

American Journal of Economics and Business Management

Vol. 9 Issue 10 **| pp.** 1301-1312 **| ISSN:** 2576-5973

Available online @ https://www.globalresearchnetwork.us/index.php/ajebm

Article

Dispatching Terminal-Less Partial Truckloads on A Long-Haul Corridor: An Exact Set-Packing Benchmark, A Detour-Radius Filter and Anchored Large Neighbourhood Search

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Abstract: Where no less-than-truckload terminal network exists, small consignments can still share a truck if a platform assigns two to four of them to one vehicle that unloads them in sequence without rehandling. We formulate the carrier-side dispatch problem for such partial-truckload trips on a linear corridor with spur drops, en-route pickups, delivery deadlines, dynamic mass and volume limits, last-in-first-out loading, three pickup modes and a pickup time budget. Because the corridor fixes the visiting order and feasibility is hereditary, the problem is solved exactly by enumerating feasible groups and solving a set-packing model. A marginal-profit rule gives a closed-form detour radius that can filter offers. On 120 synthetic instances calibrated to the 1,250-km Tashkent–Nukus corridor in Uzbekistan, the exact method needs 40 s on average at 60 consignments. An ablation shows that trying every consignment as the trip anchor (multi-start) is what lifts greedy insertion from a 26–30% to a 4–7% mean optimality gap; ranking candidates by destination tiers makes it slightly worse. A large neighbourhood search started from anchored construction reaches a mean gap of 0.9–2.4% within a few seconds for up to 60 consignments and scales to 300 consignments. Even optimal plans leave many consignments unserved; with an unconstrained fleet 26% remain unprofitable, which supports filtering loads before they are shown to carriers.

Keywords: partial truckload; freight consolidation; pickup and delivery; LIFO loading; set packing; large neighbourhood search; digital freight platform; Central Asia.

Citation: Akhmadov, O & Ismoilova, G. Dispatching Terminal-Less Partial Truckloads on A Long-Haul Corridor: An Exact Set-Packing Benchmark, A Detour-Radius Filter and Anchored Large Neighbourhood Search. American Journal of Economics and Business Management 2026, 9(10), 1301-1312

Received: 03th Jul 2026
Revised: 18th Aug 2026
Accepted: 05th Sep 2026
Published: 26th Oct 2026

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1. Introduction

Small consignments of 50 kg to a few tonnes are expensive to move over long distances. A shipper that hires a whole truck pays for capacity it does not use, and less-than-truckload (LTL) carriers, which consolidate such consignments through terminal networks, exist only where freight density justifies the capital that those networks require. In many lower-middle-income economies the middle ground is filled informally: drivers combine several shippers' goods on one trip by phone or through brokers, without a price rule, a loading plan or a record of who carries what. Digital freight platforms could organise this practice. On a partial-truckload (PTL) trip two to four consignments travel together, are loaded in sequence and are unloaded one after another without passing through a terminal. Shared-truckload services in the United States operate this way,

carrying several shippers' partial loads in one trailer on multi-stop trips without intermediate handling [1].

Every time a truck becomes available, the platform must decide which consignments it should carry. The mass and the volume on board change at every stop and must stay within the vehicle's limits; consignments must be stacked so that each can be unloaded without moving the others; each extra stop and detour costs time and fuel and may push later drops past their deadlines; and collecting cargo from shippers' premises delays the departure of everyone else on the truck. A consignment that fits physically may still reduce the trip's profit [2].

The paper makes four contributions. First, it gives a linear formulation of the carrier-side PTL dispatch problem on a corridor with spur drops, en-route pickups, deadlines, dynamic capacity, last-in-first-out (LIFO) loading — which on a corridor reduces to pairwise incompatibilities — a stop cap, pickup modes and a pickup time budget. Second, it shows that the corridor fixes the visiting order and that feasibility is hereditary, so the problem can be solved exactly by group enumeration and set packing; this provides an exact benchmark and an exact dispatch tool for pools of a few dozen consignments. Third, it derives from a marginal-profit acceptance rule a closed-form detour radius that can serve as an offer filter, and a corrected condition for extending a trip beyond its destination. Fourth, it reports a computational study with an ablation of construction heuristics and a large neighbourhood search (LNS), calibrated to the 1,250-km Tashkent–Nukus corridor in Uzbekistan. The ablation separates the effect of multi-start anchoring from that of destination-tier rules, which the first version of this study conflated [3].

The paper is limited to dispatch. It does not model how shippers' payments are set or shared, how carriers choose between informal and platform work, or how waiting time and return loads change; revenues are taken as given by a posted tariff. Section 2 reviews related work, Section 3 states the model, Section 4 describes the solution methods and Section 5 reports the computational study; Section 6 turns to the implications and limits of the study, and Section 7 concludes.

