GREEN LOGISTICS:
ASSESSMENT OF FREIGHT MARKET SHIFTS USING A DYNAMIC INTERMODAL NETWORK ANALYSIS METHODOLOGY

HANI S. MAHMASSANI

Erasmus University, Rotterdam
February 12, 2010
Organization of Presentation

• Motivation: Barriers to seamless operation
• Evaluating operational changes:
  – Network modelling platform
• Operational and service design scenarios
  – Border crossing time improvements
  – Terminal improvements
  – Infrastructure improvements
  – Scheduling constraints and priorities
• The take-away: potential of operational changes
• Design Application I: Scheduling with Elastic Demand
• Design Application II: Freight Tariff Design
EU Freight Sector Policy Context

• Major motivation: heavy costs of road congestion in terms of productivity, energy, air quality and carbon footprint

• Freight sector policy driven by improving sustainability through shifts from road to rail: increase rail market share, recognizing role of intermodal and sea-based transport

• Key instrument: Legislation in 2001, updated in 2006–EC Directives of the Rail Infrastructure Package:
  – Intended as “coherent set of legislation fundamentally reforming market access rules in view of integrating the European rail service market”
Rail freight sector in Europe not well developed compared to rest of world

Top 10 World Rail Systems in Freight Tonne-Kilometers

- US (Class I's)
- China
- Russia
- Canada
- Europe
- India

Modal share of rail freight in Europe has decreased over the past decade.
Barriers To Implementation of Directives

1. Technological: incompatibilities in gauge, electrification, communication, standards
2. Operational: different practices in different countries, border crossings, scheduling constraints, passenger priority
3. Institutional: entrenched government bureaucracies; incumbent undertakings resistant to change
4. Legal and administrative: laws and regulations remain to be harmonized to comply with interoperability directives
5. Financial: private capital skittish to invest in risky business
6. Social/cultural: varying degree of support for EU policies, for sustainability goals (red vs. blue states…)
REORIENT Corridor

6th Framework Coordinated Action Program

Consortium
TOI (lead)
Maryland
Bologna
Napier
DLR
Demis bv.

This Work
Elise Miller-Hooks
Kuilin Zhang
April Kuo
Rahul Nair
Aaron Kozuki
Jing Dong
Jason Lu
Introduction

• Analysis of the complex interactions over space and time associated with the movement of freight over intermodal networks entails use of sophisticated network modeling methodologies.

• The modeling of multiple-product intermodal freight flow over multimodal networks has attracted much interest (though limited application in practice) in the last four decades, using both analytical and simulation approaches:
  – Analytical approach examples: Harker and Friesz (1986), Crainic et al. (1990), Fernandez et al. (2004), etc.
  – Major software tool: STAN (Crainic and INRO)
  – Simulation approach: Mahmassani et al. (TRB 2007)

• THIS TALK: a. Implementation, validation, and application to a practical large-scale network (the European REORIENT corridor), of the a simulation-based intermodal freight DTA model
  b. Design applications to scheduling with elastic demand, and freight tariff setting/pricing
Overall network modeling structure

Role of the model

Demand
Network Services

Mode and Path Choice
Assignment
Simulation
Links Nodes
Intermodal Path Computation

Scheduling Algorithm
Route Design Model

CDM Operational Rules

Modal/Market Shares, by Service Travel Times, Terminal Delays
Problem statement and assumptions

• Assumptions
  – Given time-dependent OD demand tables (multiple products)
  – Calibrated mode/carrier choice model (truck only, intermodal container, and multimodal combination)
  – Multimodal network with train/ferry timetable
  – Terminal service time probability distribution functions

• Solve for
  – Assignment of time-varying multiple product (commodities) shipments to intermodal paths through network, and
  – Associated service levels and delays

• Methodological Approach
  – Simulation-assignment iterative solution framework
Shipper decisions and shipment assignment to multimodal network

- Shippers (or their agents) are the decision-makers
  - Shippers determine the transport choice for their respective shipments based on available service supply
  - Aggregate demand are compiled into to shipment units that are unitized (containers, swap-bodies or semi-trailers) or railcars (i.e. bulk commodities)
  - A logit-based discrete choice model for joint mode and route choices made by shippers with regard to each shipment (i.e. shippers’ choices are reflected in shipments’ choices)
  - A set of alternatives (mode-path combinations) consists of a multidimensional choice set that includes mode, path, service, and carrier for each shipment product type (with associated specific attributes)
Utility function and estimation

• Data source:
  – a survey of shippers conducted by the Norwegian Institute of Transport Economics

