya Pradesh	Bhopal	89.00	86.40	6,185	5.28	6.19	Assam Valley
Chhattisgarh	Raipur	28.30	27.47	5,408	4.59	5.41	Assam Valley
Maharashtra	Mumbai	137.70	133.67	8,250	6.87	5.46	Dooars
Goa	Panaji	2.23	2.16	6,542	7.28	1.51	Karnataka
West (other UTs)	Daman	0.54	0.52	8,248	6.92	5.55	Dooars
Assam	Guwahati	29.00	28.15	1,331	2.65	0.00	Other N. India
Bihar	Patna	73.30	71.16	3,476	3.55	3.48	Assam Valley
West Bengal	Kolkata	86.70	84.16	3,159	3.43	2.67	Assam Valley

Jharkhand	Ranchi	19.38	18.81	4,000	4.02	4.00	Assam Valley
Odisha	Bhubaneswar	25.10	24.37	4,493	4.46	4.49	Assam Valley
North East (other)	Shillong	10.30	10.00	1,826	2.85	1.47	Assam Valley
Tamil Nadu	Chennai	61.70	59.90	6,466	6.07	2.40	Tamil Nadu
Karnataka	Bengaluru	44.80	43.49	5,485	6.30	1.40	Tamil Nadu
Kerala	Thiruvananthapuram	33.60	32.62	4,970	7.68	1.14	Kerala
Telangana	Hyderabad	23.70	23.01	6,898	5.68	6.90	Assam Valley
Andhra Pradesh	Vijayawada	38.10	36.99	6,279	5.20	6.28	Assam Valley
South (other UTs)	Puducherry	1.10	1.07	5,943	6.38	2.12	Kerala

5.4 Unbalanced supply and the 2024 shortfall

When the 35.0 M kg deficit is left unscaled and supplied by a zero-cost dummy origin, the whole shortfall falls on Maharashtra, the market with the highest marginal delivered cost. The cost of the remaining flows is INR 504.38 crore. In 2024 domestic supply fell to 1,028.61 M kg, because production fell by 7.8% and exports rose by 10.6% (Tea Board of India, 2025a; Tea Board of India, 2025b). Against unchanged demand, the shortfall is 168.4 M kg. The optimal response leaves Maharashtra entirely to other sources (137.7 M kg), followed by Jammu and Kashmir (16.6), Gujarat (13.6) and Daman (0.5). The ordering follows the marginal costs in Table 6. When the domestic crop is short, the western and far-northern markets are the ones that imports, stocks or price-driven demand adjustments should serve first.

5.5 Tariff structure and multimodal transport

Table 7 reports the optimal plan under alternative cost structures. With the national flat rate of INR 3.78 per tonne-km, the optimizer chooses a different plan, moving 401.6 M kg to different routes. Evaluated at the directional zonal rates, that plan costs 0.4% more than the true optimum. Ignoring the directional structure of Indian freight rates is therefore only a small error at national scale, though not zero. A planner who uses the distance-band road tariff instead obtains a plan that costs 3.9% more at zonal rates. Under every road tariff, optimization saves 16.9–19.1% compared with pooled sourcing.

When each route can use the cheaper of road and road–rail–road movement at DPIIT’s distance-band costs, 83.8% of the tonnage moves by rail. Freight cost falls to INR 409.2 crore, 23.6% below the all-road optimum under the same distance-band tariff, and emissions fall from 137.3 to 56.6 kt CO₂e (58.8%). This is an upper bound. The DPIIT study cautions that rail’s theoretical advantage is often not realised for fragmented general cargo, because first- and last-mile costs and handling delays erode it (NCAER, 2025). The bound is nonetheless large enough to justify trials of consolidated rail movement on the longest corridors, from North Bengal and Assam to Gujarat, Maharashtra and the north-west.

Table 7. Optimal plans under alternative freight cost structures (INR crore per year).

