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Service Design Models for Rail Intermodal Transportation

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Abstract. Intermodal transportation forms the backbone of the world trade and exhibits significant growth resulting in modifications to the structure of maritime and land-based transportation systems, as well as in the increase of the volumes and value of intermodal traffic moved by each individual mode. Railroads play an important role within the intermodal chain. Their own interests and environment-conscious public policy have railroads aiming to increase their market share. To address the challenge of efficiently competing with trucking in offering customers timely, flexible, and "low"-costing transportation services, railroads propose new types of services and enhanced performances. From an Operations Research point of view, this requires that models be revisited and appropriate methods be devised. The paper discusses some of these issues and developments focusing on tactical planning issues.

Keywords. Intermodal transportation, freight rail carriers, tactical planning, full-asset-utilization policies, intermodal shuttle networks, service network design.

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I. Introduction

Intermodal transportation forms the backbone of the world trade and exhibits significant growth. The value of multimodal shipments in the U.S., including parcel, postal service, courier, truck-and-rail, truck-and-water, and rail-and-water, increased from about $662 billion to about $1.1 trillion in a period of nine years (1993 to 2003; USDOT, 2006). In the same period, the total annual world container traffic grew from some 113.2 millions of TEUs (20 feet equivalent container units) to almost 255 millions, reaching an estimated 304 millions of TEUs by 2005.

Intermodal transportation involves, sometimes integrates, at least two modes and services of transportation to improve the efficiency of the door-to-door distribution process. The growth in intermodal traffic thus resulted in significant modifications to the structure of maritime and land-based transportation systems as well as in major increase of the volumes and value of intermodal traffic moved by each individual mode. Thus, for example, in 2003, for the first time ever, intermodal freight surpassed coal as a source of revenue for major, Class I, U.S. railroads, representing 23% of the carriers' gross revenue (USDOT, 2006). The growth of intermodal rail traffic in the U.S., which reached 11 million trailers (26% of total) and containers (76%) in 2004, is the direct result of the rapid growth in the use of containers for international trade, imports accounting for the majority of the intermodal activity (USDOT, 2006).

Governmental policy may also contribute to re-structuring intermodal transportation and shifting parts of the land part of the journey from trucking towards rail and water (interior and coastal navigation). This is, for example, the main focus of the European Union as stated in its 2001 White Paper on transportation (European Commission, 2001). The reason for this is to reduce road congestion and promote environmentally friendlier modes of transportation. The instruments favoured to implement such policies vary from road taxes to penalize truck-based transportation to the support of new rail services for intermodal traffic.

The performance of intermodal transportation depends directly on that of the key individual elements of the chain, navigation companies, railroads, motor carriers, ports, etc., as well as on the quality of their interactions regarding operations, information, and decisions. The Intelligent Transportation Systems and Internet-fuelled electronic business technologies provide the framework to address the latter challenges. Regarding the former, carriers and terminals, on their own or in collaboration, strive to continuously improve their performance. Railroads are no exception. Indeed, for intermodal as for general traffic, railroads face significant challenges to efficiently compete with trucking in offering customers timely, flexible, and "low"-cost, long-haul transportation services.

Railroads are rising to the challenge by proposing new types of services and enhanced performances. Thus, North-American railroads have created intermodal subdivisions that operate so-called "land-bridges" providing efficient container transportation by long, double-stack trains between the East and the West coasts and between these ports and the industrial core of the continent (so-called "mini" land-bridges). Most North-American railroads are now enforcing some form of scheduled service. In Europe, where congestion has long forced the scheduling of trains, the separation of the infrastructure ownership from service providing increases the

competition and favours the emergence of new carriers and services. Moreover, the expansion of the Community to the east provides the opportunity to introduce new services that avoid the over-congested parts of the European network. New container and trailer-dedicated shuttle-train networks are thus being created within the European Community.