• Systematic utility function
  – Truck Only mode
    \[ V_{TO}^p = -0.3038 \times 10^{-5} \times TravelTime \times D_{TT-S}^p \times Value^p \]
    \[ -0.2151 \times 10^{-6} \times TravelTime \times D_{TT-L}^p \times Value^p \]
    \[ -1.8411 \times \frac{Price^p}{Value^p} \times TravelDist \]
  – Intermodal “mode”
    \[ V_{IM}^p = -0.5215 - 0.4616 \times 10^{-5} \times \beta_{TT-S}^{IM} \times TravelTime \times D_{TT-S}^p \times Value^p \]
    \[ -0.2151 \times 10^{-6} \times TravelTime \times D_{TT-L}^p \times Value^p \]
    \[ -1.8411 \times \frac{Price^p}{Value^p} \times TravelDist \]
    \[ + 1.6001 \times D_{Hazard}^{IM} \]

Short path tt dummy (<70 hrs)
Long path tt dummy
Hazmat dummy
**Consolidation at Origin:** Shipment transfer from trucks.

**Intermodal Terminal:** Shipment transfer from trucks to railcars.

**Shuttle Service (for traditional trains):** From terminal to classification yard.

**Classification Yard:** Train assembly process. Not required for intermodal block trains.

**Border Station:** Train is delayed.

**Port:** Transfer of shipments from railcars to ferry. Ferries move based on given timetables.

**Destination:** Unloading shipments.

**Classification Yard:** Train is disassembled. For intermodal block trains, this process is not required.

**Shuttle Service (for traditional trains):** From classification yard to port.

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**Simulation-assignment method:**

- Processes simulated to determine processing costs and times at nodes and links of path.
- Shipments assigned using joint mode-path choice assignment.
- Detailed representation allows us to test various policies, such as infrastructure improvements, service frequency changes, and improvement in border crossing procedures.
Multimodal Freight Network Simulator

**Inputs:**
- OD flow;
- Path split;
- Mode share.

**Demand loading:**
- Shipment generation;
- Shipment consolidation;
- Conveyance loading.

**Link moving:**
- Truck moving;
- Shuttle train moving;
- Train moving;
- Ferry moving.

**Node/mode transfer:**
- Truck transfer at road intersection;
- Train transfer at intermediate station;
- Mode transfers at intermodal transfer terminal, classification yard, and port.

$t = t + 1$

Have all shipments reached their respective destinations? Or, Is simulation time at the end of planning horizon?

- Yes → Stop
- No → $t = t + 1$
Terminal process: generalized bulk queueing model

Arrival queue ($\sum G^x / G^x / 1$):

$$\text{EPDT}_i = \begin{cases} \text{AT}_i + W_i + \sum_x S_i & \text{for classification yards} \\ \text{AT}_i + W_i + S_i & \text{for terminals and ports} \end{cases}$$

where,

- $i$ = element;
- $x$ = bulk size;
- $\text{EPDT}_i$ = Earliest Possible Departure Time for element $i$ (same for all elements in same bulk);
- $\text{AT}_i$ = Arrival Time for element $i$ (same for all elements in same bulk);
- $W_i$ = waiting time for element $i$ (same for all elements in a same bulk) in arrival queue; and,
- $S_i$ = service time for element $i$ (stochastic) on process.

Departure queue ($G^x / GD^y / 1$):

$$\text{SD}_i = \text{ADT}_i - \text{EPDT}_i$$

where,

- $\text{SD}_i$ = Schedule Delay for element $i$;
- $\text{ADT}_i$ = Actual Departure Time for element $i$ based on bulk departure time (e.g. timetable);
- $G^x$ = general bulk arrival process;
- $GD^y$ = general dependent service process based on bulk departure time (e.g. timetable);
- $x$ = arrival bulk size; and,
- $y$ = departure bulk size.
Process at a classification yard

- Locomotive
- Railcar to destination 1
- Railcar to destination 2
- Railcar to destination 3
- Bulk arrival
- Bulk departure
- Process at classification yard
- Queueing
- Bulk Service

\[ \text{AT}_i \]

\[ \text{Train 1} \]

\[ \text{Train 2} \]

\[ \text{Train 3} \]

\[ W_i \]

\[ \Sigma_x S_i \]

\[ \text{Train 4} \]

\[ \text{Train 5} \]

\[ \text{Train 6} \]

\[ \text{ADT}_i \]
Port shipment processing

Unloading time

Scheduled delay

Loading time

Storage Area

Indirect transfer

Direct Transfer

Transport time within terminal

Truck unloading

Train unloading

Ferry unloading

Ferry loading

Truck loading

Train loading
Solution framework: implementation considerations for large-scale networks

