Improving Integer Programming-Based Neighborhood Search for LTL Load Plan Design

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WHAT TO REMEMBER

1. Load planning for LTL trucking, a problem of service network design, has grown in complexity.

2. New tools needed for load planning
   - Faster transit times
   - Service requirements

3. Our approach
   - Detailed time-expanded network model
   - Very large path-selection IP with intree constraints
   - IP-based neighborhood search solution approach

4. Results
   - *Intree* neighborhood search: 3-5% $ savings
   - *New or old tree* neighborhood search: 35-40% $ savings
**What does an LTL carrier do?**

- Transports shipments from multiple origins to destinations
  - Individual shipments are small, do not fill trailer ("less-than-truckload")
  - Each shipment has service requirement (# of business days)
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  - Two terminal types
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    - Breakbulks (BB - "Hub")
  - Trailer-to-trailer freight transfer: crossdocking
    - Handling cost
    - Requires time, from 30 min to a few hours
What does an LTL carrier do?

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- High-volume operations
  - Each week, a large US carrier
    - Moves hundreds of millions lbs freight
    - Hauls trailers millions of miles
    - Spend millions of dollars on linehaul operation
LTL OPERATIONS
LTL OPERATIONS

- Customer
- End-of-Line
- Breakbulk / Relay

Origin → Destination

IPLS for Load Planning
LTL Operations

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LTL Operations

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Origin

Handling

Destination
LTL linehaul service network design

**Load planning**

Given:
- Terminal locations
- Terminal types
- Transportation, handling cost structure

Determine:
- Unique freight transfer path for each (origin, destination) terminal pair
LTL linehaul service network design

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**Loosely-scheduled operations**

Given a load plan, freight arriving at terminals loaded into trailers, then dispatched using scheduled drivers, on-call “extra board” drivers, and third-party outsourcing (rail)
**Definition**

Freight transfer paths

- A freight path is a sequence of direct trailer moves (*directs*)
- Freight assigned to direct \((A, D)\) is loaded into a trailer at \(A\) and unloaded for transfer at \(D\)
OVERLAPPING FREIGHT PATHS AND CONSOLIDATION

Simple illustration

Diagram showing overlapping freight paths with cities such as SEA, MAC, ATH, CLT, ATL, CHI, PHX, and DEN.
OVERLAPPING FREIGHT PATHS AND CONSOLIDATION

Simple illustration
LOAD PLAN IN-TREE STRUCTURE

- Set of directs forming freight paths to destination terminal $d$ is directed intree
- Triples $(i, d, j)$ for all $i, d$ define load plan
  - All originating and transfer freight at $i$ bound for final destination $d$ is loaded into a trailer bound for next destination $j$
Deterministic tactical planning models

- Flat (static) network, sequential empties
  - Powell and Koskosidis (1992)
- Dynamic network, sequential empties, no intree
  - Farvolden and Powell (1994)
Models supporting LTL load planning

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- Detailed dynamic network, integrated empties
  - Erera, Hewitt, Savelsbergh, Zhang (under review)
  - Erera, Lindsey, Savelsbergh (working paper)
OVERVIEW OF OUR APPROACH

One week wrapped dynamic network with overnight detail
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Why?

- More accurately model consolidation timing
- Input O-D freight volume to vary by day-of-week
- Properly represent scheduled outsourced transportation (rail)
- Model weekend operations
OVERVIEW OF OUR APPROACH
Path-based freight transfer path selection IP
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**Why?**
- IP given limited set of service-feasible paths
- Arc-based model impractical
**Overview of our approach**

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- Input freight imbalance creates implicit empty movement “demand”
- Creates opportunities for low-cost transfer of backhaul freight
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**Dynamic Network and Freight Paths**

**Dynamic Network**

- Node: Terminal and time
- Arc: Freight direct or holding, or empty trailer move or holding
- Commodity: Freight demand from \((o, t_1)\) to \((d, t_2)\) each day.
Dynamic Network and Freight Paths

Feasible Freight Path Generation

- \( m \) minimum cost flat network paths
- timed variants of each flat network path
Timed Freight Paths

An two-day commodity originating Monday with slack time

new freight available
**Optimization Model**

Linear multi-commodity flow IP with side constraints

**Objective Function**

Minimize sum of:

- Transportation costs (linear in integer trailer variables)
- Holding costs (linear in integer path variables)

**Constraints**

- Select one path for each commodity
- Ensure that a single outbound direct is selected from each terminal $i$ for freight destined to $d$ [or, one direct for each $i, wd(i)$]
- Only allow selection of paths if all component directs are selected
- Count required trailers for each direct
- Ensure trailer count balance at all nodes (empty repositioning)
**Load Plan IP**

\[
\begin{align*}
\text{min} & \quad \sum_{a \in A} c_a \tau_a + \sum_{k \in K} \sum_{p \in P(k)} h_p q_k x_p^k \\
\text{subject to} & \quad \sum_{p \in P(k)} x_p^k = 1 \quad \forall k \in K \\
& \quad \sum_{\ell \in \delta^+(u)} y_{\ell}^d \leq 1 \quad \forall u \in U, \forall d \in U \\
& \quad \sum_{p \in P(k): a \in p} x_p^k \leq y_{\ell(a)}^{d(k)} \quad \forall k \in K, \forall a \in A \\
& \quad \sum_{k \in K} \sum_{p \in P(k): a \in p} q_k x_p^k \leq \tau_a \quad \forall a \in A \\
& \quad \sum_{a \in \delta^+(v)} \tau_a - \sum_{a \in \delta^-(v)} \tau_a = 0 \quad \forall v \in V
\end{align*}
\]
Gigantic Real-world Instances