The planning and management processes of these new railroad-based intermodal systems and operations are generally no different from those of "traditional" systems in terms of issues and goals, profitability, efficiency, and customer satisfaction. The "new" operating policies introduce, however, elements and requirements into the planning processes which, from an Operations Research point of view, require that models be revisited and appropriate methods be devised.

This paper aims to discuss some of these issues and developments. It focuses on the tactical planning of rail intermodal services in North America and Europe and is based on a number of observations and on-going projects. Its goal is to be informative, point to challenges, and identify opportunities for research aimed at both methodological developments and actual applications.

II. Intermodal and Rail-based Transportation

Many transportation systems are *multimodal*, their infrastructure supporting various transportation modes, such as truck, rail, air, and ocean/river navigation, carriers operating and offering transportation services on these modes. Then, broadly defined, *intermodal transportation* refers to the transportation of people or freight from their origin to their destination by a sequence of at least two transportation modes. Transfers from one mode to the other are performed at *intermodal terminals*, which may be a sea port or an in-land terminal, e.g., rail yards, river ports, airports, etc. Although both people and freight can be transported using an intermodal chain, in this paper, we focus on the latter.

The fundamental idea of intermodal transportation is to *consolidate* loads for efficient long-haul transportation performed by large ocean vessels and, on land, mostly by rail and truck. Local pick-up and delivery is usually performed by truck. Most of the freight intermodal transportation is performed by using containers. Intermodal transportation is not restricted, however, to containers and intercontinental exchanges. For instance, the transportation of express and regular mail is intermodal, involving air and land long-haul transportation by rail or truck, as well as local pick up and delivery operations by truck (Crainic and Kim, 2006). Moving trailers on rail is also identified as intermodal. In this paper, we focus on container and trailer-based transportation by railroads.

Intermodal transportation systems and railroads may be described as being based on *consolidation*. A consolidation transportation system is structured as a *hub-and-spoke* network, where shipments for a number of origin-destination points may be transferred via intermediate consolidation facilities, or *hub*s, such as airports, seaport container terminals, rail yards, truck break-bulk terminals, and intermodal platforms. An example of such a network with three hubs and seven regional terminals is illustrated in Figure 1 (Bektas and Crainic, 2007). In hub-and-spoke networks, low-volume demands are first moved from their origins to a hub where traffic is sorted (classified) and grouped

(consolidated). The aggregated traffic is then moved in between hubs by efficient, "high" frequency and capacity, services. Loads are then transferred to their destination points from the hubs by lower frequency services often utilizing smaller vehicles. When the level of demand is sufficiently high, direct services may be run between a hub and a regional terminal.
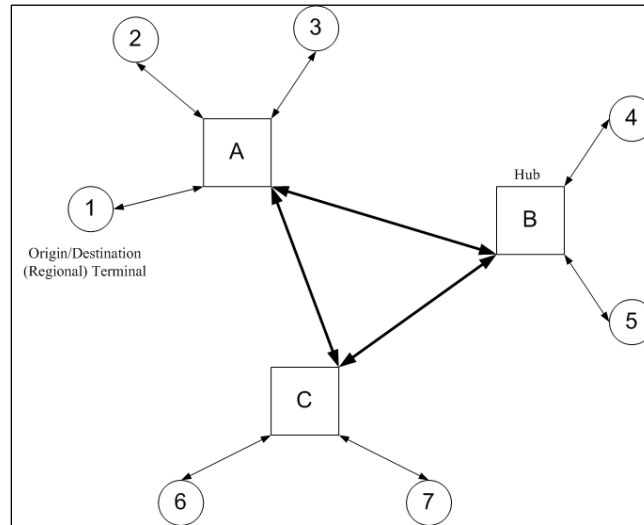

Figure 1. A hub-and-spoke network (Bektaş and Crainic, 2007)

Railroads operate most of their services according to a double-consolidation policy based on a series of activities taking place at rail hubs, the so-called *classification* or *marshalling yards*. The first consolidation activity concerns the sorting and grouping of railcars into *blocks*. A block is thus made up of cars of possibly different origins and destinations, which travel as a single unit between the origin and destination of the block. Consequently, the only operation that could be performed on a block at a yard which is not its destination is to transfer it from one service to another. The second consolidation activity taking place at yards, known as *train make up*, concerns the grouping of blocks into trains.