Transport requests served without transshipment are covered by the general pickup and delivery problem. In the classification of static pickup and delivery problems a corridor PTL trip with en-route pickups belongs to the one-to-one family, and it becomes a multi-drop distribution problem if every consignment departs from the same city. Time windows add the scheduling layer studied in vehicle routing since Solomon. When cargo cannot be rehandled, loading must follow a LIFO order. Routing problems with loading constraints are reviewed by Iori and Martello for the pickup and delivery travelling salesman problem with LIFO loading, Carrabs, Cordeau and Laporte proposed variable neighbourhood search and branch-and-cut solves most instances with up to 17 requests within ten minutes. Cherkesly, Desaulniers and Laporte developed branch-price-and-cut algorithms for the pickup and delivery problem with time windows and LIFO loading. For the trips studied here, which carry at most four consignments along a line, LIFO feasibility can be checked directly [4].

Construction heuristics for routing go back to the savings algorithm of Clarke and Wright and to Solomon's insertion heuristics which initialise a route with a seed customer — typically the farthest unrouted customer or the one with the earliest deadline — and then insert customers by a cost criterion. The anchor of a PTL trip in this paper plays the role of Solomon's seed; what differs is that every consignment is tried as the anchor and that trips compete across heterogeneous truck classes. Improvement methods range from tabu search to adaptive large neighbourhood search, which Ropke and Pisinger applied to the pickup and delivery problem with time windows our LNS borrows its destroy-and-repair structure and noise, in a much simpler form [5].

Freight consolidation has been studied at several levels. Inside the vehicle, consolidation creates economies of scale in LTL carriers' bids. Between carriers and shippers, horizontal cooperation, request exchange and cost allocation raise utilisation but need rules that participants accept for collaborative multi-stop truckload shipping, core-based allocation has been proposed because the core may be empty. On platforms, matching and pricing strategies for multi-delivery-point service have been analysed for

freight online-to-offline platforms electronic marketplaces for truckload transport range from combinatorial auctions to open exchanges digital platforms for road freight management have been grouped into eight types and evidence on the economic impact of digitalisation in transport logistics is still at an early stage. Empty running and its causes, including geographic imbalance and search frictions motivate the problem but are outside the scope of this paper [6].

A corridor is represented by positions along a trunk road measured from the dispatch city (position 0). A point p has trunk position x_p and lateral offset δ_p; points with $\delta_p > 0$ lie on spurs and are served by driving δ_p out and back from their trunk node. Consignment i has an origin point o(i) (the dispatch city or an en-route city), a drop point p(i), mass q_i, volume v_i, revenue r_i from the platform's posted tariff, a delivery deadline b_i, and a pickup mode m_i with extra distance Δd_i^p and time Δt_i^p for collection in the dispatch city. Truck k of class h(k) has payload Q_k, useful volume V_k, variable cost c_k per kilometre and a maximum of N_k consignments. A trip starts from the dispatch city once collection is finished, picks up cargo in en-route cities, ends at its farthest drop and is evaluated on the forward leg; the value of the return leg is discussed in Section 3.5.

For ranking and pricing, mass and volume are combined in the chargeable weight

$$w_i = \max(q_i;\ v_i/\varphi), \qquad (1)$$

where φ is the volume–mass equivalence in m^3 per chargeable tonne. The vehicle constraints are imposed on mass and volume separately, because the ratio V_k/Q_k differs between classes.

Let $z_{ik} \in \{0, 1\}$ indicate that consignment i is assigned to truck k, $u_{pk} \in \{0, 1\}$ that truck k stops at point p, $y_k \in \{0, 1\}$ that truck k is dispatched, and $X_k \geq 0$ the trunk distance it drives. Let c_o be the cost of an additional stop and c_t the value of an hour of truck time. The platform maximises the total trip profit

$$\max \Sigma_k \left[\Sigma_i (r_i - c_k \Delta d_i^p - c_t \Delta t_i^p)\, z_{ik} - c_k X_k - \Sigma_p\, 2c_k \delta_p\, u_{pk} - c_o(\Sigma_p\, u_{pk} - y_k) \right] \qquad (2)$$

subject to

$$z_{ik} \leq u_{p(i)k}, \quad z_{ik} \leq u_{o(i)k}\ (o(i) \neq 0), \quad u_{pk} \leq y_k, \quad X_k \geq x_p u_{pk} \quad \forall i, p, k, \qquad (3)$$

$$\Sigma_{i \in B(\ell)}\, q_i\, z_{ik} \leq Q_k y_k, \quad \Sigma_{i \in B(\ell)}\, v_i\, z_{ik} \leq V_k y_k \quad \forall \ell, k, \qquad (4)$$

$$\Sigma_i\, z_{ik} \leq N_k y_k \quad \forall k, \qquad \Sigma_k\, z_{ik} \leq 1 \quad \forall i, \qquad (5)$$

$$z_{ik} + z_{jk} \leq 1 \quad \forall k, \forall (i, j) \in I^{LIFO}, \qquad (6)$$

$$\Sigma_i\, \Delta t_i^p\, z_{ik} \leq T^{pick} \quad \forall k, \qquad (7)$$

$$A_{pk} = \Sigma_i\, \Delta t_i^p\, z_{ik} + (x_p + \delta_p)/u + \Sigma_{q \prec p}\, (2\delta_q/u + \sigma)\, u_{qk}, \quad A_{p(i)k} \leq b_i + M(1 - z_{ik}) \quad \forall i, p, k. \qquad (8)$$