Saia, a large U.S. super-regional LTL carrier

- 93 EOLs
- 61 transfer terminals (BBs and smaller transfer points)
- Flat network directs $|L| = 15,658$
- Time-space nodes $|N| = 4,718$
- Time-space arcs $|A| = 502,946$

| Instance   | # Commodities | # Paths $\sum_{k \in K} |P(k)|$ |
|------------|---------------|-------------------------------|
| Mar09-W1   | 36,135        | 2,978,300                     |
| Mar09-W2   | 36,218        | 2,979,323                     |
| Mar09-W3   | 36,599        | 2,981,454                     |
| Mar09-W4   | 36,783        | 2,982,673                     |
**Integer Programming Based Local Search**

**IP-based LS Using Single Intree Neighborhood**

**Require:** Current load plan solution \((\bar{y}, \bar{x}, \bar{\tau})\)

```
while search time has not exceeded time limit \( T \) do
  Choose a destination terminal \( d \)
  Solve* Single Intree IP for \( d \)
  if New solution has lower cost than current then
    Update \((\bar{y}, \bar{x}, \bar{\tau})\)
  end if
end while
```
SEARCHING SINGLE INTREE NEIGHBORHOOD

**SINGLE INTREE IP**

Given single $d$ and $K(d)$:

- Fix $y = \bar{y}$, $x = \bar{x}$ in Load Plan IP, except those involving $d$ or $k \in K(d)$
- Compute arc freight flows $f_a$
- Create Load Plan IP with only variables for $d$ and $K(d)$
- Add trailer bounds $\tau_a \geq \lceil f_a \rceil$
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### SOLVING SINGLE INTREE IP

- CPLEX 11 (or Gurobi)
- MIPemphasis = integer feasibility
- Gap 0.1%, short time limit $T' << T$
RESULTS AND IDEAS FOR IMPROVEMENT

IP Based LS using Single Intree Neighborhood Results

- Initial load plan from carrier
- 6 hour solution time limit
- Cost savings of 3 to 5% found
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- Use neighborhoods that attract freight to (or reduce freight from) a direct used by many destinations
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NEW IDEAS

- Use neighborhoods that attract freight to (or reduce freight from) a direct used by many destinations
- Replace empty balance constraints with trailer flow bounds updated periodically within search
When changing freight paths into ATL, some paths into BIR should be simultaneously changed
NEW OR OLD TREE NEIGHBORHOOD

SETS OF INTERACTING O-D PAIRS

- Two options
  - Attract freight to direct \((i, j)\)
  - Reduce freight from direct \((i, j)\)
NEW OR OLD TREE NEIGHBORHOOD

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**New or Old Tree Neighborhood**

**Sets of Interacting O-D Pairs**

- Two options
  - *Attract freight to direct* \((i,j)\)
  - *Reduce freight from direct* \((i,j)\)
NEW OR OLD TREE IP

\[ \min \sum_{a \in A} c_a \tau_a + \sum_{k \in K'} \sum_{p \in P(k)} h_p q_k x_p^k \]

subject to

\[ \sum_{p \in P(k)} x_p^k = 1 \quad \forall k \in K' \]

\[ x_p^k \leq 1 - z_d \quad \forall d \in D', k \in K'(d), p \in P(k, NewTree(d)) \]

\[ x_p^k \leq z_d \quad \forall d \in D', k \in K'(d), p \in P(k, OldTree(d)) \]

\[ \sum_{k \in K'} \sum_{p \in P(k)} q_k x_p^k + f_a \leq \tau_a \quad \forall a \in A \]

\[ x_p^k, \quad z_d \text{ binary} \]

\[ \tau_a \geq Empties_a \text{ and integer} \]
Empty Balancing Outside of IP

Substantially reduce IP size within neighborhood search

Periodic Empty Balance

- Every $k$ neighborhood search iterations, solve empty balance MCNF on time-space network
- Let $Empties_a$ be number of empty trailers moving on time-space arc $a$
## INTEGER PROGRAMMING BASED LOCAL SEARCH

### IP-based LS Using New or Old Tree Neighborhood

**Require:** Current load plan solution $(\bar{y}, \bar{x}, \bar{\tau})$ and $Empties_a$

while search time has not exceeded time limit $T$ do

Choose whether to attract or reduce freight

Choose a direct $(i, j)$

Solve* New or Old Tree IP

if New solution has lower cost than current then

Update $(\bar{y}, \bar{x}, \bar{\tau})$

end if

if iterations since last empty balance exceeds threshold then

Solve Empty Balance MCNF generating new $Empties_a$

end if

end while
NEW RESULTS

1. Search IP Speed
   - *Intree*: 90s limit, 75% to optimality
   - *New Or Old Tree*: 30s limit, 97% to optimality
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2. Cost Reduction from Base Plan: 1 hour

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LTL Service Network Design Tools

1. Weekly Tactical Planner
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2. Weekly Operation Scheduler and Cost Estimator
   - Build dispatches and driver tours
   - More accurate cost estimator for load plan

IPLS for Load Planning
LTL Service Network Design Tools

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3. Daily Load Plan Adjuster
   - Multiple daily updates for load plans given freight pickups
   - GRASP
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