A *Lead-Time* based Approach for Planning Rail-Truck Intermodal Transportation of Dangerous Goods

Vedat Verter • Manish Verma

Desautels Faculty of Management, McGill University, Montreal, PQ, Canada
Faculty of Business Administration, Memorial University, St. John's, NL, Canada
vedat.verter@mcgill.ca • mverma@mun.ca

1. Introduction

Intermodal transportation has experienced a phenomenal growth over the past two decades, and continues to be one of the rapidly growing segments of the transportation industry. This has been attributed to the competitive pressures on global supply chains, the increasing demand for new service patterns driven by ocean carriers as well as the globalization of industry. Rail-truck intermodal transportation (IM) combines accessibility advantage of road networks with scale economies associated with railroads in moving shipments. In comparison with the use of traditional train services, the main attractiveness of IM for shippers is its reliability in terms of on-time delivery.

In addition to regular freight, IM has been used for moving hazardous materials (hazmats) since 1970s. The volume of cargo that is potentially harmful for human health and the environment have increased significantly over the past two decades. For example, the Bureau of Transportation Statistics estimated that in 1997 over one and half million tons of hazmats were shipped across the U.S. intermodal transportation system. This statistic is already qualified as an underestimate by the 2002 Commodity Flow Survey in the U.S. In addition, the U.S. Chemical Manufacturers Association estimates that the total volume of hazmats shipped by 2020 will be 5.1 billion tons, which according to the U.S. Department of Transportation will be increasingly carried via intermodal transportation channels.

Despite the increasing significance of IM in carrying hazmats, this is an area that has not been studied in hazmat logistics literature. In this paper, we present a first attempt for the development of an analytical framework for planning rail- truck intermodal transportation of hazmats. As a basic problem, we focus on a single pair of intermodal rail terminals (IMRTs), with a number of intermodal train services between them. Since the current network of IMRTs is rather sparse in North America, a significant majority of the shippers have a single IMRT in their vicinity. A bi-objective optimization model to plan and manage intermodal shipments where route determination is driven by the delivery-time (or, lead-time) specified by the customers is developed. Transport risk is represented by population exposure due to the truck and rail shipments. The proposed solution methodology takes advantage of the analytical properties of the problem. A realistic size problem instance from Canada is solved, and will be used for presenting a number of managerial insights.

2. The Model

An IM system can be modeled as a *just-in-time* movement of traffic, both hazardous and non-hazardous, in an intermodal chain while ensuring that the delivery takes place by the specified time. It is important to note that an intermodal chain, formed by the three links -inbound drayage, rail-haul, and outbound drayage- is feasible only if the total time needed to complete the set of link activities is less than the time specified by the receiver. This implies that shipments from a shipper to a receiver can be split between different intermodal chains as long as such chains are feasible. Since drayage is not subject to any capacity constraint it will not experience any flow splitting, but maximum permissible train length would force consignment splitting for train services if such shipments are likely to exceed specified length. Hereafter we denote the time specified by the receiver as *lead-time*, which plays a major role in the construction of feasible intermodal chains. We assume that IM trains of same service class (speed) on the same route arrive at the destination IMRT around the same time. Therefore, if the maximum train length is exceeded, then the containers that belong to a shipment can be split between such trains.

Our objective is to determine best shipment plan for hazardous and non-hazardous freight in a rail-truck intermodal network, while being able to deliver these shipments by the specified lead times specified by the receivers.

Our notation and the model are provided below.

Sets:

I:	Set of shippers, indexed by *i*.
J:	Set of receivers, indexed by *j*.
P_i:	Set of paths between origin IMRT and shipper *i*, indexed by *p*.
P_j:	Set of paths between destination IMRT and receiver *j*, indexed by *q*.
T:	Set of train service types between the IMRT pair, indexed by *s*.