Although a hub-and-spoke network structure results in a more efficient utilization of resources and lower costs for shippers, it also incurs a higher amount of delays and a lower reliability due to longer routes and the additional operations performed at terminals. Carriers thus face a number of issues and challenges in providing services that are simultaneously profitable and efficient for the firm and high quality and cost effective for customers. Operations Research has contributed a rich set of models and methods to assist addressing these issues and challenges at all levels of planning and management, classically identified as *strategic* (long term), *tactical* (medium term), and *operational* (short term). A more in-depth treatment of these topics may be found, for example, in the reviews of Cordeau, Toth, and Vigo (1998), Crainic and Laporte (1997), Crainic (2003), and Crainic and Kim (2006). In this paper, we focus on tactical planning issues.

III. New Rail Intermodal Services

Traditional railroad operating policies were based on long-term contracts, providing "sure" high volumes of (very often bulk) freight to move. Cost per ton/mile (or km) was the main performance measure, with somewhat little attention being paid to delivery performance. Consequently, rail services in North America, and mostly everywhere else in the world, were organized around loose schedules, indicative cut-off times for customers, "go-when-full" operating policies, and significant marshalling activities in yards. This resulted in rather long and unreliable trip times that generated both inefficient asset utilization and loss of market share. This was not appropriate for the requirements of intermodal transportation and the North American rail industry responded through (Crainic, Bilegan, and Gendreau, 2006):

1. A significant re-structuring of the industry through a series of mergers, acquisitions, and alliances which, although far from being over, has already drastically reduced the number of companies resulting in a restricted number of major players.

2. The creation of separate divisions to address the needs of intermodal traffic, operating dedicated fleets of cars and engines, and marshalling facilities (even when located within regular yards). Double-stack convoys have created the land-bridges that ensure an efficient container movement across North America.

3. An evolution towards planned and scheduled modes of operation and the introduction of booking systems and full-asset-utilization operating policies.

Booking systems bring intermodal rail freight services closer to the usual mode of operation of passenger services by any regular mode of transportation, train, bus, or air. In this context, each class of customers or origin-destination market has a certain space allocated on the train and customers are required to call in advance and reserve the space they require. The process may be phone or Internet based but is generally automatic, even though some negotiations may occur when the train requested by the customer is no longer available. This new approach to operating intermodal rail services brings advantages for the carrier, in terms of operating costs and asset utilization, and the customers (once they get used to the new operating mode) in terms of increased reliability, regular and predictable service and, eventually, better price.

A full-asset-utilization operation policy generally corresponds to operating regular and cyclically-scheduled services with fixed composition. In other words, given a specific frequency (daily or every given number of days), each service occurrence operates a train of the same capacity (length, number of cars, tonnage) and composition, that is, the same blocks, each block with the same definition, origin, destination, number of cars, and the same distribution of cars among its composing origin-destinations.

Assets, engines, rail cars and even crews, assigned to a system based on full-asset-utilization operation policies can then "turn" continuously following circular routes and schedules (which include maintenance for vehicles and rest periods for crews) in the time-space service network, as schematically illustrated in Figure 2 for a system with three yards and six time periods (Andersen, Crainic, and Christiansen, 2006). The solid lines in Figure 2a represent services. There is one service from node 1 to node 3 (black arcs) and one service from node 3 to node 2 (grey arcs), both with daily frequency. Dotted arcs indicate repositioning moves (between different nodes) and holding arcs

(between different time representations of same node). One feasible vehicle circuit in the time-space service network is illustrated in Figure 2b. The vehicle operates the service from node 3 to node 2, starting in time period 1 and arriving in time period 3. Then from period 3 to period 4 the vehicle is repositioned to node 1, where it is held for two time periods. In period 6 the vehicle operates the service from node 1 to node 3, arriving at time 1 where the same pattern of movements starts all over again. The planning of systems operating according to such policies requires the development of new models and methods, as described in the next section.