Here $B(\ell)$ is the set of consignments whose origin lies at or before and whose drop lies after the start of trunk leg ℓ; I^{LIFO} is the set of pairs with $x_{o(j)} > x_{o(i)}$ and $x_{p(j)} > x_{p(i)}$; u is the effective speed including rest; σ the service time per stop; $q \prec p$ denotes points visited before p (smaller trunk position, or the same trunk node served earlier); and M is a large constant [7].

The objective counts the trunk distance to the farthest stop, the spur detours and every stop beyond the first. Constraint (4) is the dynamic capacity condition: on each trunk leg the mass and volume on board are those of consignments already loaded and not yet unloaded. Constraint (5) caps consignments per trip and assigns each consignment to at most one truck — on a platform, an accepted consignment disappears from all other carriers' offers. On a corridor, LIFO loading means that a consignment loaded later must be unloaded no later, so it reduces to the pairwise incompatibilities (6). Constraint (7) bounds the delay that collection imposes on shippers who brought their cargo themselves, and (8) computes arrival times along the fixed visiting order and enforces deadlines. All constraints are linear. The general pickup and delivery formulation with arc variables reduces to (2)–(8) because, on a corridor, any route that visits points out of trunk order is dominated by the ordered route (Section 4.1).

Before a consignment joins a trip, its revenue is compared with the costs it adds:

$$\Delta\Pi_i = r_i - c_k \Delta d_i - c_o \Delta n_i - c_t \Delta t_i > 0, \qquad (9)$$

where Δd_i is the extra distance, Δn_i the number of extra stops and Δt_i the extra collection time. A consignment that fits physically but violates (9) is rejected: the aim is to fill the truck with profitable capacity, not merely to fill it [8].

Lemma 1 (detour radius). A consignment that is brought by its shipper and delivered to a new spur point at lateral distance δ_i from a trunk node not beyond the trip's farthest drop satisfies (9) if and only if

$$\delta_i < \delta_{max}(r_i) = (r_i - c_o) / (2c_k). \qquad (10)$$

Proof. The consignment adds δ_i out and back and one stop, so $\Delta\Pi_i = r_i - 2c_k\delta_i - c_o$. □

The radius grows linearly with revenue and falls with the truck's cost per kilometre. If the new drop lies on the trunk, the condition is $r_i > c_o$; if it lies beyond the current farthest drop x_{max}, the trip is extended and the condition becomes $r_i > c_k(x_{p(i)} - x_{max} + 2\delta_i) + c_o$. Deadlines (8) and capacity (4) still apply, so (10) is necessary, not sufficient, for acceptance. Its use is as a filter: consignments outside the radius of a truck class are not shown to it [9].

Without terminals, a consignment and a truck meet in one of three ways: the shipper delivers the cargo to the truck at the stand (mode 1), the truck collects it on its way out of the city (mode 2), or the truck makes a dedicated trip to the shipper's premises (mode 3). The carrier's collection cost is

$$C_i^{col} = c_k\Delta d_i^p + c_t\Delta t_i^p + c_o, \qquad (11)$$

which is zero in mode 1 and largest in mode 3. A collection fee A_i is acceptable to both sides only if

$$C_i^{col} \le A_i \le C_i^{own}, \qquad (12)$$

where C_i^{own} is the shipper's cost of bringing the cargo itself. Below the lower bound the service is subsidised by the other shippers on the truck; above the upper bound the shipper chooses mode 1; if $C_i^{col} > C_i^{own}$, collection is not offered. Collection time also delays departure and therefore every arrival in (8), which is why the budget (7) is needed.

The carrier's result is formed over the round trip, $Z^{cyc} = R^f + R^b - C^{cyc}$, where R^f and R^b are the forward and return revenues and C^{cyc} includes waiting. When demand at the end of the corridor exceeds the capacity of trucks dispatched there, trucks bound for an intermediate city can be asked to continue. Let β_1 and β_2 be the probabilities of finding a return load at the original end point L_1 and at the new end point L_2. Continuing from L_1 to L_2 km is worth it for the carrier if the extra payment satisfies

$$P^{ext} \ge c_k(L_2 - L_1) + c_t\Delta t + c_k[(1 - \beta_2)L_2 - (1 - \beta_1)L_1], \qquad (13)$$

where the bracket is the change in the expected cost of an empty return: the carrier would have faced the risk of returning empty from L_1 anyway, so only the difference is charged. The term vanishes, or becomes a discount, when the new end point offers better return prospects. A platform should therefore offer such extensions together with a return load. Condition (13) is not part of the computational study, which optimises the forward leg only [10].