Variables:

$X(h)_{ij}^{p}$:	Number of hazmat containers sent from shipper *i* to receiver *j* using path *p* for inbound drayage.
$X(\bar{h})_{ij}^{p}$:	Number of regular containers sent from shipper *i* to receiver *j* using path *p* for inbound drayage.
$X(h)_{ij}^{ns}$:	Number of hazmat containers sent from shipper *i* to receiver *j* using n^{th} intermodal train of service type *s*.
$X(\bar{h})_{ij}^{s}$:	Number of regular containers sent from shipper *i* to receiver *j* using intermodal train service type *s*.
$X(h)_{ij}^{q}$:	Number of hazmat containers sent from shipper *i* to receiver *j* using path *q* for outbound drayage.
$X(\bar{h})_{ij}^{q}$:	Number of regular containers sent from shipper *i* to receiver *j* using path *q* for outbound drayage.
N^{s} :	Number of intermodal trains of service type *s*.

Indicator Variables:

$$Y_{ij}^{p} = \begin{cases} 1 \; if \;\; X(h)_{ij}^{p} > 0 \text{ or } X(\bar{h})_{ij}^{p} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$Y_{ij}^{q} = \begin{cases} 1 \; if \;\; X(h)_{ij}^{q} > 0 \text{ or } X(\bar{h})_{ij}^{q} > 0 \\ 0 \text{ otherwise} \end{cases}$$

$$Y_{ij}^{s} = \begin{cases} 1 \; if \;\; X(h)_{ij}^{ns} > 0 \text{ or } X(\bar{h})_{ij}^{s} > 0 \\ 0 \text{ otherwise} \end{cases}$$

Parameters:

$C(h)_{i}^{p}$:	Cost of moving one hazmat container from shipper *i* using path *p* of for inbound drayage.

$C(\bar{h})_i^p$: Cost of moving one regular container from shipper *i* using path *p* of for inbound drayage.

$C(h)^s$: Cost of moving one hazmat container using intermodal train service of type *s*.

$C(\bar{h})^s$: Cost of moving one regular container using intermodal train service of type *s*.

$C(h)_j^q$: Cost of moving one hazmat container to receiver *j* using path *q* of for outbound drayage.

$C(\bar{h})_j^p$: Cost of moving one regular container to receiver *j* using path *q* of for outbound drayage.

C^s : Fixed Cost of operating an intermodal train service of type *s*.

$E(h)_i^p$: Population exposure due to moving one hazmat container from shipper *i* using path *p* of for inbound drayage.

$E(h)_j^q$: Population exposure due to moving one hazmat container to receiver *j* using path *q* of for outbound drayage.

$E(h)^{ns}(.)$: Population exposure as a function of moving the number of hazmat containers on n^{th} intermodal train service of type *s*.

U^s : Number of containers that can be loaded on intermodal train service of type *s*.

$D(h)_{ij}$: Number of hazmat containers demanded from shipper *i* by receiver *j*.

$D(\bar{h})_{ij}$: Number of regular containers demanded from shipper *i* by receiver *j*.

$t(in)_i^p$: Inbound drayage time for shipper *i* using path *p*.

$t(s)$: Travel time of intermodal train service *s*.

$t(out)_j^q$: Outbound drayage time for receiver *j* using path *q*.

L_j : Delivery Lead time specified by receiver *j*.

Min

$$Exposure: \sum_i \sum_j \sum_p E(h)_i^p X(h)_{ij}^p + \sum_n \sum_s E(h)^{ns} \left(\sum_i \sum_j X(h)_{ij}^{ns} \right) + \sum_i \sum_j \sum_q E(h)_j^q X(h)_{ij}^q$$

$$Cost: \quad \sum_i \sum_j \sum_p \left[C(h)_i^p X(h)_{ij}^p + C(\bar{h})_i^p X(\bar{h})_{ij}^p \right]$$
$$+ \sum_s \sum_i \sum_j \left[C(h)^s X(h)_{ij}^s + C(\bar{h})^s X(\bar{h})_{ij}^s \right]$$
$$+ \sum_i \sum_j \sum_q \left[C(h)_j^q X(h)_{ij}^q + C(\bar{h})_j^q X(\bar{h})_{ij}^q \right] \qquad (1)$$
$$+ \sum_s C^s N^s$$