Cost structure	Optimal cost	Pooled cost	Saving	Cost at zonal rates
Directional zonal road rates (base)	512.62	630.50	18.7%	512.62
Flat national road rate (INR 3.78/t-km)	664.52	799.64	16.9%	514.76
Distance-band road rates	535.34	662.06	19.1%	532.74
Best of road and road–rail–road (distance)	409.21	481.53	15.0%	–

Cost structure	Optimal cost	Pooled cost	Saving	Cost at zonal rates
bands)				
Location of the “other North India” origin: Agartala 18.8%, Siliguri 18.7% saving (base Guwahati 18.7%)				

5.6 The cost of sourcing diversification

The optimal plan serves 21 of the 27 markets from a single origin, which leaves them exposed to a crop failure, strike or flood in that region. Figure 4 shows the minimum cost when no origin may supply more than a share β of any market. Diversification is inexpensive at first. Capping any origin at 90% of a market raises cost by 0.3%, at 70% by 1.6% and at 60% by 2.6%, and the number of routes used rises from 35 to 60–62. The cost then rises more steeply, to 5.3% at $\beta = 0.5$. Below 49% the problem is infeasible, because Assam Valley alone holds 49.1% of domestic supply and could not ship all of it under such a cap. In the terms of Tomlin (2006), the 60% cap buys substantial mitigation for a premium of INR 13.3 crore a year, about 11% of the saving that optimisation delivers.

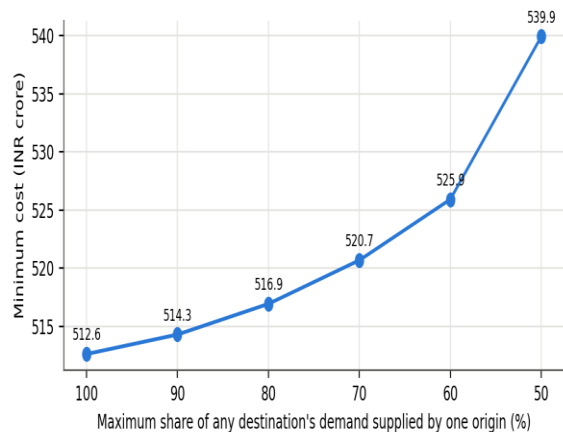


Figure 4. Minimum annual freight cost when no single origin may supply more than a given share of any market's demand.

VI. DISCUSSION

6.1 Managerial implications for FMCG companies

Allocation is worth about a fifth of freight cost. For a category with a sharply separated geography of production and consumption, deliberate origin-to-market allocation reduces freight cost by 18.7% compared with pooled sourcing. At the national scale

of the tea market this is INR 117.9 crore a year, achieved without new assets. For an individual FMCG company the absolute figure scales with its volume, but the percentage applies to any company whose blending and sourcing ignore destination.

Regionalised sourcing rules are simple to implement. The optimal plan reduces to a few rules that a procurement team can apply directly. South Indian tea stays in the south. Terai serves the north-west. Dooars and Darjeeling serve the western coast. Assam Valley serves the Gangetic plain, the east, central India and the Telugu states. Where blend specifications allow, packers can buy at the auction centres that serve each zone and blend for regional rather than national formulations.

Dual prices support pricing and procurement decisions. The market potentials show where freight-to-serve is highest, which bears on regional price differentiation and on where to locate packing capacity. The origin rents show how much more a kilogram of southern or North Bengal tea is worth to the domestic system than a kilogram of Assam tea. That premium is relevant both to procurement bids and to decisions about which teas to export.

Resilience is cheap at moderate levels. A 60% cap on dependence on any origin costs 2.6% more. This is a modest insurance premium for an agricultural supply chain exposed to weather and floods, of the kind seen in the 11.5% fall in domestic supply in 2024.

Modal shift is the next frontier. The road–rail option could cut a further quarter of freight cost and more than half of emissions in theory. Realising even part of it requires consolidation at origin hubs such as Guwahati and Siliguri, and rail-linked distribution centres in the west and north, in line with the National Logistics Policy (Ministry of Commerce and Industry, 2022).

6.2 Methodological implications

On this real instance, Vogel's method was the best of the classical heuristics, as on random benchmarks (Mathirajan and Meenakshi, 2004). However, its 5.3% gap would cost INR 27 crore a year if it were used without the MODI improvement. Because the exact optimum takes milliseconds to compute, the textbook heuristics are best treated as teaching tools and starting points, not as planning methods. The duals, which the heuristics alone do not provide, carry much of the managerial insight.

6.3 Limitations

- **Aggregation.** Origins and markets are represented by single nodes. Intra-state distribution, packing locations and the auction stage are not modelled. One artefact is that the Guwahati node is both an origin and a market, so its route has zero cost.
- **Benchmark.** Actual inter-state flows are not published, so the saving is measured against pooled sourcing and not against observed practice.
- **Homogeneous product.** Tea is treated as a single product. In practice CTC, orthodox and green teas and regional flavour preferences limit substitution between origins. The diversification analysis captures this only partly.
- **Data years and balancing.** The 2023 consumption survey and production statistics come from different sources and differ by 2.9%. Imports and stocks are not attributed to states.
- **Emission factors.** UK government factors are used in the absence of official Indian factors for each vehicle class.