1. Pre-defined paths for new services and historical paths
2. An efficient grand path set (3.2 millions shipments v.s. 20 thousands spatial paths)
3. Multi-resolution simulation interval 0.1 min (road) v.s. 1 min (rail)

1. Pre-defined path set generation
2. Initial shipment assignment
3. Multi-resolution multimodal freight network simulation
4. Time-dependent intermodal least-cost paths
5. Mode-path choice set generation
6. Shipment dynamic micro-assignment
7. Update of mode and path assignment
8. Convergence checking

N

n=n+1

Y

Stop
The REORIENT corridor

<table>
<thead>
<tr>
<th>Network</th>
<th># of Nodes</th>
<th># of Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail part</td>
<td>5577</td>
<td>5753</td>
</tr>
<tr>
<td>Road part</td>
<td>4713</td>
<td>5460</td>
</tr>
<tr>
<td>Sea part</td>
<td>54</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>10344</td>
<td>11234</td>
</tr>
</tbody>
</table>

The corridor spans 23 countries
## Demand and existing freight tariff scheme

- **3.2 million shipments per week (2006)**
- **5.8 million for forecast year 2020**
- **Source: ETIS**
- **117 x 117 O-D zone pairs**
- **11 commodity types**
- **2 manifestations (‘bulk’ and ‘unitized’)**

<table>
<thead>
<tr>
<th>Description</th>
<th>Ton/TEU</th>
<th>Import Flows</th>
<th></th>
<th>Export Flows</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>€/ton</td>
<td>s.d.</td>
<td>€/ton</td>
<td>s.d.</td>
</tr>
<tr>
<td>Agricultural products and live animals</td>
<td>12.74631</td>
<td>192.11</td>
<td>440.11</td>
<td>184.99</td>
<td>317.2</td>
</tr>
<tr>
<td>Foodstuffs and animal fodder</td>
<td>13.31296</td>
<td>276.13</td>
<td>661.47</td>
<td>230.32</td>
<td>358.3</td>
</tr>
<tr>
<td>Solid mineral fuels</td>
<td>18.40739</td>
<td>116.72</td>
<td>1678.30</td>
<td>121.49</td>
<td>1841.1</td>
</tr>
<tr>
<td>Petroleum products</td>
<td>14.92787</td>
<td>109.93</td>
<td>228.82</td>
<td>44.94</td>
<td>63.1</td>
</tr>
<tr>
<td>Ores and metal waste</td>
<td>16.14077</td>
<td>89.04</td>
<td>269.82</td>
<td>70.54</td>
<td>160.9</td>
</tr>
<tr>
<td>Metal products</td>
<td>15.25173</td>
<td>212.82</td>
<td>487.00</td>
<td>223.05</td>
<td>1078.5</td>
</tr>
<tr>
<td>Crude and manufactured minerals, building materials</td>
<td>15.07911</td>
<td>321.49</td>
<td>2461.83</td>
<td>236.05</td>
<td>1476.5</td>
</tr>
<tr>
<td>Fertilizers</td>
<td>18.45192</td>
<td>58.91</td>
<td>147.86</td>
<td>93.32</td>
<td>481.8</td>
</tr>
<tr>
<td>Chemicals</td>
<td>14.04991</td>
<td>957.13</td>
<td>5955.17</td>
<td>1149.15</td>
<td>10085.2</td>
</tr>
<tr>
<td>Machinery, transport equipment, manufactured articles and miscellaneous articles</td>
<td>9.290191</td>
<td>805.45</td>
<td>4090.65</td>
<td>9493.87</td>
<td>159626.8</td>
</tr>
<tr>
<td>Crude oil</td>
<td>16.23117</td>
<td>159.30</td>
<td>1526.82</td>
<td>83.02</td>
<td>200.8</td>
</tr>
</tbody>
</table>
Illustration of convergence pattern

![Graph showing convergence pattern](chart.png)
Validation of model split

This model

European Commission 2005: 17.4%
Four proposed service routes

T1 = Green (Bulk)
Swinoujscie - Vienna/Bratislava - Budapest

T2 = Yellow (Unitized)
Trelleborg-Swinoujscie-Bratislava/Vienna

T3 = Red (Unitized)
Gdansk/Gdynia-Bratislava/Vienna-Budapest-Beograd-Thessalonica

T4 = Blue (Bulk and Unitized)
Bratislava-Budapest-Bucharest-Constantia
If we build it, will they come?
Proposed Services

