A Centralized Time-Dependent Multiple Carrier Collaboration Problem for Less-than-Truckload Carriers

by

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ABSTRACT

This paper addresses a time-dependent centralized multiple carrier collaboration problem (TD-MCCP) for the small- to medium-sized less-than-truckload (LTL) industry. The TD-MCCP represents a collaborative strategy in which a central entity (such as a 3PL firm) seeks to minimize the total system costs of an LTL carrier collaborative consisting of multiple collaborating carriers, by identifying collaborative opportunities over a shared network under three rate-setting behavioral strategies and a leasing alternative. In contrast to conventional time-dependent network problems that typically view demand as dynamic, in the proposed LTL multiple carrier collaboration framework, capacities are time-dependent but known a priori, and demand is fixed. The TD-MCCP is modeled as a binary (0-1) multi-commodity minimum cost flow problem formulation for two rate-setting behavioral cases and solved using a branch-and-cut algorithm. The first case studies the effect of a single rate behavioral strategy at a time, and the second case studies the effect of multiple rate behavioral strategies simultaneously. Numerical experiments are conducted to seek insights on the computational performance of the TD-MCCP formulations under various network sizes and number of shipments. The results indicate that the attractiveness of the time-dependent multiple carrier collaboration paradigm increases with a volume-oriented rate-setting strategy. Also, a volume-oriented rate strategy has the potential to increase the capacity utilization of carriers seeking to minimize empty-haul trips. Finally, the leasing alternative can serve as a viable option for a centralized collaborative system, especially when affordable collaborative capacity is scarce.

Keywords: Collaborative logistics, Freight transportation, Less-than-truckload trucking, Minimum cost flow
INTRODUCTION

The Internet and information communication technologies (ICT) are becoming an integral part of the operations of many trucking companies; the potential for leveraging ICT exists especially for the small- to medium-sized less-than-truckload (LTL) trucking segment. Since the advent of the Internet in the 1990s, the freight transportation industry has become more competitive than ever before. To survive in such an environment, carriers are beginning to explore collaborative strategies as a means to maintain a competitive edge. One manifestation of this shift is in the possibility of LTL carrier-carrier collaboration, which seeks to exploit synergies (for example, excess capacity availability) in operations (1). The imperative for these smaller carriers to consider cooperative alliances also arises due to the need to address many emerging concerns such as the increase in shipper requirements, and the role of the Internet and ICT technologies in enhancing competition. Thus, a key operational challenge for carrier-carrier collaborative networks is to address these issues within a cooperative alliance and to create win-win situations for all members in the alliance.

LTL carrier collaboration can be a powerful new paradigm for improving operations. By collaborating, small- to medium-sized LTL carriers can increase asset utilization (such as unused capacity) and strengthen their market position. The challenge for a collaborative effort is in trying to find a balance between the multiple requests of the LTL carriers requiring resources and the available transportation capacity to service those requests. This balance depends on the affordability of the transportation services provided to the collaborative member carriers, as well as on the shipment size and value. An agreement between member carriers would entail that both the parties involved in a collaborative transaction believe that they are benefiting from that transaction (for example, through reduced costs or larger profits).

In summary, carrier collaboration among multiple carriers can be induced by identifying win-win solutions for the members in the collaborative. One potential approach to identify such solutions is to study the rate-setting dynamics (behavior) of these small- to medium-sized LTL carriers. This is because the rate-setting behavioral strategies of carriers can provide insights on the operational characteristics that may lead to a successful collaborative effort. For example, carriers that are trying to establish density between specific facilities or transit corridors may be more inclined to charge reduced rates for providing capacity in those corridors in a collaborative setting. From an implementation perspective, if a third party logistics (3PL) firm undertook the task of identifying collaborative opportunities for member clients needing capacity, it could search for carriers that are trying to establish density on various transit corridors first. With the advances in the ICT domain, 3PL firms can easily keep track of carriers in their systems and continually update their rate-setting tendencies (since rates may also change depending on the economic climate or other unforeseen events).