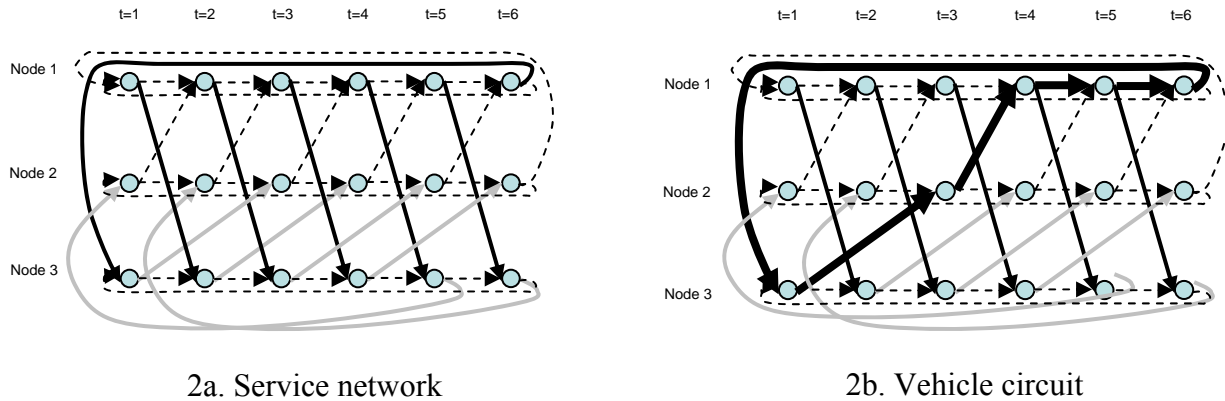| 2a. Service network | 2b. Vehicle circuit |

Figure 2. Full-asset-utilization-based service network and vehicle circuit

(Andersen, Crainic, and Christiansen, 2006)

Most Western Europe railroads have for a long time now operated their freight trains according to strict schedules, similarly to their passenger trains. This facilitated both the interaction of passenger and freight trains and the quality of service offered to customers. Particular characteristics of infrastructure (e.g., low overpasses) and territory (short inter-station distances) make for shorter trains than in North America and forbid double-stack trains. Booking systems are, however, being implemented and full-asset-utilization and revenue management operating policies are being contemplated. Moreover, intermodal shuttle-service networks are being implemented in several regions of the Union to address the requirements of the European Commission policy and the congested state of the infrastructure (e.g., Andersen and Christiansen, 2006 and Pedersen and Crainic, 2007).

Indeed, European railroads face a number of particular challenges. First, the rail infrastructure, as almost the entire transportation infrastructure in Europe, is very congested. Second, the liberalization of the rail industry in Europe has lead to a separation of the traditional national rail companies into infrastructure owners and service operators. The former manage the infrastructure and associated network capacity, while the latter operate trains according to the capacity acquired from the infrastructure managers. This liberalization favours the emergence of new rail operators providing specialized services, in particular intermodal rail shuttle services between cities with high traffic demand.

The limited capacity of most of the infrastructure, at least in the western part of the network, together with the increasing number of operators, forces the allocation of

capacity according to pre-defined routes and times, which makes planning decisions and the efficient utilization of resources more difficult. The European Union, the member states, and the corresponding rail authorities are implementing steps, however, towards interoperability and an interconnected trans-European rail network for freight trains, the so-called *freight freeways* (European Commission, 1996). As a result, one assists at the emergence of large service networks across the European continent operated by single operators or by alliances of operators, similar to those seen in the airline industry. The resulting service networks will be complex to plan and operate and appropriate models and methods must be developed. Pedersen and Crainic (2007) detail the case and propose a first service network design model.

