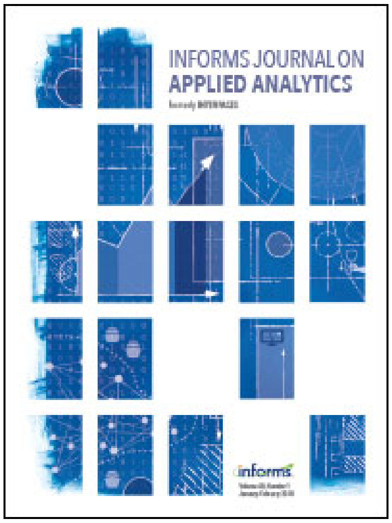

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Pricing Anomalies and Arbitrage in Container Transport in India

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Abstract. Intermodal transportation requires multiple entities to manage diverse resources under complex regulations and contracts. In this paper, we carry out a multidisciplinary cross-functional analysis of container rail haulage pricing and operations in India. We discover that the total haulage cost of a container train unduly depends on the position of the containers within the train, which is referred to here as *position arbitrage*. The main objective of this paper is to introduce and analyze this new concept of arbitrage for the first time in the literature. We derive the limits to the arbitrage, present management insights and empirical results, and explain that the arbitrage is undesirable because of its adverse effects on the efficiency of the container supply chain. With a real case, we empirically show that container train operators can save an average of 450 million INR annually by exploiting the arbitrage. On completion of dedicated freight corridors, the annual total value of the arbitrage can increase by one billion Indian rupees. This research is also beneficial for the railways to understand the implications of haulage pricing on operational efficiency and also for the port operators and shippers to understand the implications of the arbitrage for their operations.

History: This paper was refereed.

Keywords: container shipping • pricing • transportation economics • supply chain collaboration • Indian Railways

Introduction

With increasing intermodal container traffic and environmental concerns, double-stack container trains are gaining ever-greater importance worldwide, especially in India, China, Australia, Brazil, and North America. The double-stacking of containers, as shown in Figure 1, almost doubles the carrying capacity of a train. Thus, compared with single-stack container trains, double-stack trains significantly reduce the per-container requirement of locomotives, wagons, crew, and capacity in the rail network. Double-stack train operations started in Indian Railways (IR) in 2006. However, existing low-clearance bridges, tunnels, and overhead catenary (electric wiring) are obstacles that continue to prevent double-stacking in many countries and most of IR's network. With double-stack trains being about 30% more cost efficient than single-stack trains, there has been a huge investment in developing India's first dedicated freight rail corridors (DFCs) that will increase double-stack operations manifolds by 2021 (Dedicated Freight Corridors Corporation of India Ltd. 2020).

In this paper, we analyze the complexities arising in container train operations and pricing because of the loading of multiple types of containers on multiple types of wagons in different loading patterns (e.g., double-stack, single-stack, and empty wagon) in India. To our knowledge, for the first time in the literature, we demonstrate how the current pricing of rail haulage creates an arbitrage opportunity for container train operators (CTOs). We refer to this new opportunity as *position arbitrage* owing to its similarity with the *spatial arbitrage* in economics and define it as the process of exchanging the positions of containers in trains with the sole objective of taking advantage of price differences that far exceed the associated cost of container handling.

The paper is organized as follows. First, we explain the relevant operations of the container supply chain in India. We describe the existing position and time arbitrage opportunities for double-stack trains. Next, we explain why a mathematical model is necessary for an optimal exploitation of the arbitrage. We analyze managerial implications of the arbitrage for the railways, CTOs, terminal operators, and shippers and show empirical evidence that the arbitrage adversely affects the efficiency of the container supply chain. We explain that a revised pricing approach can eliminate the position arbitrage and its negative externalities. We conclude with a conjecture that some other forms of arbitrage may continue to exist even if the position arbitrage is eliminated.

Container Supply Chain and Rail Haulage Charges in India

The contracts between different entities of the container supply chain and a typical flow of export containers

Figure 1. (Color online) Double-Stack Train Operations Under High-Rise Overhead Electric Line in Indian Railways (Press Information Bureau 2020)

are illustrated in Figure 2. Typically, a customer or freight forwarder can negotiate the price payable to the CTO for the rail haulage of their containers. The CTOs own the rolling stock, manage container train operations, and pay rail haulage charges (RHC) to IR for using its network infrastructure and services (locomotive, crew, and ancillary).

The terminal and port operators are responsible for the intraterminal handling and storage of containers. The operators load and unload trains according to the instructions of the CTOs and vessels according to the instructions of the shipping lines. IR and shipping line teams carry out inspections to ensure safe loading of trains and vessels, respectively. The end customers are concerned about safe, economical, and timely delivery of their containers only and not about the internal functioning of the container supply chain.

The rectangular box in Figure 3 shows the network that has been benefiting from double-stack operations since 2006. Thanks to the significant benefits of double-stacking, it is also quite economical for the CTOs to convert their single-stack trains at the nearest possible hub into double-stack trains even if doing so entails some extra handling costs and delay. For example, export containers of the single-stack trains originating from Ludhiana, where double-stacking is not feasible, can be double-stacked at the nearest available hub in Haryana or Rajasthan state; see Upadhyay (2020) for more details. For confidentiality, we have made minor changes in the data and Figure 3 that do not affect the results of this study.

For operational reasons, IR allows all CTOs to run trains consisting of either 40 or 45 wagons each. In order to justify the financial risk associated with the very large investments of the CTOs in their rolling stock and infrastructure, IR specifies the RHC that may remain unchanged for up to two years. All CTOs are subject to the exact same terms of operations and pricing from IR for the container haulage. A simplified structure of RHC applicable since 2006 is illustrated in Table 1. In this table, for a transit distance mentioned in the first column, the RHC for the movement of an empty flat wagon (in Indian rupees (INR) per 20-foot equivalent unit (TEU)) are mentioned in the second column. The RHC for 20-foot containers (referred to as 20s) for the increasing weight slabs (breaks) are mentioned in the last five columns. A 40-foot container occupies double space (two TEUs), and the RHC for the 40-foot containers (referred to as 40s) are 1.8 times the RHC for the 20s mentioned in Table 1.

For the railways, double-stacking on a train can double the revenue while leading to only a minor increase in variable costs. Therefore, in order to incentivize double-stacking in one of the largest and most congested rail networks in the world, IR charges the containers loaded in the upper-stack position at 50% and in the lower-stack position at 100% of the rates mentioned in Table 1. The total RHC for a container train traversing distance d can be calculated using the following formula.

$$\text{Total\_RHC} = \sum_{i \in I_L} Q_{id} + 0.5 \sum_{i \in I_U} Q_{id} + N \cdot E_d. \qquad (1)$$

Here, I_L and I_U, respectively, are the sets of containers loaded in the lower and upper stack of the train and N is the total number of empty wagon slots (measured in TEUs) in the train. Further, Q_{id} and E_d, respectively, refer to the RHC of container i and the empty wagon (per TEU) traversing distance d as

Figure 2. (Color online) Container Supply Chain in India for Export Containers; Import Containers Flow in the Opposite Direction