VII. CONCLUSION

This paper applied the classical transportation problem to the national distribution of packaged tea in India, an FMCG category whose production and consumption lie at opposite ends of the country. Supply, demand, road distances and directional freight rates were all taken from official sources. The optimal allocation costs INR 512.6 crore a year, 18.7% less than pooled national sourcing, and moves 16.9% fewer tonne-kilometres. Vogel's approximation method came within 5.3% of the optimum, and the MODI method closed the gap in 16 iterations. The dual prices identify the location rent of each producing region and the marginal cost of serving each market. They show that the western markets are the first to be left short when supply falls, as happened in 2024. Diversifying supply is inexpensive up to a 60% cap on any single origin. A shift of long hauls to rail could cut freight cost by about a further quarter and emissions by more than half.

Several extensions would strengthen the analysis. Packing plants and auction centres could be modelled as transshipment nodes (Orden, 1956) with fixed opening costs. Tea grades and blend requirements could be represented as a multi-commodity problem. Seasonal production and inventory could be modelled over several periods. If company-level flow data became available, the benchmark could be replaced with observed practice. The same approach applies to other FMCG categories whose raw materials are concentrated in a few regions, such as edible oils, spices and coffee.

REFERENCES

- [1]. Adlakha, V., & Kowalski, K. (2003). A simple heuristic for solving small fixed-charge transportation problems. *Omega*, 31(3), 205–211. [https://doi.org/10.1016/S0305-0483\(03\)00025-2](https://doi.org/10.1016/S0305-0483(03)00025-2)
- [2]. Appa, G. M. (1973). The transportation problem and its variants. *Operational Research Quarterly*, 24(1), 79–99. <https://doi.org/10.1057/jors.1973.10>
- [3]. Benrqya, Y. (2019). Costs and benefits of using cross-docking in the retail supply chain. *International Journal of Retail & Distribution Management*, 47(4), 412–432. <https://doi.org/10.1108/IJRDM-07-2018-0119>
- [4]. Charnes, A., & Cooper, W. W. (1954). The stepping stone method of explaining linear programming calculations in transportation problems. *Management Science*, 1(1), 49–69. <https://doi.org/10.1287/mnsc.1.1.49>
- [5]. Dantzig, G. B. (1951). Application of the simplex method to a transportation problem. In T. C. Koopmans (Ed.), *Activity analysis of production and allocation* (pp. 359–373). Wiley.
- [6]. Das, A., & Mishra, R. (2019). Value chain analysis of tea and constraints faced by the small tea growers in India with special reference to state Assam. *International Journal of Current Microbiology and Applied Sciences*, 8(12), 1592–1601. <https://doi.org/10.20546/ijemas.2019.812.191>
- [7]. Dekker, R., Bloemhof, J., & Mallidis, I. (2012). Operations research for green logistics: An overview of aspects, issues, contributions and challenges. *European Journal of Operational*