Subject to:

$$\sum_p X(h)_{ij}^p = \sum_n \sum_s X(h)_{ij}^{ns} \qquad \forall i, j \qquad (2)$$

$$\sum_p X(\bar{h})_{ij}^p = \sum_s X(\bar{h})_{ij}^s \qquad \forall i, j \qquad (3)$$

$$\sum_n \sum_s X(h)_{ij}^{ns} = \sum_q X(h)_{ij}^q \qquad \forall i, j \qquad (4)$$

$$\sum_s X(\bar{h})_{ij}^s = \sum_q X(\bar{h})_{ij}^q \qquad \forall i, j \qquad (5)$$

$$\sum_q X(h)_{ij}^q = D(h)_{ij} \qquad \forall i, j \qquad (6)$$

$$\sum_q X(\bar{h})_{ij}^q = D(\bar{h})_{ij} \qquad \forall i, j \qquad (7)$$

$$\sum_n \sum_i \sum_j \left[X(h)_{ij}^{ns} + X(\bar{h})_{ij}^s \right] \le U^s N^s \qquad \forall s \qquad (8)$$

$$t(in)_i^p Y_{ij}^p + t(s) Y_{ij}^s + t(out)_j^q Y_{ij}^q \le L_j \qquad \forall p, i, j, q, s \qquad (9)$$

$$MY_{ij}^p \ge X(h)_{ij}^p \qquad \forall p, i, j \qquad (10)$$

$$MY_{ij}^p \ge X(\bar{h})_{ij}^p \qquad \forall p, i, j \qquad (11)$$

$$MY_{ij}^q \ge X(h)_{ij}^q \qquad \forall q, i, j \qquad (12)$$

$$MY_{ij}^q \ge X(\bar{h})_{ij}^q \qquad \forall q, i, j \qquad (13)$$

$$MY_{ij}^s \ge X(h)_{ij}^{ns} \qquad \forall n, s, i, j \qquad (14)$$

$$MY_{ij}^s \ge X(\bar{h})_{ij}^s \qquad \forall s, i, j \qquad (15)$$

Sign Restriction Constraints on flow variables: $X \ge 0$ integer; $N^s \ge 0$ integer; and, $Y \in \{0,1\}$ on all indicator variables.

This is a bi-criteria problem, with risk and cost objectives as represented in (1). The cost objective contains inbound drayage cost, rail-haul cost, outbound drayage cost, and the fixed cost to operate different types of train services. The risk objective represents population exposure due to inbound and outbound drayage as well as each train operating between the IMRTs. Note that the transport risk associated with a train is a function of the hazmat containers in its cargo, and hence we have an additional superscript n to keep track of this number for each train. It is important to note that the risk function $E(h)^{ns}(.)$: is indeed nonlinear. Constraints (2) through (5) represent the transshipment nature of the two terminals, while accounting for different types of train services in the network. It should be noted that transshipment constraints for hazmat and regular freight have to be distinguished in order to track them independently. Constraints (6) and (7) ensure that each receiver's hazmat and regular freight demands are satisfied. The maximum numbers of containers that can be loaded on each type of intermodal train are imposed by (8), which also determine the number of trains needed for each service type. The lead-time constraints (9), ensure that delivery takes place by the specified deadline from each shipper to each receiver. These constraints evaluate, based on travel and activity times, the feasibility of the three transport links of an IM chain. Note that the train segment evaluation involves comparing different available options. Constraints (11) to (15) determine values of the indicator variables based on the values of the flow variables. For example, if flow variable moves on a certain path then the indicator variable corresponding to that path will be activated, which in turn will be used in (9) to evaluate the feasibility of including the path in the formation of a complete intermodal chain.

We developed a solution procedure for the proposed model, which is based on a decomposition of the problem into its cost and risk components. This decomposition is possible because the pair of IMRTs act as transshipment points through which all the demand is served. Consequently, the drayage and rail-haul portions of the problem can be solved separately. For space considerations, the details of the solution algorithm are not provided in this extended abstract. Interested readers are invited to contact the authors for a full manuscript.