2. Materials and Methods

2.1 Exact method: group enumeration and set packing

Proposition 1. For a given group G of consignments and truck class h, (i) the cheapest feasible visiting order serves points by increasing trunk position, each spur from its trunk node; (ii) if G is feasible under (4)–(8), every subset of G is feasible.

Proof. (i) The trunk distance of any order is at least x_{max}, attained only without backtracking; spur detours and stop counts do not depend on the order; and serving points in trunk order gives every point its earliest possible arrival, so it is also the best order for deadlines. LIFO-compatible groups can be unloaded in this order by (6). (ii) Removing a consignment removes load from every leg, removes at most one stop and one spur, and shortens collection; all arrivals become no later, so (4)–(8) remain satisfied. □

By (i), the profit $\pi(G, h)$ and the feasibility of any group follow in closed form; by (ii), all feasible groups can be generated level by level from feasible smaller groups. The dispatch problem then becomes the set packing problem

$$\max \sum_{(G,h)} \pi(G, h)\, y_{Gh} \quad \text{s.t.} \quad \sum_{(G,h):\, i \in G} y_{Gh} \le 1 \ \ \forall i, \quad \sum_G y_{Gh} \le K_h \ \ \forall h, \quad y_{Gh} \in \{0, 1\}, \qquad (14)$$

where K_h is the number of available trucks of class h and only groups with $\pi(G, h) > 0$ are generated. Model (14) is solved with HiGHS through SciPy. Its solution is optimal for (2)–(8).

2.2 Construction heuristics

All construction heuristics build trips sequentially. At each step the best trip is built for every truck class that still has idle trucks, and the most profitable (class, trip) pair is committed; construction stops when no trip with positive profit remains. The heuristics differ only in how a trip is built, which allows an ablation (Tables 3–4).

1. **H1 — single-start greedy.** The trip starts from the single consignment with the highest stand-alone profit and repeatedly inserts the feasible consignment with the largest marginal profit (9) until no insertion is profitable or the cap N_k is reached.
2. **MS — multi-start.** Every free consignment is tried as the starting consignment (the anchor) and the most profitable resulting trip is kept.
3. **MSR — multi-start with anchor restriction.** As MS, but only consignments whose drop is not beyond the anchor's are eligible, so the anchor is the farthest drop of the trip — the analogue of Solomon's farthest-customer seed [3].
4. **H2 — MSR with destination tiers.** Candidates are ranked lexicographically by tier and then by marginal profit: tier I — the anchor's drop point; tier II — the anchor's cluster (same trunk node, reached by a spur); tier III — intermediate points. This is the rule an operator or driver would apply by hand.
5. **MSk — scalable MSR.** Only the k = 3 heaviest consignments (by chargeable weight) of each drop point are tried as anchors, so the number of starts depends on the number of points rather than of consignments.

2.3 Large neighbourhood search

LNS starts from the MSk solution and runs 3,000 destroy-and-repair iterations. Destroy operators remove one or two whole trips (probability 0.4), a random 10–30% of the assigned consignments (0.3), or 30–70% of the consignments sharing a drop position with a randomly chosen one (0.3). Repair first inserts removed and unassigned consignments into existing trips by best marginal profit, then opens idle trucks with anchored construction (MSR on small pools, MSk otherwise). In half of the repairs the insertion gains and the trip scores are multiplied by a random factor in [0.75, 1.25], following the noise idea of Ropke and Pisinger [10]; without it, deterministic repair rebuilt the same trips and the search stalled on small instances. A candidate is accepted if it improves the current solution or, otherwise, with simulated-annealing probability, with a starting temperature of 1% of the initial profit falling linearly to zero. Every evaluation uses the exact trip profit and feasibility check of Proposition 1.

Quality is measured by the optimality gap, Gap = $(Z^{exact} - Z^{heur}) / Z^{exact} \times 100\%$, or, where the exact optimum is not available, by the gap to the best known solution. Speed-ups are reported as geometric means of T^{exact}/T^{heur}.

3. Results

Instances are synthetic but calibrated to the Tashkent–Nukus corridor (Table 1). Trunk positions and spur offsets are stylised approximations, not surveyed distances. Eighty per cent of consignments originate in Tashkent and the rest are picked up en route in Samarkand or Bukhara; destinations are drawn with the largest weight on the Nukus cluster. Masses are log-normal with a median of 1.5 t, truncated to 0.05–8 t, and volumes are mass times a density ratio drawn uniformly from 1.5–8 m^3/t, so that both mass-bound and volume-bound consignments occur; these distributions are assumptions, and Section 5.6 varies the tariff. Deadlines equal the direct travel time to the drop point multiplied by a slack drawn from [0.9, 1.3], plus 6 h. Truck payloads and volumes come from manufacturers' data for common classes; costs are assumptions. The fleet has $K_h = \max(1, \text{round}(s_h\lceil n/5\rceil))$ trucks of each class with shares s_h = 0.4, 0.3 and 0.3 for the 15-t, 9-t and 5-t classes; because of rounding the total fleet K differs slightly from $\lceil n/5\rceil$ (Table 2) [11].