To alleviate the congestion in the "central" part of the network while working towards the goal of increasing the market share of rail and navigation, new intermodal services are being studied using the networks of countries that have recently joined the Union. Andersen and Christiansen (2006) describe such a project. The Polcorridor Logchain study (Polcorridor, 2006) aims to develop a new intermodal transport corridor between Northern and South-Eastern Europe taking advantage of previously unused railway capacity in Poland, the Czech Republic and Austria, and thus create a fast and reliable transport solution than can compete with the more traditional route through Germany. The authors propose a formulation to determine an optimal service level and design that accounts for both operating costs and a number of service quality criteria. An extensive network of inland waterways, sea transport, trucking services, and other railway lines will be used as distribution networks at the extremities of the new network. This requires *external* synchronization of schedules with partner carriers. *Internal* synchronization is also required to account for power-equipment switching at particular borders due to different technical standards between participating national railroads. Andersen, Crainic, and Christiansen (2006) propose formulations for this case.

IV. Impact on Planning Models

A study of the trends observed in North America and Europe, illustrated by the cases mentioned in the previous section, indicates a number of converging issues. One may sum up these issues by noticing that the operations and asset management of intermodal railroads are more and more similar to those of long-haul passenger transportation, airlines and fast rail, particularly. Services are thus precisely scheduled and service space is booked in advance. Moreover, schedules are repetitive (cyclic) and synchronized, both internally among the railroad's own services and externally with those of partner carriers. This implies tighter consolidation, classification, transfer, and make-up operations at terminals, as well as scheduling assets for maximum but efficient utilization.

Traditionally, planning was performed through a series of tasks, planning models being used one after another to address particular issues: design of the service network and schedules, power (locomotive) assignment and management, empty railcar repositioning and fleet management, and so on. This approach was not particular to railroads or freight transportation, since it resulted from the traditional management structure of the carriers and the limitations of our capabilities in addressing large-scale combinatorial formulations with complex additional constraints. Managerial structures evolve and our capabilities are continuously being enhanced, both in terms of computer power and methodology sophistication. The trend towards integrated models that address

several issues previously treated separately, initially observed within the airline industry (e.g., Barnhart *et al.*, 2003) is now influencing the development of planning methods for railroad operations, most particularly within the field of intermodal transport.

To briefly illustrate these issues and the corresponding challenges, consider that to adequately plan operations according to a full-asset-utilization operating policy requires the asset circulation issue to be integrated into the service network design model.

Recall that service network design is concerned with the planning of operations related to the selection, routing, and scheduling of services, the consolidation and make-up activities at terminals, and the routing of freight of each particular demand through the physical and service network of the company (see, for example, the surveys of Crainic, 2000, for service network design, Crainic, 2003, for long-haul land transportation, Crainic and Kim, 2007, and Macharis and Bontekoning, 2004, for intermodal transportation, Christiansen, Fagerholt, and Ronen, 2004, and Christiansen *et al.*, 2007, for maritime navigation, and Cordeau, Toth, and Vigo, 1998, for railroads). These activities are a part of tactical planning at a system-wide level. The two main types of decisions considered in service network design aim the determination of the service network and the routing of demand. In the railroad context, the former refers to selecting the train routes and attributes, such as the *frequency* or the *schedule* of each service. The latter is concerned with the *itineraries* that specify how to move the flow of each demand, including the services and terminals used, the operations performed at these terminals, etc. The objective is generally concerned with the minimization of a global measure of the performance of the system that includes operating costs of providing services, performing yard operations, and moving freight, as well as service-quality measures usually based on delays to equipment and loads. The term "generalized cost" is often used in these cases.