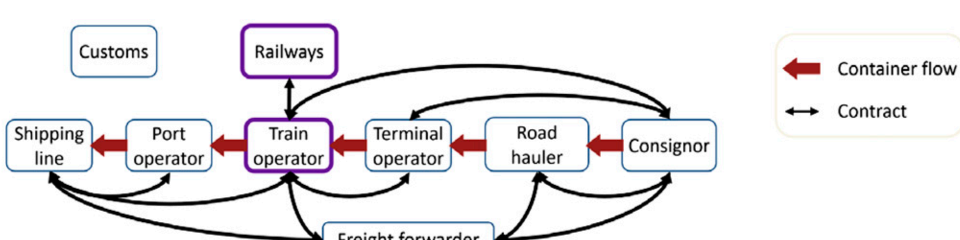
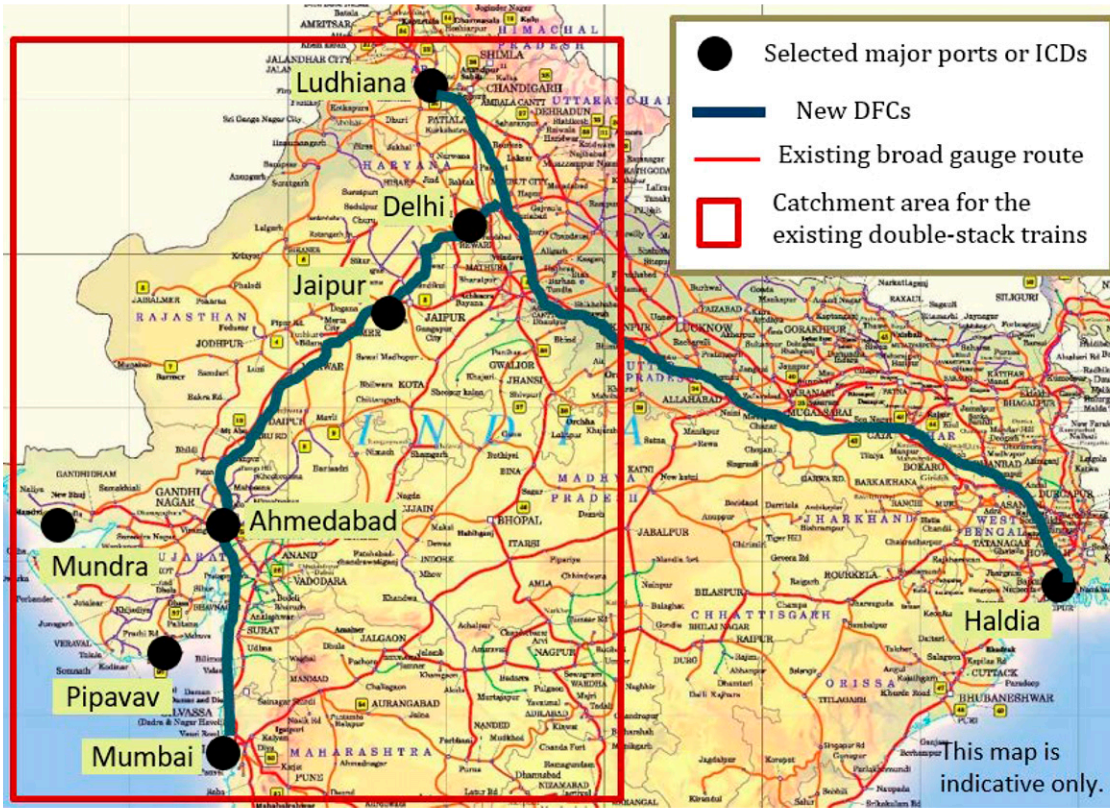


Figure 3. (Color online) Illustrative Double-Stack Railway Network in India



Source. https://erail.in/info/railway-maps-indian-railways/1808.

mentioned in Table 1. Note that, to keep the vertical center of gravity (CG) low, double-stacking is permitted only if there is no empty wagon in the train. So Equation (1) provides the total RHC for a double-stack train with N being zero and for a single-stack train with I_U being an empty set.

For brevity, we define a *bundle* as a package of the necessary services offered by IR to a CTO for transporting a given set of containers through a given train. It is rational that the RHC for a bundle should be an increasing function of the total weight of the containers, train size, and transit distance because these factors increase the operational costs for IR. However, we demonstrate that the differential pricing of upper- and lower-stack positions and indirect pricing of empty wagons (rather than all wagons, empty or loaded) are anomalies that have created a new association between the total RHC and the position of the containers within the train.

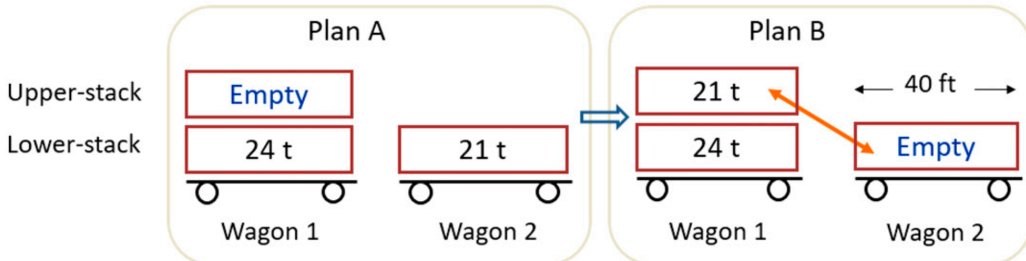
We show that, even for a given bundle, a CTO has an opportunity to significantly reduce the total RHC by optimizing the positions of the containers within the train. The exploitation of this profit-maximizing opportunity by the CTOs is referred to here as position arbitrage (or as just arbitrage). We show that the arbitrage introduces inefficiencies in the container supply chain, and it is possible to carry out the same container transport at a lower total system cost by eliminating the arbitrage.

It is noteworthy here that RHC account for about 50% of the total operating cost for the CTOs, and this arbitrage has existed since 2006 because of the contractual

Table 1. Illustrative Structure of Container Rail Haulage Charges in IR as per the RHC Circular (2018)

		20-foot container weight slab (in tonnes)				
Distance slab	Empty wagon	Empty	<18	18–24	24–28	>28
Kilometers	INR/TEU	INR	INR	INR	INR	INR
1,201–1,300	12,400	13,300	17,700	22,500	28,300	34,000
3,401–3,500	32,600	34,900	46,500	59,400	74,300	90,200

Figure 4. (Color online) Example of the Position Arbitrage Between Upper- and Lower-Stack Containers



agreements between IR and the CTOs. Therefore, this research is beneficial for a dozen CTOs, which can exploit the arbitrage to increase their profit; for the railways, which can revise their pricing and operating policy to increase the efficiency of intermodal operations; and for terminal operators and shippers, which can understand how the arbitrage is adversely affecting their operations.

Position Arbitrage in Container Trains

In order to explain and illustrate arbitrage for double-stack trains, we consider a set of three 40s, one empty and the others with gross weights of 21 and 24 tonnes, respectively, loaded on the two wagons shown in Figure 4. For a 1,255-km haulage of these three containers according to plan A, a CTO would pay 1.8 × (22,500 + 22,500 + 0.5 × 13,300) = INR 92,970, which is calculated using Table 1 and Equation (1). However, the CTO can also pay a much lower RHC, INR 84,690, by adopting load plan B. Both load plans A and B can be used for transporting the same set of containers having the same weight loaded on the same train dispatched at the same time on the same route. Both plans A and B also satisfy all the safety and operational requirements that are discussed later in this paper. However, the RHC corresponding to plan B is considerably (8.9%) lower than that of plan A because the 50% saving on the RHC of the upper-stack container increases with an increase in the container weight slab.