For each $n \in \{10, 20, 30, 40, 50, 60\}$, 20 instances were generated with seeds $7000 \cdot n + s$, s = 0, …, 19, and solved by the exact method and all heuristics; instances with $n \in \{100, 200\}$ (10 each) and n = 300 (5) were solved by the heuristics only. All codes are written in Python 3.12 and run on one core of a desktop computer, so absolute times would be much lower in a compiled implementation; relative times are more informative.

Table 1. Instance parameters (illustrative assumptions)

Parameter	Value
Trunk positions, km	Jizzakh 200, Samarkand 300, Navoi 430, Bukhara 570, Urgench 1,080, Nukus 1,250
Spur drops (offset, km)	Khiva 30; Khodjeyli 15, Chimbay 75, Kungrad 110
Origins (share)	Tashkent 0.80, Samarkand 0.12, Bukhara 0.08
Truck classes (Q t / V m^3 / c_k UZS per km)	T5: 5.0 / 23.4 / 3,000; T9: 9.0 / 35.0 / 4,000; T15: 15.0 / 50.3 / 5,000
Volume–mass equivalence φ	4 m^3 per chargeable tonne
Posted tariff (base case)	260,000 + 520·distance UZS per chargeable tonne; minimum 150,000 UZS
Stop cost c_o; time value c_t	150,000 UZS; 60,000 UZS per hour
Effective speed u; service time σ	25 km per elapsed hour (≈600 km/day); 1.5 h per stop
Deadlines	direct time × U[0.9, 1.3] + 6 h
Pickup modes (share of Tashkent cargo)	1: 0.5; 2: 0.3 (2–6 km, 0.2–0.5 h); 3: 0.2 (10–40 km, 0.8–1.6 h)
Stop cap N_k; pickup budget T^{pick}	4 consignments; 3 h

Source: authors' assumptions; payloads and volumes from manufacturers' catalogues for the 5-t and 9-t classes and nominal market values for the 15-t class.

3.1 Scaling of the exact method

Table 2. Size and run time of the exact method (means over 20 instances)

n	Trucks K	Feasible profitable groups	Enumeration, s	Total (enumeration + MILP), s
10	3	68	0.00	0.01
20	4	1,138	0.04	0.20
30	6	4,453	0.17	0.67
40	7	16,599	0.53	2.43
50	10	37,319	1.32	8.65
60	13	91,861	2.77	39.97

Source: authors' computations.

Table 2 shows that the number of columns grows roughly with the fourth power of n, from 68 at n = 10 to 91,861 at n = 60. Enumeration stays cheap (2.8 s at n = 60); it is the set-packing MILP that grows fast, and the mean total time reaches 40 s at n = 60. Deadlines matter for the instance structure: in the n = 30 instances they remove 40% of the profitable groups but lower the optimal profit by only 1.6%, because the excluded groups are mostly dominated by groups with fewer stops [12].

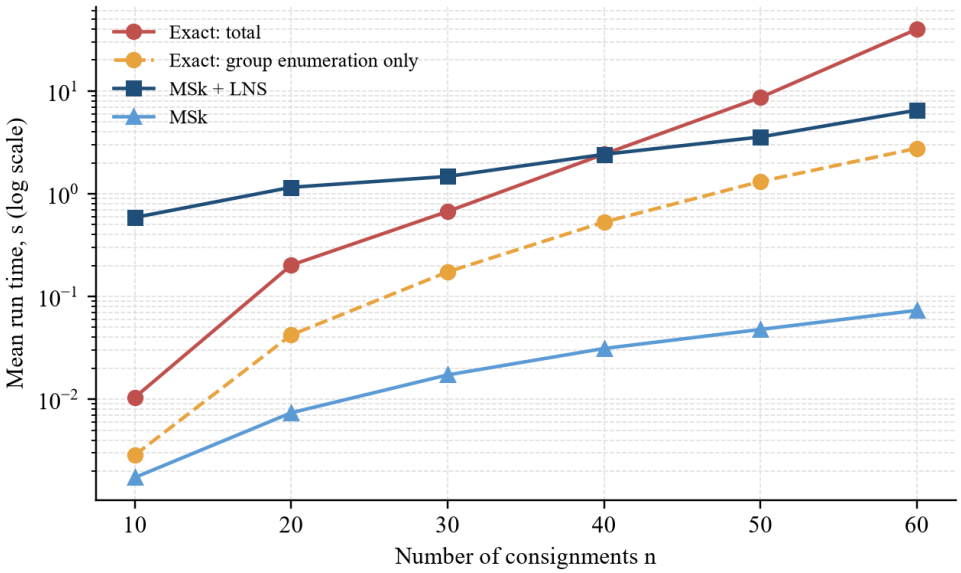


Figure 1. Mean run time of the exact method and the heuristics.
Source: authors' computations.