3. Case Study: IM Shipments from Quebec to British Columbia

A realistic problem instance based on intermodal shipments across Canada by CPR (-one of the two major railroad companies in the country) is developed and solved using the proposed methodology. In Canada, the westbound traffic volume via IM is significantly larger than that for the eastbound traffic. Therefore, the problem instance focuses on intermodal shipments from Quebec to British Columbia that contain hazardous as well as regular freight. Although the IM infrastructure and population data used in this case are accurate, hypothetical demand data were used to safeguard confidentiality. The randomly generated demand between origin-destination pairs range from 5 to 23 containers, while the number of containers with hazardous cargo vary from 2 to 11. A total of 1036 container shipments are to be planned among 100 origin-destination pairs, where each shipment delivery needs to be made within the stipulated lead time. We adopt CPR's *door-to-door* service plan with their equipment in this paper.

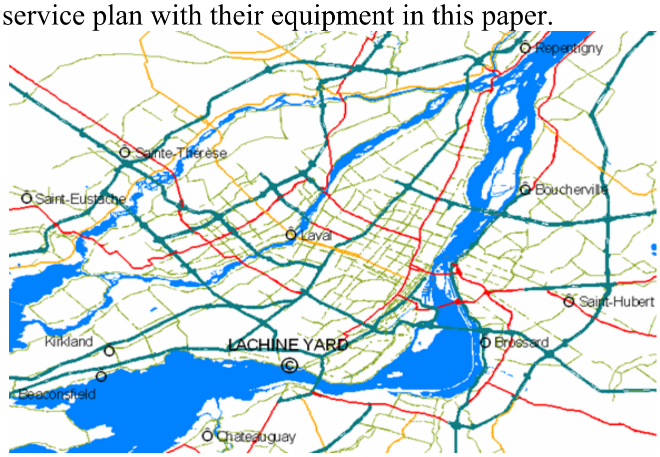

Figure 1: The shippers and the Lachine IMRT

We assume that there are ten shippers in Quebec, distributed around the Island of Montreal, and each has to fulfill (hazmat and non-hazmat) orders of ten customers in British Columbia. The ten shippers are at Repentigny, Boucherville, Saint Hubert, Brossard, Chateauguay; Beaconsfield, Kirkland, Saint-Eustache, Sainte-Therese, and Laval (see Figure 1). The IMRT in *Lachine* municipality, on the Island of Montreal, is the only intermodal terminal available to these ten shippers. Each shipper is linked to Lachine IMRT through the road network. The thicker links in Figure 1 represent the expressways, whereas the thinner links depict roads of other types. Among the multiplicity of available routes, it is natural for a truck driver to take the shortest path between the shipper and the IMRT irrespective of the nature of cargo. We assume that these shipments are directed to the Delta Port in *Vancouver*, British Columbia, which is the destination IMRT in this problem instance. The ten receivers are: Kelowna, Kamloops, Burnaby, Surrey, Richmond, Haney, Coquitlam, Forest Hills, Prince George, and Prince Rupert (for the six receivers closest to Vancouver. We assume that the truck driver stays on-site during loading and unloading at the shipper and receiver locations.

Figures 2a and 2b depict the southern and northern intermodal train routes between Montreal and Vancouver, respectively. On each route, there are two types of train services operating between the IMRT pair, a *regular* train service and a *premium* train service that is roughly 25% faster. As mentioned earlier, we assume that all parties strive for a *just-in-time* approach and hence the waiting times prior to loading, unloading and transshipment activities along the IM chain are negligible. Furthermore we assume that there is enough equipment at each stage of the IM chain to prevent any congestion.