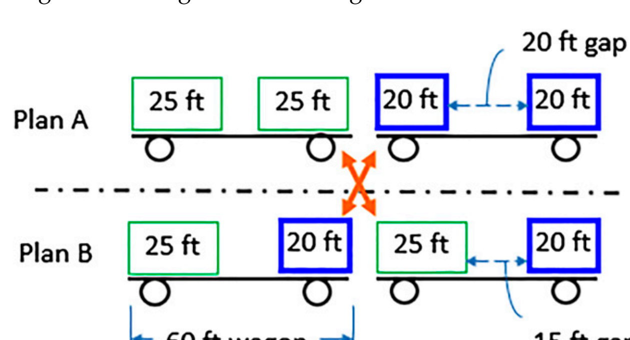
Extending this real-life example to a train of 45 wagons, a CTO can make an additional profit of up to INR 182,160 per train by exploiting the potential 22 arbitrage opportunities in the train. Note that, although the CTO's revenue is fixed at the time of the container booking itself, the exact position of the container in the train is finalized much later, just before the train departure.

In this paper, we use *arbitrage gain* to refer to the guaranteed risk-free savings for the CTO accrued by swapping a heavier container in the lower stack with a lighter container in the upper. Even if the wagons have already been loaded according to plan A, the arbitrage gain (e.g., INR 8,280 in Figure 4) is so high that the CTO still prefers to reduce the RHC through an additional, otherwise unproductive, exchange of containers required to execute the arbitrage. This can be seen as a *pure arbitrage* opportunity because the cost of swapping the containers is always less than 5% of the arbitrage gain as mentioned by Upadhyay (2020).

For brevity, we provide simple examples throughout this paper. However, all the containers in Figure 4 as well as in the subsequent examples can also be replaced with a more diverse mix of containers. For example, in Figure 4, the arbitrage gain remains the same when the 24-tonne 40-foot is replaced by a pair of 20s together weighing up to 40 tonnes, and the arbitrage gain is reduced to half when the empty container is replaced with a 17-tonne 40-foot.

For completeness, we show briefly that the arbitrage opportunities can exist even in single-stack trains if the extant RHC formula is used in case of different lengths of containers and wagons. Consider a set of two 60-foot wagons loaded with two 20-foot and two 25-foot (or 28-foot) containers as shown in Figure 5. For a loading of the containers according to plan A, the last wagon has an empty slot of length 20 foot that incurs empty wagon haulage charges for one TEU—in other words, INR 12,400 calculated for 1,255 km from Table 1. When the haulage of empty wagons is charged on a per-TEU basis, the unused 20-foot space on the last wagon is chargeable unlike the unused 10-foot space on the first wagon. However, if the same set of containers is loaded according to plan B,

Figure 5. (Color online) Potential Example of Position Arbitrage in Two Single-Stack Loading Plans



both of the wagons are left with a space of 15 foot (less than one TEU), which is not chargeable. In this example, the arbitrage gain is INR 12,400, a significant cost savings for the CTO.

The arbitrage in single-stack trains has negative externalities for wagon imbalance and fuel consumption. But we choose not to explain this further because the traffic of other types of containers (e.g., 10-, 25-, 45-, and 48-foot lengths) is much less than 20s and 40s, and different lengths of wagons are also less common globally. Therefore, we focus only on the arbitrage opportunities in the double-stack trains, which have a significant impact on the container train operations in India.

Time Arbitrage in Container Trains

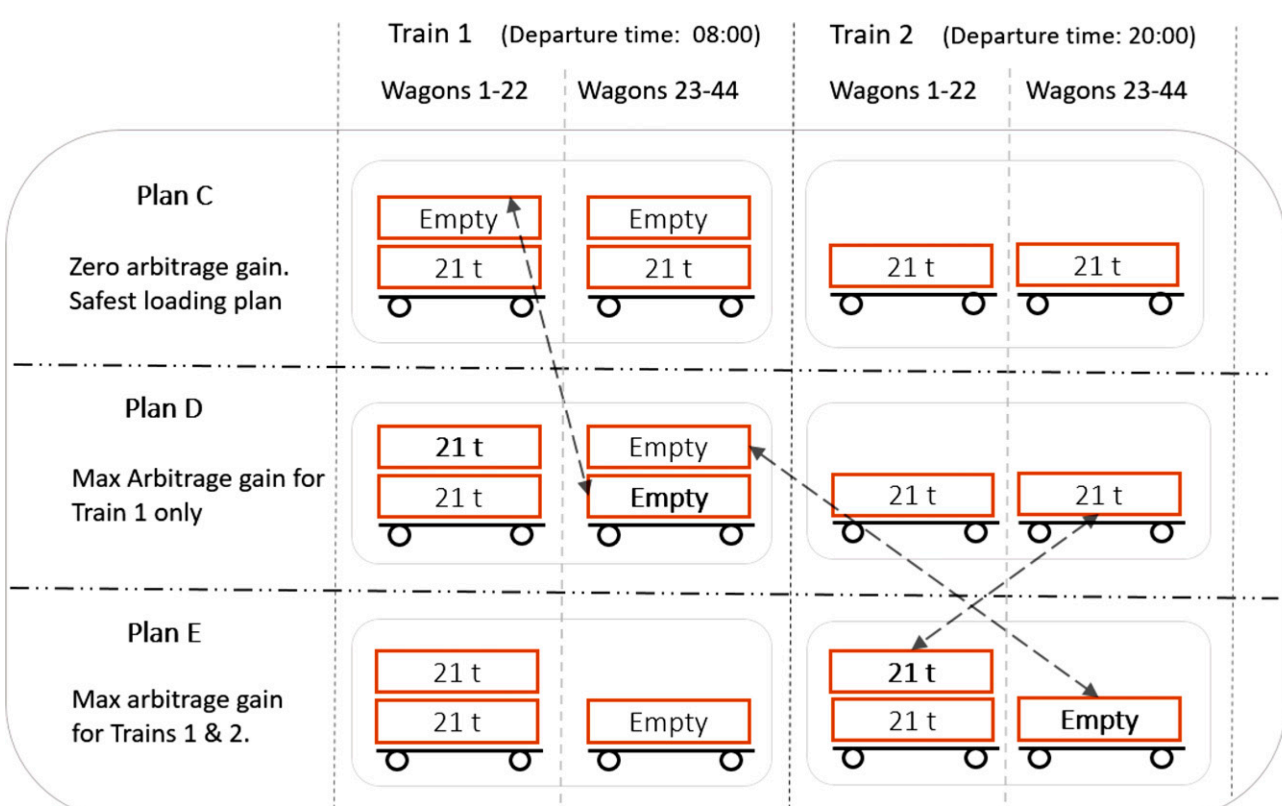
There are further implications of the arbitrage for the load planning of multiple trains. For a simple illustration of the time arbitrage associated with the position arbitrage, we consider two identical trains of 44 wagons each as shown in Figure 6 with a gap of about 12 hours between their expected departure times. It is very common to have a time gap between the trains on an identical route because of network congestion, demand factors, and the preference for sequential loading of trains that improves asset utilization.