3.2 Heuristic quality and ablation

Table 3. Mean optimality gap (%, ± half-width of the 95% confidence interval; 20 instances per size)

n	H1	MS	MSR	H2	MSk	LNS	LNS max	LNS optimal	T^{LNS}, s
10	28.5 ± 14.7	5.7 ± 4.0	7.2 ± 4.7	7.5 ± 4.9	7.2 ± 4.7	0.7 ± 0.7	5.4	16	0.59
20	29.2 ± 12.5	3.6 ± 1.4	3.9 ± 1.6	9.0 ± 3.1	4.2 ± 2.2	1.0 ± 0.9	5.7	12	1.16
30	25.5 ± 10.1	7.3 ± 2.7	7.6 ± 2.6	10.0 ± 3.1	8.2 ± 2.5	2.4 ± 1.6	9.9	7	1.47
40	30.2 ± 6.2	6.0 ± 1.6	6.3 ± 1.5	7.2 ± 1.6	6.4 ± 1.8	0.9 ± 0.4	2.4	7	2.42
50	28.9 ± 6.2	7.0 ± 1.5	7.3 ± 1.7	8.7 ± 1.5	8.4 ± 1.8	1.9 ± 0.6	4.3	0	3.57
60	28.4 ± 5.0	7.3 ± 1.7	7.3 ± 1.7	7.6 ± 1.5	8.2 ± 1.7	1.6 ± 0.5	3.5	0	6.51

Source: authors' computations.

Table 4. Ablation: paired differences in optimality gap, n = 20–60 (100 instances)

Component	Mean change in gap, p.p.	Better	Worse	Ties	Wilcoxon signed-rank
Multi-start vs single start (MS − H1)	-22.20	98	1	1	$p < 0.001$
Anchor restriction (MSR − MS)	+0.25	9	16	75	$p = 0.030$
Destination tiers (H2 − MSR)	+2.00	35	61	4	$p < 0.001$
Three anchors per point (MSk − MSR)	+0.57	18	49	33	$p = 0.001$
Large neighbourhood search (LNS − MSk)	-5.49	93	0	7	$p < 0.001$

Source: authors' computations; negative values mean that the component lowers the gap.

Tables 3–4 and Fig. 2 give the results. Single-start greedy insertion (H1) performs poorly, with mean gaps of 25.5–30.2%. Trying every consignment as the anchor (MS) removes most of this error: the gap falls by 22.2 percentage points on average, to 3.6–7.3%. Restricting candidates to drops not beyond the anchor (MSR) changes little (mean change +0.25 p.p., $p = 0.030$), which shows that the gain comes from multi-start, not from anchoring as such [13]. Ranking candidates by destination tiers (H2) raises the gap by 2.00 p.p. on average (61 instances worse, 35 better, $p < 0.001$). The tier rule therefore has a cost in profit; it remains useful as a transparent rule for operators building trips by hand, but it should not be presented as an improvement in quality. Limiting anchors to three per drop point (MSk) costs 0.57 p.p. ($p = 0.001$) but makes construction independent of n in the number of starts. LNS improves on MSk in 93 of 100 instances and never makes it worse; its mean gap is 0.9–2.4% and its worst case 9.9%, at 1.2–6.5 s per instance [14].

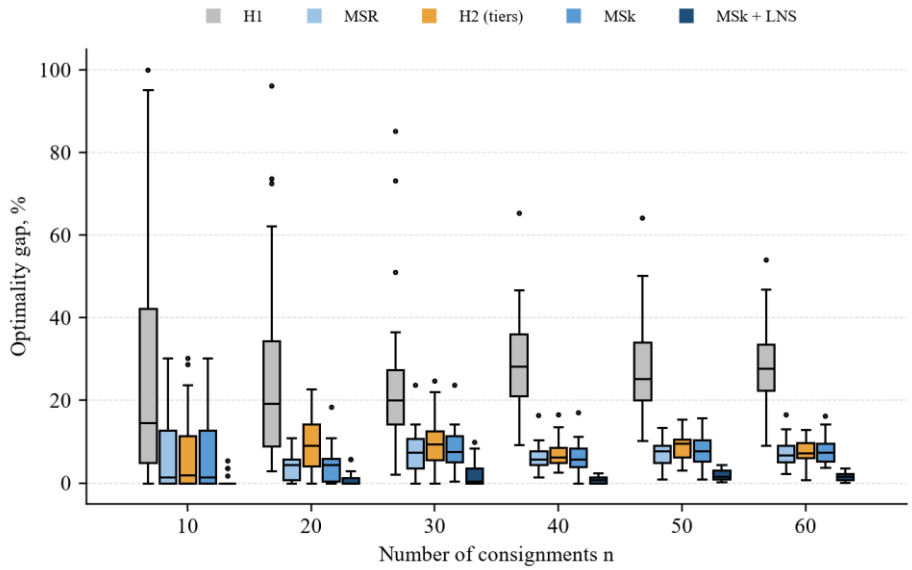


Figure 2. Distribution of optimality gaps by instance size.
Source: authors' computations.