• New rail services on current network
• New rail services on improved network
  – Multi-voltage locomotives
  – Improved signaling (e.g. ERTMS) along route from Gdansk to Thessaloniki
  – ICT for improved border station performance
  – 20% increase in speeds in Poland
  – Electrification of all tracks on proposed services
Services: Catchment Area
(Origins of shipments using new services)
Illustrative results: barrier reduction at borders

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Border crossing times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>3-4 hours</td>
</tr>
<tr>
<td>Sophisticated</td>
<td>15-45 min</td>
</tr>
</tbody>
</table>
Illustrative results: Infrastructure improvements

- A bundle of infrastructure improvements:
  - 20% increase in rail maximum speeds in Poland
  - that would result from improvements in the track, electrification of track along all newly proposed services,
  - terminal processing time improvements

Increase serviced flows by 33%
Relaxing Time of Day Scheduling

### Level 1
- Night time only

### Level 2
- Additional day time operations with strict priority for passenger trains.

14.9% increase in intermodal flows
Sum of Parts

- Services attract more freight when offered together
The take-away

- Improved border operations, infrastructure improvements, greater access to services, relaxing scheduling constraints have considerable potential to increase intermodal rail share.
- Further improvement possible through more sophisticated operation of the rail network to allow more efficient priority allocation to different services.
- Managing the rail system in the 21st Century will require new management models. Most promising models will be based on collaborative decision-making architectures.
Organization of Presentation

• Motivation: Barriers to seamless operation

• Evaluating operational changes:
  – Network modelling platform

• Operational and service design scenarios
  – Border crossing time improvements
  – Terminal improvements
  – Infrastructure improvements
  – Scheduling constraints and priorities

• The take-away: potential of operational changes

• Design Application I: Scheduling with Elastic Demand

• Design Application II: Freight Tariff Design
Freight train scheduling with elastic demand

• Goal
  – Provide competitive tactical train schedule that reflects demand along network and objectives of both carriers and shippers

• Solution approach
  – Optimization model and solution technique that seek optimal timetable
  – Iterative procedure (REORIENT Consortium, 2007) for updating timetable in response to scheduling delay and demand estimates
Create timetable for inelastic demand

**Initial timetable**
- No conflict between trains
- Minimum train frequency
- Assign earliest feasible track capacity to track segment

**Modified timetable**
- Adjust departure time at terminal based on shipment delay
- Train travel within certain range of speed
- Create additional train slots

**Final timetable**
- Subset of modified timetable
- Minimize operational cost and train delay

**Train slot**
- Use of route from shipment origin to destination during given time period
Train slot selection model

- Binary capacitated multi-commodity network flow problem
- Objective
  - Minimize operational cost and train delay
    
    \[
    \text{Min } z(x) = \sum_{k \in K} \sum_{i \in I} c_i y_i + \sum_{k \in K} \sum_{i \in I} \rho(\mu_i)
    \]
    
    \(\rho(\mu_i)\): delay cost of each train slot \(i \in I^k\)
    
    \(c_i\): operational cost for each train slot \(i \in I^h\)
    
    \(y_i \in \{0, 1\}\)
    
- Decision-maker’s preferences for delay and cost minimization reflected through appropriate weights on delay and cost components of objective function
Train slot selection model

• Constraints
  – Force number of train slots that pass each terminal \( l \) in given time interval \( t \) to be no larger than number of train slots necessary to transport shipments at terminal \( l \) in time interval \( t \)

\[
\sum_{k \in K} \sum_{i \in T} \delta_{lt}(y_i) y_i \leq u_{lt}, \quad \forall l \in L \quad \forall t \in T
\]

\( u_{lt} \): maximum number of train slots pass loading/unloading terminal \( l \in L \) at time \( t \in T \)

  – Ensure that total number of train slots on each route satisfies suggested train frequency on each route

\[
\sum_{k \in K} \sum_{i \in T} \delta_{lt}(y_i) y_i = \eta^k, \quad \forall l \in L \quad \forall t \in T
\]

\( \eta^k \): suggested train frequency for each route \( k \in K \)
Solution technique for train slot selection model

• Column generation-based technique
  – Decompose multi-commodity network flow into single-commodity flows
    • Restricted master problem
      – Subset of variables in original problem
    • Sub-problem for each commodity
      – Find column (train slot) with minimum reduced cost for each service route
      – Shortest path problem
        \[ \lambda_i^k = c_i + \rho(\mu_i) + \sum_{i \in I} \sum_{j \in J} \delta_{ij}(y_{ij}) \sigma_{ij} - \sigma_k, \quad \forall i \in I^k \quad \forall k \in K \]