Suppose there are 88 total 40s (44 empties and the remaining 44 having a weight of 21 tonnes) that should be loaded on the first train according to plan C. However, in order to maximize the arbitrage gain, the CTO should load these containers according to plan D for train 1. Although plan D provides the optimal arbitrage gain for the single-train scenario, this plan may not provide the optimal gain if we also consider the loading of the next train.

Suppose 44 total 40s, weighing 21 tonnes each, are to be loaded on the next train, train 2 in Figure 6. There is no arbitrage gain for train 2 loaded according to plan D because the 44 containers can only be loaded in the single stack. However, because every CTO has the flexibility of assigning the desired containers to the trains, the CTO can maximize the arbitrage gain further by delaying the 22 empty containers of train 1 and loading these on train 2. Compared with load plan D, plan E doubles the arbitrage gain for the two trains.

This process of reducing RHC by swapping container positions across trains is termed *time arbitrage* owing to its similarity with time arbitrage in economics. In a common application of the time arbitrage, a CTO holds some containers, which have been or can be loaded in the current train, just to load these in the next train to gain a guaranteed lower cost and, hence, higher total profit. Note that only containers with flexible service requirements can be loaded on later trains. In brief, time arbitrage is a manifestation of position arbitrage across multiple trains.

Figure 6. (Color online) An Example of the Time Arbitrage Associated with the Position Arbitrage



Unlike position arbitrage within a train, time arbitrage requires advance information on the availability of containers and trains. Even in the case of uncertain information, experienced terminal managers may still delay some containers just to exploit the arbitrage expected on later trains. This approach is termed *speculative time arbitrage* instead of risk-free time arbitrage.

For example, it is easy to exploit time arbitrage in the traditional empty flow directions in which train space utilization is always low and the arbitrage gain can never be negative. As a rule of thumb for empty flow directions, if a nonurgent, heavy 40 foot cannot be loaded in the upper stack of a train, then this container should be delayed because it may be possible to load the container in the upper stack of the next train to exploit the arbitrage. Later in this paper, we discuss the service requirements and negative externalities of time arbitrage for the container supply chain.

Exploiting Arbitrage

Arbitrage exists because there can be multiple feasible loading plans to assign a given set of containers to a given set of wagons, and the total RHC associated with these different loading plans can differ. Because we can always swap a heavier 40 in the upper stack with a lighter 40 in the lower stack and there is differential pricing of upper and lower stacks, we obtain the following necessary and sufficient condition for the existence of arbitrage in a given train: If there exists a feasible train-loading plan with a 40 of heavier weight slab in the upper stack and a 40 of a lighter weight slab in the lower stack, then there exists an arbitrage opportunity.

All of the major CTOs use enterprise resource planning applications that provide the necessary information on containers and trains. However, despite having this real-time information and an understanding of the arbitrage conditions, the operations team cannot identify and exploit all of the arbitrage opportunities because train load planning is a complex combinatorial optimization problem. With an enormous number of ways of assigning containers to wagons, it is not possible to fully analyze the vast amount of data manually and to consider numerous feasibility constraints while optimizing a train loading plan. We refer the readers to Upadhyay (2020) for more details of the complexity of the operations that indirectly explains why the arbitrage has remained undetected for almost a decade.

Because the loading of a train typically takes about five to six hours, there is always a possibility that, when some containers are being loaded to exploit arbitrage, any uncertainty in the execution of the loading plan can make it difficult to exploit all of the opportunities before the train departure time. Therefore, an optimization model is necessary for both identifying and exploiting all of the arbitrage opportunities.

We summarize only the key operations that are necessary to analyze arbitrage. In India, only four patterns are allowed for the loading of 20s and 40s as shown in Figure 7. The fifth pattern is an empty wagon. Loading of 20s in the upper stack is not allowed for safety reasons. Furthermore, a train-loading plan should satisfy the following constraints. The total weight of all of the containers loaded on each wagon must not exceed the payload limit of the wagon. For safety and stability of double-stack loading, the weight of the upper container should not be more than the total weight of the lower-stack container(s) loaded on the wagon.

The container-to-wagon assignment decisions depend on the rail operations in the network and handling operations at the terminal. The RHC and transit time associated with the container rail haulage are many times higher than the cost and time associated with the intraterminal container handling. Therefore, minimization of the total RHC is given utmost priority. However, the terminal operator has the flexibility to change the container-to-wagon assignments to minimize the intraterminal handling cost such that the RHC is not increased as discussed further in the next section.

For a succinct exposition of the arbitrage concept, we present a simplified version of the container train load planning (CTLP) model in Upadhyay (2020) for maximizing the arbitrage gain for only one single-destination train at a time (see Appendix A). However, our analysis of the arbitrage and the model can also be extended for planning multiple trains having intermediate train stops.

The CTLP model focuses on optimal design of a bundle in order to minimize mainly the total RHC for the CTO. Because an empty train incurs the least RHC and the revenue from the containers is fixed, the

Figure 7. (Color online) The Set of Container Loading Patterns Allowed in India

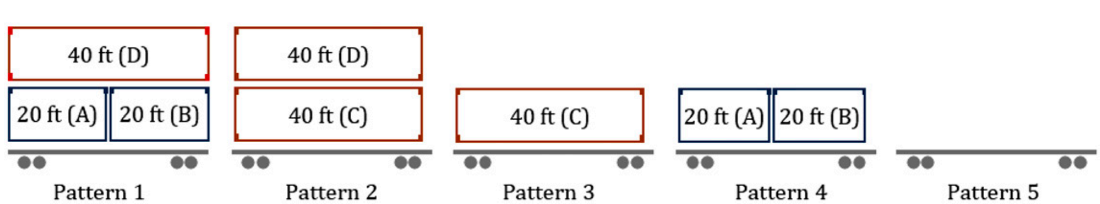
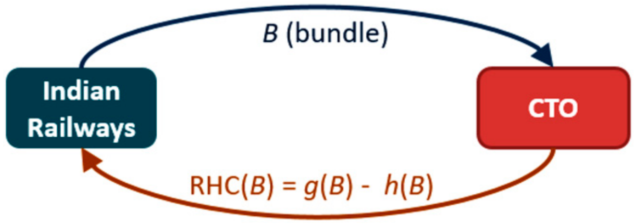


Figure 8. (Color online) The RHC Depends on the Arbitrage Gain Achieved by the CTO



objective function is formulated as maximization of profit, which is revenue minus RHC. Note that the container positions play an important role in the objective function because the arbitrage can increase the profit significantly. Based on this CTLP model, we present empirical results and management insights in the next section.

Arbitrage Analysis and Externalities

For clarity, we can break down the total RHC for a bundle B (as defined in Equation (1)) into two components: maximum possible RHC for the bundle, $g(B)$, and the arbitrage gain, $h(B)$, as shown in Figure 8.

Because the arbitrage gain can increase the profit significantly, arbitrage directly affects the design of the bundle itself. In this section, we demonstrate that arbitrage has only negative externalities for all concerned parties, and therefore, the optimal utility of a bundle for the container supply chain in the presence of arbitrage can never be better than the optimal utility in the absence of arbitrage.