The smallest instances (n = 10) behave differently: with only three trucks and few profitable trips, a single wrong choice costs a large share of the optimum, so construction gaps are wide (H1 up to 100%). LNS reduces the mean gap to 0.7% and finds the optimum in 16 of 20 cases; at this size, however, the exact method is the obvious choice (0.01 s) [15].

3.3 Larger instances

Table 5. Larger instances: gap to the best known solution (%) / mean time (s)

n	Inst.	K	H1	MSk	LNS	Cons. per truck (LNS)	Fill γ (LNS)	Served, % (LNS)
100	10	20	29.3 / 0.02	7.8 / 0.15	0.0 / 18.9	3.45	0.91	69
200	10	40	27.5 / 0.07	7.0 / 0.44	0.0 / 116.1	3.34	0.94	67
300	5	60	28.7 / 0.23	8.0 / 1.09	0.0 / 503.1	3.47	0.93	69

Source: authors' computations; the best known solution is the best of the three methods.

For 100–300 consignments the exact method is no longer practical, and the methods are compared with the best solution found (Table 5, first columns). LNS provides the best known solution in every instance; construction alone (MSk) is 7.0–8.0% below it and H1 27–29% below. The time of LNS grows from 19 s at n = 100 to 503 s at n = 300 in this Python implementation (the five n = 300 instances were run as parallel processes, which may inflate their times). Because a platform's offers to a carrier are valid for a limited time (an

hour in the platform for which the model was specified), this is fast enough to re-optimise whenever a truck or a batch of loads arrives at a major dispatch point [16].

3.4 Structure of the solutions and unserved consignments

Table 6. Optimal dispatch plans and the sources of unserved consignments (means)

n	Trucks K	Upper bound 4K/n, %	Trucks sent	Cons. per truck	Fill γ	Served, %	Unserved: fleet cap, p.p.	Unserved: other, p.p.
10	3	100	2.05	2.91	0.83	57	0	43
20	4	80	3.65	3.20	0.80	58	20	22
30	6	80	5.75	3.25	0.85	62	20	18
40	7	70	6.95	3.39	0.90	59	30	11
50	10	80	9.95	3.46	0.91	69	20	11
60	13	87	12.50	3.42	0.87	71	13	16

Source: authors' computations; γ is the larger of the mass and volume shares on the first leg; the fleet cap is 1 − min(1, 4K/n).

Dispatched trucks carry 3.0–3.5 consignments, close to the cap of four, and their fill on the first leg, measured by the binding dimension, is 0.80–0.91 in the optimal plans (Table 6). The optimal plans nevertheless leave 29–43% of the consignments unserved. For n ≥ 20 a large part of this is mechanical: with K trucks and at most four consignments per trip, at most 4K consignments can be carried, and this cap accounts for 13–30 percentage points [17]. To isolate the role of profitability, the n = 30 instances were re-solved with an unconstrained fleet (Table 7): the optimal plan then serves 74% of the consignments, so about 26% are not worth carrying on any trip under the acceptance rule — mostly light consignments to spur points or intermediate cities. A platform that shows every load to every carrier invites carriers to accept trips that the model would reject; the radius (10) and the marginal rule (9) can filter offers before they are made.

Sensitivity and the detour radius

Table 7. Sensitivity of the n = 30 instances (20 instances each; means)

Case	Groups	Optimal profit, million UZS	Trucks sent	Cons. per truck	Fill γ	Served, %	LNS gap mean / max, %
Base case	4,453	17.26	5.75	3.25	0.85	62	2.4 / 9.9
Ample fleet (K_h = n)	4,453	20.90	6.45	3.48	0.79	74	1.0 / 3.5
Weight-tapered tariff	1,679	7.56	5.30	3.53	0.86	62	2.5 / 14.5
No deadlines	7,434	17.54	5.75	3.28	0.86	63	3.1 / 15.0

Source: authors' computations. Weight-tapered tariff: revenue proportional to $w_i^{0.8}$, so that small consignments pay more per tonne.