- Research, 219(3), 671–679.
<https://doi.org/10.1016/j.ejor.2011.11.010>
- [8]. Department for Energy Security and Net Zero (DESNZ) and Department for Environment, Food & Rural Affairs. (2025). Greenhouse gas reporting: Conversion factors 2025. UK Government, London.
- [9]. Fisher, M. L. (1997). What is the right supply chain for your product? *Harvard Business Review*, 75(2), 105–116.
- [10]. Ford, L. R., & Fulkerson, D. R. (1956). Solving the transportation problem. *Management Science*, 3(1), 24–32.
<https://doi.org/10.1287/mnsc.3.1.24>
- [11]. Forrest, J., & Lougee-Heimer, R. (2005). CBC user guide. In *Emerging theory, methods, and applications (INFORMS TutORials in Operations Research*, pp. 257–277). INFORMS.
<https://doi.org/10.1287/educ.1053.0020>
- [12]. Hitchcock, F. L. (1941). The distribution of a product from several sources to numerous localities. *Journal of Mathematics and Physics*, 20(1–4), 224–230.
<https://doi.org/10.1002/sapm1941201224>
- [13]. Juman, Z. A. M. S., & Hoque, M. A. (2015). An efficient heuristic to obtain a better initial feasible solution to the transportation problem. *Applied Soft Computing*, 34, 813–826.
<https://doi.org/10.1016/j.asoc.2015.05.009>
- [14]. Kirca, Ö., & Şatir, A. (1990). A heuristic for obtaining an initial solution for the transportation problem. *Journal of the Operational Research Society*, 41(9), 865–871.
<https://doi.org/10.1057/jors.1990.124>
- [15]. Klingman, D., Napier, A., & Stutz, J. (1974). NETGEN: A program for generating large scale capacitated assignment, transportation, and minimum cost flow network problems. *Management Science*, 20(5), 814–821.
<https://doi.org/10.1287/mnsc.20.5.814>
- [16]. Koopmans, T. C. (1949). Optimum utilization of the transportation system. *Econometrica*, 17 (Supplement), 136–146.
<https://doi.org/10.2307/1907301>
- [17]. Luxen, D., & Vetter, C. (2011). Real-time routing with OpenStreetMap data. In *Proceedings of the 19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems* (pp. 513–516). ACM. <https://doi.org/10.1145/2093973.2094062>
- [18]. Mathirajan, M., & Meenakshi, B. (2004). Experimental analysis of some variants of Vogel's approximation method. *Asia-Pacific Journal of Operational Research*, 21(4), 447–462.
<https://doi.org/10.1142/S0217595904000333>
- [19]. Melo, M. T., Nickel, S., & Saldanha-da-Gama, F. (2009). Facility location and supply chain management: A review. *European Journal of Operational Research*, 196(2), 401–412.
<https://doi.org/10.1016/j.ejor.2008.05.007>
- [20]. Ministry of Commerce and Industry, Government of India. (2022). National Logistics Policy. Department for Promotion of Industry and Internal Trade, New Delhi.
- [21]. Mitchell, S., O'Sullivan, M., & Dunning, I. (2011). PuLP: A linear programming toolkit for Python. Department of Engineering Science, University of Auckland.
- [22]. National Council of Applied Economic Research (NCAER). (2025). Assessment of logistics cost in India (prepared for the Logistics Division, Department for Promotion of Industry and Internal Trade). Government of India, New Delhi.
- [23]. NITI Aayog, Rocky Mountain Institute, & RMI India. (2021). Fast tracking freight in India: A roadmap for clean and cost-effective goods transport. NITI Aayog, New Delhi.
- [24]. Orden, A. (1956). The transshipment problem. *Management Science*, 2(3), 276–285.
<https://doi.org/10.1287/mnsc.2.3.276>
- [25]. Reinfeld, N. V., & Vogel, W. R. (1958). *Mathematical programming*. Prentice-Hall.
- [26]. Samuelson, P. A. (1952). Spatial price equilibrium and linear programming. *American Economic Review*, 42(3), 283–303.
- [27]. Shimshak, D. G., Kaslik, J. A., & Barclay, T. D. (1981). A modification of Vogel's approximation method through the use of heuristics. *INFOR: Information Systems and Operational Research*, 19(3), 259–263.
<https://doi.org/10.1080/03155986.1981.11731827>
- [28]. SteadieSeifi, M., Dellaert, N. P., Nuijten, W., Van Woensel, T., & Raoufi, R. (2014). Multimodal freight transportation planning: A

- literature review. *European Journal of Operational Research*, 233(1), 1–15.
<https://doi.org/10.1016/j.ejor.2013.06.055>
- [29]. Takayama, T., & Judge, G. G. (1964). Equilibrium among spatially separated markets: A reformulation. *Econometrica*, 32(4), 510–524.
<https://doi.org/10.2307/1910175>
- [30]. Tea Board of India. (n.d.). Executive summary of study on domestic consumption of tea in India. Tea Board, Kolkata.
- [31]. Tea Board of India. (2024). Executive summary: Pilot study on domestic consumption of tea in India (prepared by BDO India LLP, April 2024). Tea Board, Kolkata.
- [32]. Tea Board of India. (2025a). State wise/region wise and month wise tea production for the year 2024 and 2024–25, with 2023 (Jan–Dec). Tea Board, Kolkata.
- [33]. Tea Board of India. (2025b). Region wise tea exports during 2025 (Jan–Apr), 2024 and 2024–25 (final), with 2023 (Jan–Dec). Tea Board, Kolkata.
- [34]. Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science*, 52(5), 639–657.
<https://doi.org/10.1287/mnsc.1060.0515>