Implications for CTOs

The CTOs should focus on the utilization of the heavy 40s because the savings (50% discount) for the upper-stack containers are greater for the heavier-weight slabs. In Appendix B, we show that the arbitrage gain in one swap operation is maximum when a 40 foot of the highest-weight slab is swapped with another 40 foot of the lowest-weight slab. We derive limits to the arbitrage gain for a container train in Appendix B. For the current operations in IR, these limits imply that the arbitrage gain for a container train can vary between 0.00% and 8.92% of the total RHC for the container train.

In practice, however, the arbitrage gain depends on the actual distribution of the types, weight, and distance slabs of the containers. Therefore, in order to estimate the arbitrage gain expected in actual operations, we analyzed 250 trains planned manually and 250 trains planned using the CTLP model with all of the trains' reports randomly selected by some major CTOs over the last four years.

The arbitrage gain analysis for four trains is summarized in Table 2. The train ID and the total number of 40s and 20s loaded on the train appear in the first three columns. The actual RHC (in 1,000 INR) paid for the trains appears in the fourth column. For each train, we optimized the position of the containers within the train by solving the CTLP model using CPLEX. The optimal, minimum RHC appears in the fifth column. The *unrealized arbitrage gain*, attributable to the use of the CTLP model, appears in the 8th and 11th columns, respectively.

It is noteworthy here that the unrealized arbitrage gain is in addition to the arbitrage gain already exploited, referred to as *realized arbitrage* in Table 2, during manual planning of the trains. We observe that a few arbitrage opportunities are exploited in almost every double-stack train even when the trains are planned manually. However, the arbitrage gain is rarely optimal for such trains, and it is not possible for us to determine whether a CTO is exploiting the arbitrage deliberately or by chance.

On the other hand, we observe that the arbitrage gain was optimally exploited for trains that were planned using the CTLP model except for a few trains for which the last-minute uncertainties during the train loading might have reduced the gain. Upadhyay (2020) discusses these uncertainties, the complexity o the operations, and the CTLP results in more detail. In these cases of optimal planning, which are not illustrated in Table 2, the realized arbitrage gain for every train is always maximum (i.e., the unrealized gain is zero). Therefore, we can conclude that the arbitrage opportunities are also being exploited deliberately in IR.

In order to assess the total impact of arbitrage, we also find the maximum possible RHC for each train. For this, we change the objective to maximization of the RHC with a constraint that all the containers must be loaded on the train. The corresponding maximum RHC appears in the sixth column of Table 2. The difference between the maximum and minimum RHC, which appears in the 9th and 12th columns, is the total arbitrage gain for the train.

Empirically, we have observed the total arbitrage gain to vary between 0.0% and 5.8% (and up to INR 136,768 for a train) with an average of 3.3% of the maximum RHC, and the unrealized arbitrage gain to vary between 0.0% and 4.4% (and up to INR 112,166 for a train) with an average of 2.1%. Considering the haulage of about 5,000 double-stack trains in 2019, the average 2.1% unrealized gain implies that the CTOs can reduce their RHC by INR 247 million by maximizing the arbitrage gain using the CTLP model.

Arbitrage appears to benefit the CTOs. However, it is noteworthy that the CTOs will not have any opportunity for arbitrage if the RHC (Equation (1)) is

Table 2. Analysis of the Arbitrage Gain and the Associated Increase in the Total Weight in the Upper Stack of the Trains

Train number	Total 40s	Total 20s	Total RHC (in 1,000 INR) Actual	Minimum	Maximum	Arbitrage gain (in 1,000 INR) Realized: Maximum – actual	Unrealized: Actual – minimum	Total: Maximum – minimum	Arbitrage gain (percentage of maximum) Realized: Maximum – actual	Unrealized: Actual – minimum	Total: Maximum – minimum	Total weight in upper stack of train: Actual (tonnes)	Maximum after arbitrage (tonnes)	Increase by arbitrage (percentage of actual)
1	73	34	2,226	2,149	2,266	40	77	117	1.77	3.38	5.15	561	784	39.8
2	62	54	2,365	2,263	2,372	7	102	109	0.31	4.30	4.61	785	914	16.4
3	35	76	1,960	1,912	1,976	16	48	64	0.81	2.44	3.25	492	623	26.6
4	49	82	2,675	2,659	2,675	0	16	16	0	0.60	0.60	680	752	10.6

revised such that the RHC does not depend on the position of the containers on the train. During our interactions with the CTOs, the managers were able to understand through Figure 8 that only the total RHC matters, and elimination of the arbitrage will benefit the CTOs by simplifying their processes of pricing of container haulage and train load planning because the total RHC will not depend on the position of the containers.

Arbitrage Between Cooperative CTOs

In general, cooperation among competing CTOs can increase the efficiency of their operations owing to economies of scale. Therefore, most CTOs already have a subcontracting clause that entitles a CTO to subcontract on any terms whatsoever the whole or any part of the transport, handling, and storage of containers. Furthermore, for operational reasons, the CTOs also have the flexibility of carrying the containers over a route other than the route for which the containers are booked. Therefore, the CTOs can reduce their total RHC further by maximizing their arbitrage gain from their collective pool of containers and trains.

For example, assume that the trains in Figure 6 each belong to a different CTO. Suppose both of the CTOs are planning to dispatch the two trains on the same day according to loading plan D, which provides the optimal arbitrage gain for each CTO individually. However, because a difference of about one day in the dispatching times of the containers (except the urgent containers if any) is insignificant for the practice of arbitrage, the CTOs can pool their containers in order to increase their collective arbitrage gain by an additional INR 182,160 by adopting plan E instead of plan D.

Practically, such cooperative arbitrage between two CTOs is possible for the traffic across major terminals shown in Figure 3 because the gain of INR 8,280 per container shifted is at least three times more than any potential increase in the drayage (road transport leg) cost of the container shifted. With increasing awareness of the potential for arbitrage gains and the increasing volume of container traffic, the total cooperative arbitrage gain may soon become high enough that the CTOs develop their trade relations and use a more sophisticated CTLP model designed for cooperative arbitrage.

Implications for IR

From IR's perspective, the CTOs' gain from arbitrage is a loss of revenue. For example, for the two trains in Figure 6, the arbitrage shifting from plan C to plan E implies a revenue loss of INR 364,320 for IR. Theoretically, the arbitrage limit in Appendix B implies that IR's revenue from a container train can decrease by up to 8.92% depending on the arbitrage gain exploited by the CTO. Practically, our empirical tests, illustrated in

Table 2, show that, for many years, IR has been losing an average 1.2% of RHC when the CTOs exploit the arbitrage through manual planning and an average 3.3% in the case of the CTLP model–based planning.

There are further negative externalities of the arbitrage for the safety of trains. A high CG of the double-stack wagons may cause derailment of the trains, especially on curvy sections and bridges in the presence of winds. Therefore, the CG of the wagons should be kept as low as possible to minimize the risk of train derailment (Thomas 2013).