  Modified path cost
  Shortest path cost at current iteration
Elastic demand

- Iterative simulation-based scheduling framework (REORIENT Consortium, 2007)

Diagram:
- Initial train timetable
- Suggested routes and frequencies
- Daily demand generation rate
- Zone to zone based O-D demand
- Simulation platform
- Delay to shipments in terminal
- Track capacity modification
- Updated train timetable
- Train slot selection model
- Daily demand generation rate
- Initial train timetable
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Freight tariff design under SUE flows

- Rail network improvement
  - New railway service
  - New train schedule
- Product-based freight tariff design
  - SUE flow constraint
  - Multi-product combined mode-route choice

Need to design new freight tariff!
Contributions

– Give an *MPEC formulation* for the freight tariff design under SUE flows for multi-product multimodal networks

– Propose a *gradient projection based solution method* for the problem

– Apply to a large-scale multimodal freight network, the REORIENT corridor and find an *optimal product-based price scheme*
Problem statement

• Assumptions
  – Given multimodal network topology: road and rail
  – Given train time table
  – Given time-dependent OD demands (shipments) for each product type
  – Given logit-based choice function
  – Existing intermodal pricing scheme for each product type

• Find
  – Optimal rail-based intermodal pricing scheme that maximizes total rail-based intermodal profit
    $$\pi_{1M} = R_{1M} - C_{1M} \quad R_{1M} = R_{1M}(x, u_{1M}) \quad C_{1M} = C_{1M}(FSC_{1M}, DSC_{1M}) = FSC_{1M} + DSC_{1M}(USC_{1M}, x, u_{1M})$$
  – Time-varying mode shares and path flow pattern satisfying TDMSUE conditions
Formulation

• Definition TDMSUE
  – For each OD pair, for each assignment/departure time interval, and for each product type, no shipment can reduce its perceived mode-route travel cost/disutility by unilaterally changing mode-route.

• TDMSUE conditions
  \[ x_k = q^{wp} \times P_r_k(x), \forall k \in K^{wp}, w \in W, t \in T, p \in P \]

• Parametric fixed point (FP) formulation
  • Find \( x^*(u_{IM}) \in \Omega(u_{IM}) \) satisfying \( x^*(u_{IM}) = F(x^*(u_{IM})) \)

• MPEC formulation
  • Objective function
    \[ Z(x, u_{IM}) = \sum_{w \in W} \sum_{p \in P} \sum_{k \in K^{wp}} (U^{P}_{IM} - USC^{IM}_{IM}) \times x_k(u_{IM}) \times WT^{p} \times TD^{wp}_{k} \]
  • st
    \[ x_k(u_{IM}) = q^{wp} \times P_r_k(x, u_{IM}), \forall k \in K^{wp}, w \in W, t \in T, p \in P \]
    \[ x_k(u_{IM}) \geq 0, \forall k \in K^{wp}, w \in W, t \in T, p \in P \]

TDMSUE conditions
Solution framework

Determine SUE flow pattern

Lower level problem: MSA based micro-assignment solution framework; Dynamic intermodal simulation-assignment based on a Multimodal Freight Network Simulator (Mahmassani et al., 2007)

Determine optimal pricing scheme

Gradient Projection descent direction method
Convergence pattern

Price convergence pattern

Objective function

- Obj Value
- Revenue
- Demand weighted cost
Rail carriers need to adjust the prices based on the value of product to optimize the share structure of each product type that they should carry to maximize their total profit.
Summary and conclusions

• Illustrated steps and challenges in application to a large-scale network of a dynamic intermodal freight network modeling framework for policy evaluation and market assessment of proposed new Pan-European rail services.

• Addressed methodological challenges due to the multidimensional nature of the demand (e.g. multiple product types, very large number of shipments) and the supply (e.g. multiple interacting modes, transfer processes, multiple carriers).

• Issues of system representation, problem size, computational and memory considerations, as well as limited data availability and its aggregate static nature called for methodological refinements.
Summary and conclusions

• The dynamic intermodal freight network simulation-assignment Tool provides a capability to evaluate performance measures, costs and benefits derived from implementation of
  – interoperability directives,
  – barrier-removing or barrier-reducing improvements in physical,
  – operational or managerial aspects/business practices of the rail system,
  – as well as other policy measures and potential inducements aimed towards achieving EC policy objectives.

• The simulation-assignment model can be employed as a low level model for
  – freight train scheduling with elastic demand
  – freight tariff design under SUE flows