The basic service network design mathematical models take the form of deterministic, fixed cost, capacitated, multicommodity network design (CMND) formulations (Magnanti and Wong, 1984, Crainic, 2000, Crainic and Kim, 2007). Let S represent the service network, defined on a graph $G = (N, A)$ representing the physical infrastructure of the system, which specifies the transportation services that could be offered. Each potential service $s \in S$ is characterized by a number of attributes such as its route, capacity measured in number of vehicles, length, total weight, or a combination thereof, service class indicating the speed and priority, as well as, eventually power type, preferred traffic or restrictions, etc. When schedules are to be determined, departure time from origin, as well as arrival at and departure times from intermediary stops are also included. The service network is used to move commodities $p \in P$ defined by their origins, destinations, type of product or vehicle to be used, priority class, and so on. The demand for product p is denoted by d_p. Traffic moves according to itineraries defined within the model as service paths $l \in L_p$ for commodity p, each specifying the intermediary terminals where operations (e.g., consolidation or transfer) are to be performed and the sequence of services between each pair of consecutive terminals where work is performed.

Flow routing decisions are then represented by decision variables h_l^p indicating the volume of product p moved by using its itinerary $l \in L_p$. Service-selection decision variables $y_s \text{ }^{TM}Y, s \in S$, may be used to determine the level of service offered measured as

the frequency of each selected service, that is, how often each service is run during the planning period, in which case $Y = \{y \geq 0 \text{ and } integer\}$. When schedules are to be built, the service variables stand for the decision whether to operate service s or not and y_s ™ $\{0, 1\}$. Let $F_s(y)$ and $C_l^p(y,h)$ denote the generalized cost of operating service s and moving (part of) product p demand by using its itinerary l, respectively. The model is written as

$$\text{Minimize} \qquad \sum_{s \in S} F_s(y) + \sum_{p \in P} \sum_{l \in L_p} C_l^p(y,h) + \theta(y,h)$$

$$\text{subject to} \qquad \sum_{l \in L_p} h_l^p = d_p \qquad\qquad p \in P,$$

$$(y_s, x_l^p) \in X \qquad\qquad s \in S, l \in L_p, p \in P,$$

$$y_s \in Y \qquad\qquad s \in S,$$

$$h_l^p \geq 0 \qquad\qquad l \in L_p, p \in P,$$

where $(y_s, x_l^p) \in X$ stand for the classical linking constraints (i.e., no flow may use an unselected service) as well as additional constraints reflecting particular characteristics, requirements, and policies of the particular firm (e.g., particular routing or load-to-service assignment rules). The last term of the objective function indicates additional restrictions, e.g., service capacity, expressed as utilization targets, which may be allowed to be violated at the expense of additional penalty costs. The model captures the essence of static and time-dependent formulations. In the former case, the two types of design selection decision variables may be encountered, while in the latter, binary design variables represent decisions are associated to possible departure times of given services.

To introduce the asset management considerations into the service network design model, one first adds constraints enforcing the conservation of the flow of vehicles at terminals,

$$\sum_{s \in S} y_{si^+} - \sum_{s \in S} y_{si^-} = 0 \qquad\qquad s \in S, i \in N,$$

where si^+ indicates that service $s \in S$ arrives and stops or terminates at node (yard) $i \in N$, while si^- says, symmetrically, that service $s \in S$ initiates its journey or stops and departs from node $i \in N$.

The resulting formulations, denoted design-balanced capacitated multicommodity network design problems (DBCMND) by Pedersen, Crainic, and Madsen (2006), account for coherent movements in and out of terminals (particularly when "empty" movements are allowed), but in static formulations do not provide the means to address issues related to the management of the fleet. Time-dependent formulations, where possible service departures are explicitly defined on a space-time representation of operations over the planning horizon provide the means to generate feasible vehicle circuits. The time-space network is usually built in a closed, circular fashion, to represent the cyclic repetitiveness

of the resulting schedules, and includes load and vehicle holding and, eventually, repositioning arcs.