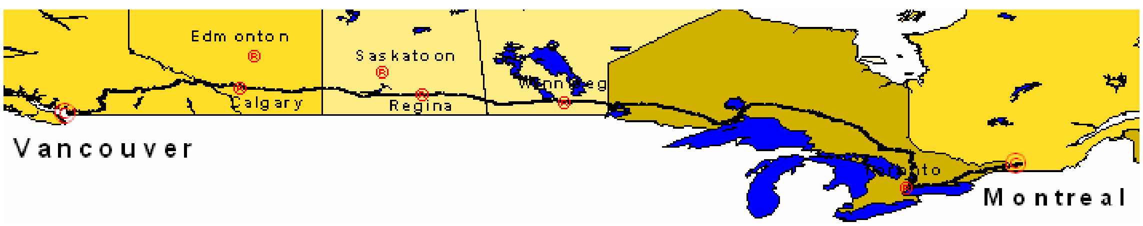

Figure 2a: The Southern IM route through Calgary

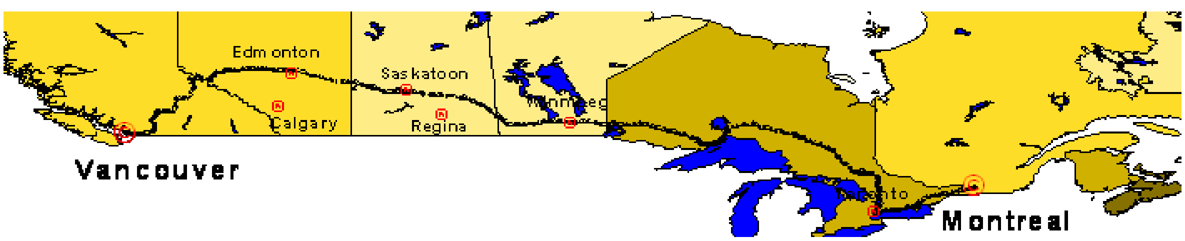

Figure 2b: The Northern IM route through Edmonton

Finally, based on our interviews with the CPR managers, we have estimated the approximate delivery times associated with each order. We estimated that the receivers at Kelowna and Kamloops want to receive their orders within 5 days (120 hrs) from the time an order has been placed. Receivers in and around Vancouver (Burnaby, Surrey, Richmond, Haney, Forest Hills and Coquitlam) have specified 3.5 days (84 hours) as the deadline. The two furthest points, Prince George and Prince Rupert, have specified 6 days for delivery.

Our presentation will report on the managerial insights gained through the analysis of this case study. Our main finding is that IM train make-up plans based on the use of trains comprising only hazmat cargo lead to considerable reductions in the population exposure. We observed that it is also possible to reduce population exposure by employing premium service (i.e. faster) IM trains so that it is feasible to use longer but less risky routes for inbound and outbound drayage.

Bibliography

Arnold, P., Peeters, D., Thomas, I., 2004. Modeling a rail/road intermodal transportation system. Transportation Research E 40(3), 225-270.

Assad, A.A., 1980. Modeling of Rail Networks: Toward a Routing / Makeup Model. Transportation Research B 14, 101-114.

Ballis, A., Golias, J., 2004. Towards the improvement of a combined transport chain performance. European Journal of Operational Research 152(2), 420-436.

Barnhart, C., Ratliff, H. D., 1993. Modeling Intermodal Routing. Journal of Business Logistics 14(1), 205-223.

Barton, J. E., Selness, C. L., Anderson, R. J., Lindberg, D. L., Foster, N. S. J., 1999. Developing a Proposal for a Multi-User Intermodal Freight Terminal as a Public-Private Partnership. Transportation Research Record 1659, 145-151.

Batta, R., Chiu, S.S., 1988. Optimal obnoxious paths on a network: transportation of hazardous materials. Operations Research 36(1), 84-92.

Bontekoning, Y. M., 2000. The Importance of New-Generation Freight Terminals for Intermodal Transport. Journal of Advanced Transportation 34(3), 391-413.

Bontekoning, Y. M., Macharis, C., Trip, J. J., 2004. Is a new applied transporation research field emerging? –A review of intermodal rail-truck freight transport literature. Transportation Research A 38(1), 1-34.

Bookbinder, J.H., Fox, N.S., 1998. Intermodal Routing of Canada – Mexico Shipments Under NAFTA. Transportation Research E 34(4), 289-303.

Calluri, V., 2004. Personal Communication.

Cordeau, J-F., Toth, P., Vigo, D., 1998. A Survey of Optimization Models for Train Routing and Scheduling. Transportation Science 32(4), 384-404.

Crainic, T.G., Kim, K.H., 2005. Intermodal Transportation. Handbooks in Operations Research and Management Science. In: G. Laporte and C. Barnhart (Eds.). Forthcoming.

Erkut, E., Tijandra, S., Verter, V., 2005. Hazardous Materials Transportation. Handbooks in Operations Research and Management Science. In: G. Laporte and C. Barnhart (Eds.). Forthcoming.

Evers, P.T., 1994. The occurrence of statistical economies of scale in intermodal transportation. Transportation Journal 33(4), 51-63.