In sharp contrast, arbitrage provides an incentive to the CTOs for loading heavier containers in the upper stack, which increases the CG of the train significantly. For example, compared with plan A in Figure 4, load plan B increases the weight of the upper-stack container by 17 tonnes for the same total weight on the wagons. This implies a significant increase of 45% in the CG of the first wagon and 31% for both the wagons combined, based on the CG Equation (2) applied to the commonly used flat wagons after assuming the CG of the containers at their geometric center. It is noteworthy here that IR allows both plans A and B because the corresponding CG is less than the maximum permissible limit. However, plan A for the train is definitely safer than plan B. The CG for a double-stack container wagon is computed as follows:

$$CG = \frac{\overline{G} \cdot \overline{W} + \left(\overline{H} + \frac{H}{2}\right)W_L + \left(\overline{H} + \frac{3H}{2}\right)W_U}{\overline{W} + W_L + W_U}. \qquad (2)$$

Here, H refers to the height of the containers and $\overline{H}$ the height of the wagon platform; $\overline{W}$ and $\overline{G}$ refer to the tare weight and CG of the wagon, respectively; and W_U and W_L refer to the total weight of the upper- and lower-stack container(s), respectively.

Based on the CG formula and mechanics, we can show that every gainful arbitrage shifting of the containers increases the CG of the associated wagons. For brevity, we skip the technical details and the effect of CG on safe speed for trains and include in the last column of Table 2 only the total weight shifted from the lower stack of the actual train to the upper stack when the arbitrage is fully exploited. Empirically, we have observed the arbitrage to increase the total weight of the upper stack by up to 302 tonnes and by up to 58% and on average by 114 tonnes and 17%.

The CTOs and terminal operators can be penalized only when IR finds that the CG has exceeded the maximum permissible limit. But the accident history of double-stack trains in Australia in 2006 and 2008, the United States in 2006 and 2008, Canada in 1999 (Australian Transport Safety Bureau 2008), and India in 2019 (Times of India 2019) show that accidents can happen even when the CG limits are being followed. Therefore, we argue that the arbitrage incentive is a harmful policy because it incentivizes the CTOs to increase the trains' CG (albeit within the permissible limit) and thereby increases the risk of train accidents.

Implications for Terminal Operators

Ideally, a CTO should share the desired train loading plan with the terminal manager at least one hour before the train loading starts so that the manager can plan the intraterminal container handling operations. Note that the planning of intraterminal container handling operations is a quite complex problem in itself; see Murty et al. (2005) for more details.

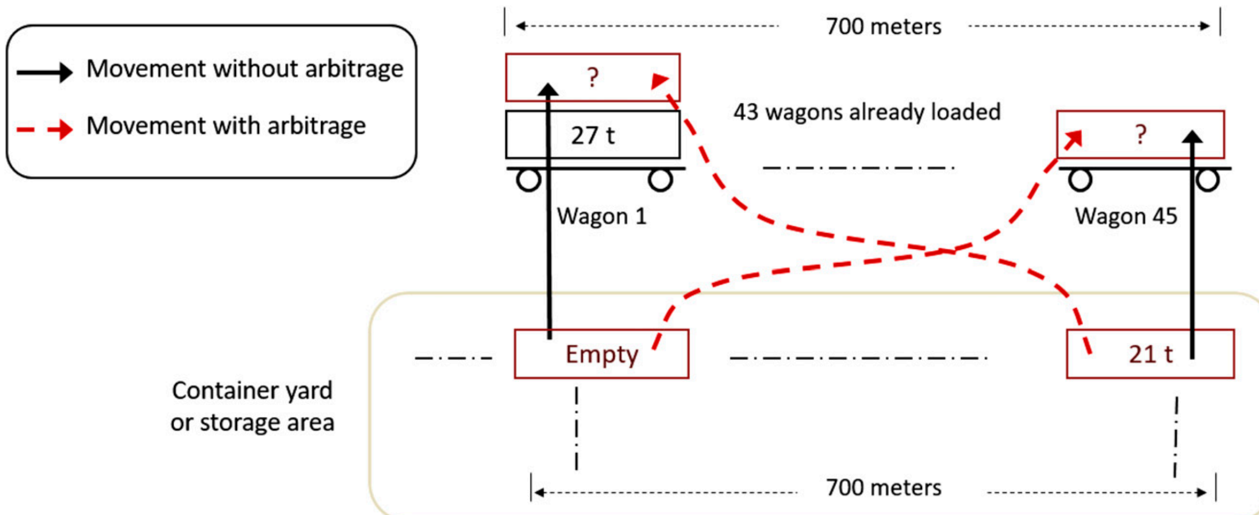
In the absence of arbitrage, the CTO is not interested in the position of the containers, and the manager has complete freedom to change the assignment of the containers to the wagons in order to minimize the gantry and truck movements as long as safety is not compromised. But the arbitrage imposes additional restrictions on the position of the containers because the arbitrage gain is many times higher than the cost of container handling (see Upadhyay 2020).

Effectively, the arbitrage-induced restrictions increase the double-handling of containers and the distance traveled by the gantries and trucks. For example, assume that the train in Figure 9 has already been loaded and only the first and last wagons are yet to be loaded with one 40 foot each. The last two 40s, one empty and the other 21 tonnes, are awaiting loading. In the absence of arbitrage, the operations team would load these containers to the nearest wagon available as shown by the black arrows. However, in the presence of arbitrage, the two containers have to be transported an additional 700 meters each, which increases both the container handling time and cost.

Sometimes, the arbitrage opportunities are identified and exploited after train loading has already begun. In such cases, arbitrage also causes additional unproductive double-handling of containers, that is, extra unloading, movement, and reloading. At many terminals owned by CTOs, the manager allows such unproductive but highly profitable double-handling of containers. Even at the other terminals, a CTO is okay with paying additional charges for such unproductive handling of containers to the terminal operator because the resultant arbitrage gain is very high.

An accurate estimation of the productivity loss at the terminals resulting from arbitrage requires a separate simulation study. However, we can conclude that the arbitrage increases the total container handling cost and time.

Figure 9. (Color online) An Illustration of How Arbitrage Increases Intraterminal Container Movements



Implications for Shippers and Consignees

Arbitrage directly affects the sequence of container dispatching and provides an incentive to unduly delay some containers. For example, according to the most profitable plan E in Figure 6, 22 containers are delayed by 12 hours just to maximize the arbitrage gain using the next train. Practically speaking, arbitrage may delay containers by up to a few days. Therefore, arbitrage can increase the expected delivery time and compromise utilization of assets.

It is noteworthy here that, even when the loading of only one train is being planned, arbitrage interferes with CTOs' policy of first-come, first-served desired for fairness in container dispatching; see Upadhyay et al. (2017) for more details. Therefore, arbitrage adversely affects the interests of both shippers and consignees.

The shippers are unable to identify small arbitrage-induced delays for two reasons. First, the CTOs always consider the service requirements of time-sensitive containers. With the help of the CTLP model (Upadhyay 2020), the CTOs can delay container dispatching to the extent that the delivery commitments are not affected. Second, because entities in the container supply chain do not disclose operational details, the shippers can see only the location status of their containers and can never identify any arbitrage-induced delay.

Overall, we can conclude that arbitrage reduces the efficiency of the container supply chain because the same container transport can be carried out at a lower total system cost without compromising the utility for any entity (railways, CTOs, port operators, and shippers). Therefore, by eliminating arbitrage and, hence, the associated negative externalities, the container supply chain can become more efficient.