This generalization of the CMND model has not been studied much. A few applications may be found in planning maritime liner (reviewed in Christiansen *et al.*, 2007) or ferry (Lai and Lo, 2004) routes and express postal services (e.g., Barnhart and Schneur, 1996 and Kim at al., 1999) where vehicles, ships and airplanes, have high acquisition and utilization costs and their management is central to the efficient operation of the system. Smilowitz, Atamtürk, and Daganzo (2003) are also studying an express postal network, but their focus is on the land fleet management. They develop a time-dependent formulation similar to the one present above and propose a procedure where, first, the linear programming relaxation of the problem is solved (approximately for large problem instances) using column generation and, second, a feasible solution is obtained by applying repetitively a sequence of rounding and cut-generation procedures.

The DBCMND is a difficult problem with an added "complexity layer" compared to the CMND and much work is required to study it and develop efficient exact and heuristic solution methods. A few efforts are under way. Pedersen, Crainic, and Madsen (2006) start from the generic DBCNDP formulation and propose a two-stage, tabu search-based meta-heuristic that is shown to be efficient for problem instances up to 700 service arcs and 400 commodities. Andersen, Crainic, and Christiansen (2007) study various problem formulations, where demand flows are represented by arc or path variables, while design decisions are represented by arcs or cycle variables. Notice that the latter correspond to circuits of vehicles, the service selection, design, decisions becoming thus implicit in the selection of strategies for fleet management. Preliminary results show a very good computational behaviour for cycle-based formulations.

Many other issues have to be addressed and offer an exiting research perspective. Consider, for instance, that actual applications bring a rich set of additional constraints that generally add to the complexity of the formulation. Thus, Pedersen and Crainic (2007) discuss the need for a more general definition of "periods" within time-dependent formulations to capture adequately the time intervals when services overlap at terminals and load transfers may be performed. The authors also emphasize the need for a more detailed representation terminal operations, loading, unloading, classification, transfer, waiting, and so on, to capture their time and capacity impacts on the general performance of the system. This aspect is also emphasized by Andersen, Crainic, and Christiansen (2006) who detail the operations in terminals connecting the system studied to adjacent maritime and land systems, and focus on the need to synchronize services both internally, among services using possibly different vehicle fleets, and externally with services belonging to neighbouring systems.

It is also worthy of consideration that, although bookings tend to "smooth" out demand, the variability inherent to the system is not altogether eliminated. Regular operations tend to be disrupted by a number of phenomena, including the fact that, for example, arrivals of ocean ships in container port terminals are not regularly distributed and custom and security verification may significantly delay the release of containers. When this occurs, rail operations out of the corresponding ports are severely strained: there might be several days without arrivals, followed by a large turnout of arriving containers. Optimization approaches (e.g., Crainic, Bilegan, and Gendreau, 2006) may be

used to adjust service over a medium-term horizon in such a way that a full-asset-utilization policy is still enforced, but a certain amount of flexibility is added to services to better fit service and demand. Such approaches may become even more effective when appropriate information sharing and container-release time mechanisms are implemented.

Many other issues offer rich research challenges and opportunities. One may mention the explicit consideration of stochastic elements in tactical planning models. Preliminary results indicate that the plans thus obtained are different and "better" from a robustness point of view, but much more work is needed in this field. Terminal issues require attention. While the literature dedicated to container port terminals is rather rich, there is almost nothing dedicated to rail yards within the intermodal context (the work by Bostel and Dejax, 1998, is the only exception we are aware of and it is directed towards an innovative but as yet not implemented rail transportation system). On a more operational level, work is required on, for example, detailed fleet management and procedures to mitigate the impact of incidents and accidents on service and to guide the process of getting back to normal operations following such disruptions.

IV. Conclusions

We have discussed a number of service and operating strategies railroads propose to increase their market share of intermodal traffic and efficiently compete with trucking in offering customers timely, flexible, and "low"-costing transportation services. This evolution, including the advance bookings and full-asset-utilization policies increasingly implemented by existing and planned railroad Intermodal systems, challenges current models and methods for the design of services and the management of operations. Focusing on tactical planning issues, we have briefly examined these impacts and have identified research challenges and opportunities.

Acknowledgments

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