Gooley, T. B., 2001. Local Connections. Logistics Management and Distribution Report 40(1), 65.

Janic, M., Reggiani, A., Nijkamp, P., 1999. Sustainability of the European Freight Transport System: Evaluation of Innovative Bundling Networks. Transportation Planning and Technology 23(2), 129-156.

Jourquin, B., Beuthe, M., Demille, C. L., 1999. Freight Bundling Network Models: Methodology and Application. Transportation Planning and Technology 23(2), 157-177.

Logistics Management, 2004. Intermodal posts record gains in 2003. Logistics Management 43(2), 15.

Macharis, C., Bontekoning, Y.M., 2004. Opportunities for OR in intermodal freight transport research: A review. European Journal of Operational Research 153(2), 400-416.

Morlok, E.K., Spasovic, L.N., 1995. Approaches for Improving Drayage in Rail-Truck Intermodal Service. Proceedings of The 1995 Pacific Rim Transportation Conference, Seattle, WA, USA.

Newman, A.M., Yano, C.A., 2000. Scheduling Direct and Indirect Trains and Containers in an Intermodal Setting. Transportation Science 34(3), 256-270.

North American Emergency Response Guidebook, 2000. Prepared by Transport Canada, U.S. Department of Transportation and the Secretariat of Communications and Transportation of Mexico.

Nozick, L.K., Morlok, E.K., 1997. A Model for Medium-Term Operations Planning in an Intermodal Rail-Truck Service. Transportation Research A 31(2), 91-107.

Powell, W.B., Carvalho, T.A., 1998. Real-Time Optimization of Containers and Flatcars for Intermodal Operations. Transportation Science 32(2), 110-126.

Priemus, H., 1999. On Modes, Nodes and Networks: Technological and Spatial Conditions for a Breakthrough Towards Multimodal Terminals and Networks of Freight Transport in Europe. Transportation Planning and Technology 23(2), 83-103.

ReVelle, C., Cohon, J., Shobrys, D., 1991. Simultaneous siting and routing in the disposal of hazardous wastes. Transportation Science 25(2), 138-145.

Richardson, H.L., 2002. Rail service on the right track-finally. Transportation and Distribution 43(2), 50-54.

Rizzoli, A. E., Fornara, N., Gambardella, L. M., 2002. A simulation tool for combined rail/road transport in intermodal terminals. Mathematics and Computers in Simulation 59(2), 57-71.

Rondinelli, D., Berry, M., 2000. Multimodal Transportation, Logistics, and the Environment: Managing Interactions in a Global Economy. European Management Journal 18(4), 398-410.

Southworth, F., Peterson, B.E., 2000. Intermodal and international freight network modeling. Transportation Research C 8, 147-166.

Stone, S., 1999. Intermodal at global watershed point. Purchasing 126(8), 103.

Stone, B.A., 1997. Profitability and Risk. Containerization International 30(11), 83-85.

Szyliowicz, J. S., 2003. Decision-making, intermodal transportation, and sustainable mobility: towards a new paradigm. UNESCO 2003. Blackwell Publishing Ltd.

Trip, J.J., Bontekoning, Y., 2002. Integration of small freight flows in the intermodal transport system. Journal of Transport Geography 10, 221-229.

U.S. Department of Transportation, Bureau of Transportation Statistics., 1997. Hazardous Materials Shipments by Mode of Transportation.

U.S. Department of Transportation., 2000. Departmentwide Program Evaluation of the Hazardous Materials Transportation Programs Final Report. March.

U.S. Department of Transportation., 2004. 2002 Economic Census: Transportation and Commodity Flow Survey. December.

Verma, M. and V. Verter 2007. Rail Transportation of Hazardous Materials: Population Exposure to Airborne Toxins, *Computers & Operations Research*, 34(5) pp. 1287-1303.

Verma, M., Verter, V., Gendreau, M., 2005. A Tactical Planning Model for the Railroad Transportation of Mixed Freight. Working Paper, Faculty of Business Administration, Memorial University.

Wiegmans, B. W., Masurel, E., Nijkamp, P., 1999. Intermodal Freight Terminals: An Analysis of the Terminal Market. Transportation Planning and Technology 23(2), 105-128.