Eliminating Arbitrage

When double-stacking operations began in 2006, it might have been easy to continue with the previous RHC formula by adding a simple rule of providing a 50% discount for containers in the upper stack. In every subsequent revision, IR made only incremental changes in the RHC based on Equation (1) rather than reevaluating the need for factors already included in Equation (1). Although it is rational to charge more for heavier, bigger, and longer-distance container trains, the practice of encouraging the double-stack loading through a discount on the upper stack is undesirable because of the negative externalities discussed.

With the beginning of operations on DFCs and increasing heterogeneity in the wagon and container fleet (Acharya 2018), there is a need to revise the rail haulage pricing given the arbitrage-related drawbacks of the current pricing approach. A thorough examination of the pricing policy for container trains is a weighty exercise that needs to consider many internal and external cost factors. However, we want to demonstrate here that arbitrage can be eliminated by making only minimal changes to the extant RHC formula.

In order to exclude arbitrage, the formula must ensure that the total RHC of any bundle is unique irrespective of the containers' positions. The arbitrage cannot exist if all types of containers and wagons are charged directly and individually. For illustration, consider the RHC Equation (3) and the corresponding revised rates shown in Table 3. This revised formula is easy to implement because there is only a minor change in the extant formula that does not require any changes in the operating rules.

$$\text{Total\_RHC} = V_d + \sum_{i \in I_L \cup I_U} Q_{id} + \sum_{k \in K} S_{kd}. \tag{3}$$

Table 3. RHC Revised for Illustrating Elimination of Arbitrage

		S_{kd} for wagon		Q_{id} for 20s in weight slab (in tonnes)					Q_{id} for 40s in weight slab (in tonnes)		
Distance slab	Fixed charge V_d	Type 1	Type 2	Empty	<10	10–18	18–26	>26	Empty	<18	>18
Kilometers	INR	INR	INR	INR	INR	INR	INR	INR	INR	INR	INR
1,201–1,300	0	24,800	NA	900	5,300	10,100	15,900	21,600	1,620	9,540	18,180
3,401–3,500	0	65,200	NA	2,300	13,900	26,800	41,700	57,600	4,140	25,020	48,240

Note. NA, not applicable in the extant RHC.

Here, V_d is a fixed rate charged on the basis of train distance only, and Q_{id} and S_{kd}, respectively, refer to the RHC of container i and of wagon k traveling distance d as mentioned in Table 3. Table 3 is for illustrative purposes only, and the rates can be calibrated by using the cost analysis techniques explained by Waters (2007) such that both of the entities, IR and the CTOs, benefit fairly from elimination of arbitrage.

Following current practice, we set $V_d = 0$ in Table 3 although a positive V_d can provide flexibility in deciding the RHC for containers and wagons more suitably. All types of flat wagons can be charged directly irrespective of their loading status. Therefore, the wagon haulage charges (S_{kd}) are double the current charges for an empty wagon per TEU mentioned in Table 1. Following the current practice, we mention the wagon charges only for one type of wagon. However, different types of wagons (e.g., type 2 in Table 3) and containers may also be differentiated for pricing purposes. Because the wagons are being charged irrespective of their loading status, the container charges (Q_{id}) can be reduced, for example, by statistical cost analysis, such that the average cost of the bundles remains unchanged.

Equation (3) includes no discount on the loading of containers in the upper stack. However, the reduced Q_{id} in Table 3 are equivalent to the upper-stack discount because V_d and S_{kd} remain the same irrespective of the containers loaded. Therefore, the revised formula can provide the same incentive for encouraging double-stacking while eliminating arbitrage. For example, in Figure 6, the CTO can pay any RHC between INR 4,090,680 and 3,726,360 for the two trains depending on the arbitrage gain. However, according to the revised formula and Table 3, there is a unique RHC of INR 3,853,520.

Conclusion

The 3,300-km-long DFCs are projected to move more than 5.3 million TEUs per year owing to lower operating costs of the higher capacity wagons in two- to three-times-longer double-stack trains (Dedicated Freight Corridors Corporation of India Ltd. 2020). Therefore, the total arbitrage gain can increase by one billion INR by 2022.

Overall, this research has the potential to significantly improve the efficiency of the container supply chain in India. CTOs would benefit from the use of the new analytics models to maximize their arbitrage gains. IR would benefit from revision of the RHC to eliminate arbitrage. The elimination of arbitrage would benefit the container transport by (i) reducing the risk of train accidents owing to the lower CG of double-stack wagons, (ii) decreasing the average cost of intraterminal gantry and truck movements required for train loading, (iii) reducing the expected container delivery time because there would be no undue incentive to delay the containers, and (iv) simplifying the processes of train load planning and pricing of container haulage for the CTOs.

Based on this research, position arbitrage, a pure arbitrage, may be eliminated. However, other forms of arbitrage opportunities with some transaction costs are likely to exist because of the operation of heterogeneous fleets in the mixed single- and double-stack network under complex operating rules; see Felthoven et al. (2014) for a further research direction.

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Appendix A. Mathematical Model to Maximize Gain from Position Arbitrage

For a given set of containers that can be loaded on a given train, the following binary integer program maximizes the arbitrage gain as well as the numbers of TEUs loaded on the train while generating a feasible loading plan. For a detailed optimization model and solution methodology, see Upadhyay (2020) and Upadhyay et al. (2017).

Sets

I	Set of candidate containers; index $i \in I$
I_{20}, I_{40}	Sets of 20s and 40s, respectively ($I = I_{20} \cup I_{40}$)
J	Set of allowed loading patterns; index $j \in J = \{1, 2, 3, 4, 5\}$
K	Ordered set of wagons in the train; index $k \in K$ also refers to the wagon's numbered position counted from the front of the train.
M	Set of loading positions shown in Figure 7, index $m \in M = \{A, B, C, D\}$

Parameters

G_k	Maximum payload limit for wagon $k \in K$
H_i^m	RHC corresponding to the assignment of container i to position m in the train
R_i	Revenue from rail haulage of container i
W_i	Gross weight of container i

Binary Decision Variables

$$x_k^j = \begin{cases} 1, & \text{if wagon } k \in K \text{ is assigned pattern } j \in J \\ 0, & \text{otherwise.} \end{cases}$$

$$y_{ik}^m = \begin{cases} 1, & \text{if a container } i \in I \text{ is assigned position } m \in M \text{ on wagon } k \in K \\ 0, & \text{otherwise.} \end{cases}$$

Formulation

$$\text{maximize} \sum_{k \in K,\ i \in I,\ m \in M} (R_i - H_i^m)\ y_{ik}^m \tag{A.1}$$

subject to

$$\sum_{i \in I_{20},\ m \in \{A,B\}} W_i\, y_{ik}^m + \sum_{i \in I_{40}} W_i\, y_{ik}^C \geq \sum_{i \in I_{40}} W_i\, y_{ik}^D, \quad \forall\, k \in K, \tag{A.2}$$

$$\sum_{j \in J} x_k^j = 1, \quad \forall\, k \in K, \tag{A.3}$$

$$\sum_{k \in K,\, m \in M} y_{ik}^m \leq 1, \quad \forall\, i \in I, \tag{A.4}$$

$$\sum_{i \in I_{20}} y_{ik}^m - x_k^1 - x_k^4 = 0, \quad \forall\, k \in K,\ m \in \{A, B\}, \tag{A.5}$$

$$\sum_{i \in I_{40}} y_{ik}^C - x_k^2 - x_k^3 = 0, \quad \forall\, k \in K, \tag{A.6}$$