Table 7 varies three assumptions. With an unconstrained fleet more trucks are sent and their fill falls (0.79 against 0.85), because additional trips are built from less compatible consignments. A weight-tapered tariff, under which small consignments pay more per tonne and large ones less, reduces the number of profitable groups from 4,453 to 1,679 and the optimal profit by more than half, but leaves the share of served consignments unchanged (62%) and raises consignments per truck to 3.53. Removing deadlines changes the plans little. LNS remains within a few per cent of the optimum in all cases, with worst cases of 3–15% [18].

The detour radius (10) makes the economics of a cluster explicit (Fig. 3). With the parameters of Table 1, a consignment paying 1 million UZS justifies a spur of up to 85 km for a 15-t truck but of up to 142 km for a 5-t truck; one paying 300,000 UZS justifies only 15 and 25 km respectively. Large trucks therefore need trips in which several consignments share the farthest drop, while small trucks can serve dispersed clusters [19].

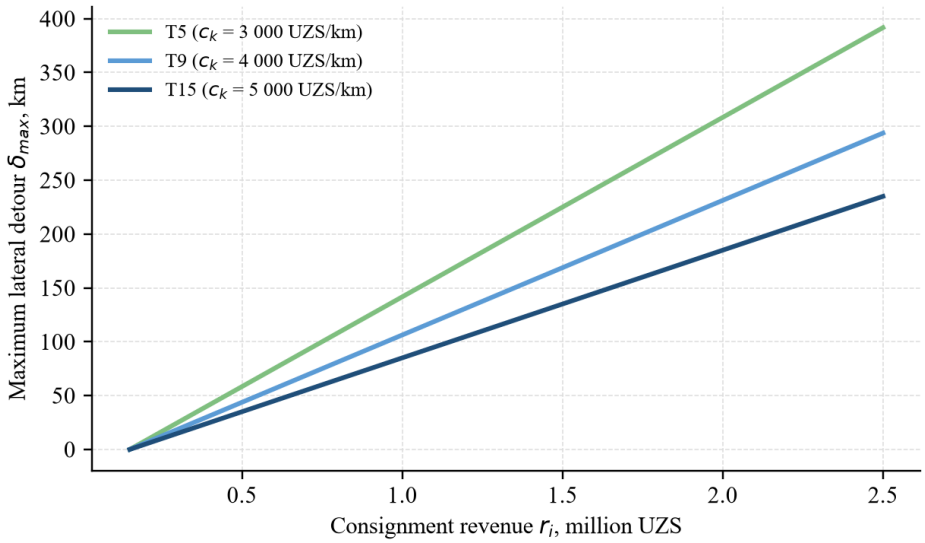


Figure 3. Maximum profitable spur detour δ_max by consignment revenue and truck class, Eq. (10).
Source: authors' computations with the parameters of Table 1.

4. Discussion

The results lead to four practical conclusions for platforms that organise terminal-less consolidation. First, at a single dispatch point with a pool of a few dozen consignments, the exact method is fast enough to be used directly; heuristics are needed for larger pools, for joint planning of several dispatch points and for repeated re-optimisation within the validity of offers. Second, the useful heuristic idea is to try many anchors — a multi-start version of Solomon's seed — and to let trips compete across truck classes; destination tiers are a convenient rule for manual planning, but in our instances they cost profit compared with ranking by marginal profit. Third, a simple LNS with noisy repair closes most of the remaining gap within seconds. Fourth, consignments should be accepted by marginal profit rather than by available space and filtered by the detour radius of the truck class, and collection from shippers' premises should be limited by a time budget and priced between the carrier's and the shipper's own cost [20].

The study has clear limitations. Instances are synthetic, distances and spur offsets are stylised, and costs, mass and volume distributions are assumptions; the results describe the behaviour of the methods, not the economics of the corridor. Revenues come from a posted tariff that does not depend on consolidation, so the model says nothing about how consolidation gains are shared between shippers and carriers; Table 7 shows that the tariff shape changes the number of profitable trips considerably [21], [22]. Only the forward leg is optimised; condition (13) is not tested. Dispatch is static and planned from one city. Extending the experiments to dynamic arrivals, several dispatch points and the return leg, implementing the methods in a compiled language, and calibrating them with platform transaction data — realised fills, collection times and carriers' acceptance decisions — are the natural next steps [23].

5. Conclusion

The paper formulated the carrier-side dispatch problem for terminal-less PTL trips on a long-haul corridor as a linear model and showed that, for trips of at most four consignments, the corridor fixes the visiting order and feasibility is hereditary, so the problem is solved exactly by group enumeration and set packing; in our implementation

this takes 40 s on average for 60 consignments. A marginal-profit rule yields a closed-form detour radius for filtering offers, and a corrected condition prices the extension of a trip. The ablation shows that multi-start anchoring, not destination tiers, drives the quality of construction, and an LNS with noisy repair stays within 0.9–2.4% of the optimum on average and scales to 300 consignments. The models and filters have been specified for an electronic freight platform piloted on the Tashkent–Karakalpakstan corridor; their calibration with transaction data is left for future work.

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