$$\sum_{i \in I_{40}} y_{ik}^D - x_k^1 - x_k^2 = 0, \quad \forall\, k \in K, \tag{A.7}$$

$$\sum_{i \in I_{20},\, m \in \{C,D\}} y_{ik}^m + \sum_{i \in I_{40},\, m \in \{A,\ B\}} y_{ik}^m = 0, \tag{A.8}$$

$$\sum_{i \in I,\, m \in M} W_i\, y_{ik}^m \leq G_k, \quad \forall\, k \in K, \tag{A.9}$$

$$x_k^j,\ y_{ik}^m \in \{0,\ 1\}. \tag{A.10}$$

The objective function (A.1) maximizes the total gain from assignment of a given set of containers to a given train. The weight of an upper-stack 40 cannot exceed the total weight of lower-stack containers according to Constraint (A.2). Constraint (A.3) assigns a feasible loading pattern to each wagon as shown in Figure 7. Constraint (A.4) ensures that a container can occupy only one position in the train. Here, 20s can occupy positions A and B in loading patterns 1 and 4 because of Constraints (A.5) and (A.8), and 40s can occupy positions C and D in loading patterns 1–3 because of Constraints (A.6)–(A.8). Constraint (A.9) ensures that the total payload on each wagon does not exceed the permissible limit.

Appendix B. Limits to the Arbitrage Gain for a Container Train

For a container train in IR, we show that the arbitrage gain can vary between 0.0% and 8.92% of the total RHC for the train. It is straightforward to see that the minimum arbitrage gain can be zero, for example, when all the containers belong to the same weight slab. According to our definition of arbitrage gain, as described in Figure 8, the gain cannot be negative.

We find the maximum possible value of the arbitrage gain (MAG) as a percentage of the total RHC for a train by induction. First, we find MAG for two wagons and show that this upper limit is also applicable for any further addition of wagons. For the purpose of finding MAG, we can ignore 20s without any loss of generality for two reasons. First, 20s cannot be loaded in the upper stack. And, second, based on the RHC since 2006, RHC for a 40 is always less than the total RHC for any pair of 20s having the total weight equal to the weight of the 40. Therefore, we find MAG considering only 40s and show that this gain cannot be increased further if any 40 is replaced with any pair of 20s.

For two wagons, we consider the four 40s (C_1 to C_4) loaded on the first two wagons shown in Figure B.1. Note that a minimum of three 40s are required for any arbitrage gain and a maximum of four 40s can be loaded on two wagons.

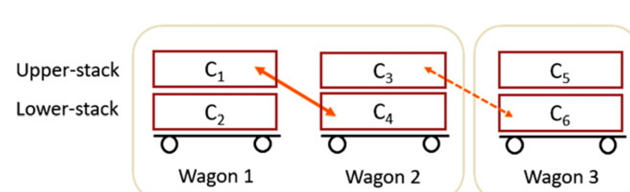
The safety Constraints (A.2) imply the following conditions for this loading plan, where w_i refers to the weight slab of container C_i.

$$w_1 \leq w_2, \tag{B.1}$$

$$w_3 \leq w_4. \tag{B.2}$$

For a gain, it is necessary to swap a heavier container (say C_4) in the lower stack with a lighter container (C_1) in the upper stack, which implies Condition (B.3). This arbitrage swap should also satisfy the safety Constraints (A.2), which implies Condition (B.4). From (B.3) and (B.4), we can conclude that there can be at most one gainful

Figure B.1. (Color online) Understanding the Upper Limit of the Arbitrage Gain



arbitrage swap among the containers loaded on a pair of wagons. Therefore, for the upper limit, we can remove container C_3 because it increases the total RHC and does not contribute to the arbitrage gain.

$$w_1 < w_4, \tag{B.3}$$

$$w_4 \leq w_2. \tag{B.4}$$

Corresponding to the arbitrage gain for the first two wagons (AG_2), the minimum and maximum total RHC are mentioned as follows. Here, Q_i refers to the RHC of container i. The RHC of a 40 in the upper stack is R times ($R < 1$) the RHC of the same 40 in the lower stack.

$$RHC_{max} = R \cdot Q_1 + Q_2 + 0 + Q_4, \tag{B.5}$$

$$RHC_{min} = Q_1 + Q_2 + 0 + R \cdot Q_4, \tag{B.6}$$

$$AG_2 = RHC_{max} - RHC_{min} = (1 - R)(Q_4 - Q_1). \tag{B.7}$$

The gain (B.7) is maximum when Q_1 is minimum and Q_4 is maximum, that is, when C_1 is empty and C_4 and C_2 both have a weight from the heaviest slab. Therefore, MAG for two wagons is as follows.

$$MAG_2 = (1 - R)\,(Q_{heaviest} - Q_{empty}). \tag{B.8}$$

Here, $Q_{heaviest}$ and Q_{empty} refer to the RHC of the heaviest slab 40 and empty 40, respectively. From (B.4), (B.5), and (B.8), we obtain MAG as a percentage of the total RHC.

$$MAG = \frac{100\,(1 - R)\,(Q_{heaviest} - Q_{empty})}{R \cdot Q_{empty} + 2\,Q_{heaviest}}. \tag{B.9}$$

In this case, a pair of 20s can replace only C_2. But this replacement can never increase MAG (B.9). Next, for three wagons, we consider wagon 3 and containers C_3 and C_6 to be available as shown in Figure B.1. Without any loss of generality, we assume that C_5 does not exist. Now, only one additional swap between C_6 and C_3 may provide an additional arbitrage gain over the previous gain (B.8) for the two wagons. Condition (B.10) is necessary to have any arbitrage gain from the swap C_6 to C_3, which is feasible along with the swap C_1 to C_4 only when Condition (B.11) is also satisfied because C_6 will be going on top of C_1.

$$Q_3 < Q_6 (\because w_3 < w_6), \tag{B.10}$$

$$w_6 \leq w_1 (\because Q_6 \leq Q_1). \tag{B.11}$$

Overall, (B.12) is a necessary condition for the arbitrage gain for the three wagons (AG_3) in (B.13).

$$Q_3 < Q_6 \leq Q_1 < Q_4, \tag{B.12}$$

$$AG_3 = (1 - R)\,(Q_4 - Q_1) + (1 - R)(Q_6 - Q_3), \tag{B.13}$$

$$\therefore MAG_3 = (1 - R)\,(Q_{4max} + Q_{6max} - Q_{1min} - Q_{3min}). \tag{B.14}$$

For the maximum gain (B.14), C_3 must be empty, C_4 the heaviest slab container, and Q_6 equal to Q_1 (B.11).

$$\therefore MAG_3 = (1 - R)\,(Q_{heaviest} - Q_{empty}). \tag{B.15}$$

Comparing MAG_3 (B.15) with MAG_2 (B.8), we can conclude that MAG as a percentage of the total RHC even in case of three wagons cannot exceed (B.9).

Furthermore, by induction, we can conclude that MAG for four or more wagons can never exceed (B.9). For an even number of wagons, MAG can equal (B.9), which can be obtained by duplicating the preceding derivation for two wagons. For the current operations in IR, MAG (B.9) possible for a container train is 8.92% of the total RHC for the train.

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Verification Letter

The paper includes anonymous sources. For verification purposes, the editor-in-chief has received a list of these sources.

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