In the rate-setting context, each carrier may consider different factors to determine the rate it will charge for fulfilling a collaborative shipment request; for example, based on the shipment type, a carrier may charge different costs for shipping perishable versus nonperishable goods. In this study, we consider three rate-setting behavioral strategies. First, some carriers may be purely revenue-driven. They will charge higher collaborative rates independent of the volume they serve; in essence they will charge a rate based on the current market value for moving a shipment (2). Second, some carriers may be volume-oriented. They are more concerned with establishing density on shipment routes between terminals; these rates are typically set to offset empty empty hauls (3). Third, some carriers may be profit-oriented. These carriers will adjust rates
through discounts; typically this rate is an average amount between the volume-oriented and the revenue-generating carriers (4). From an operational perspective, the consideration of the aforementioned rates-setting behavioral strategies for the collaborative carrier paradigm enables the investigation of the viability of an LTL carrier collaborative compared to other alternatives such as short-term leasing.

This paper introduces a framework to study multiple carrier collaboration among a group of small- to medium-sized LTL carriers under varying rate-setting behavioral strategies in a centralized setting. Here, a central entity (such as a 3PL firm) facilitates the collaboration among the member carriers with the objective of minimizing the total (collaborative) system costs subject to the rate-setting behaviors of the individual carriers. The carriers seek collaborative routes to service various shipments based on the available collaborative capacities on the associated network links. The problem is labeled the time-dependent centralized multiple carrier collaboration problem (TD-MCCP). The TD-MCCP is addressed from a planning perspective, in that the time-dependent collaborative capacities on the network links are known a priori for the entire planning horizon. Therefore, operational aspects related to link travel time variability due to congestion effects are ignored here, and the link travel times are assumed to be fixed. However, the costs associated with congestion effects due to both traffic and terminal delays are captured through holding costs that vary with the location of transfer facilities. In addition to the rate-setting behavioral strategies, short-term leasing is considered as an option to service excess demand and is captured through a leasing cost. The performance of the carrier collaborative under the varying carrier rate-setting strategies is benchmarked against the leasing option, which is an existing alternative for freight carriers.

The remainder of this paper is organized as follows. Section 2 reviews literature related to the integration of demand and supply concepts for time-dependent multiple carrier collaborative networks. Section 3 discusses the rate-setting cost parameters and the formulation of the TD-MCCP problem. Section 4 describes the numerical experiments conducted in this study. Section 5 summarizes the insights from the experiment results. It conducts sensitivity analyses, and analyzes the effects of the various rate-setting behavioral strategies on time-dependent multiple carrier collaboration. It also estimates the levels of collaborative capacity utilization. Section 6 presents some concluding comments.

**LITERATURE REVIEW**

To the authors’ knowledge, there is no existing literature on the integration of demand concepts to LTL collaborative networks. However, there have been efforts to capture carrier behavior in other collaborative contexts. Figliozzi et al. (5) developed a general framework for studying truckload (TL) carrier strategies in transportation auction marketplaces. They use agent-based simulation to gain insights on the overall market behavior in terms of efficiency and shipper services levels under various market conditions. From the carrier’s perspective, different strategies based on a non-cooperative environment with varying degrees of information-sharing and market settings were also analyzed.

Previous studies in carrier collaboration have also focused on cooperative game theoretical approaches that allocate either the resources or monetary gains to carriers based on the level of participation in the coalition. However, they do not explicitly study carrier behavior in terms of rate-setting. Krajewksa et al. (6) studied horizontal cooperation among freight carriers. The authors combine features of vehicle routing, scheduling, and game theory to
allocate requests and share the profits. The basis for the cooperation is through the submission of all requests from the collaborative. These requests are then bundled, and routes and schedules are developed. The total profit is shared among all members of the coalition based on their level of participation by using the shapely value result.

Agarwal and Ergun (7) introduce a mechanism design (reverse game theoretical approach) for service network alliances that allocates the benefits of collaboration in a decentralized setting. That is, the mechanism determines capacity exchange costs, which in turn are used by the carriers to make routing and capacity exchange decisions. They model a multicommodity flow game as a linear program (LP) for a coalition of carriers and propose an inverse optimization solution approach for obtaining the capacity exchange costs from the perspective of a single carrier. The resulting capacity exchange costs are then shown to be sufficient for the coalition through compliance of the core property, a cooperative game theory principle. However, the study assumes that an individual player can route all the demand flow in the network to maximize its total benefit. Agarwal and Ergun (8) apply the above mechanism design to a liner shipping collaborative problem.

In context of the carrier collaboration problem addressed here, the current literature either addresses the behavioral aspects of carrier collaboration with no network implications in terms of routing, or seeks to allocate resources to the collaborative by considering the network without considering behavior in terms of rate-setting strategies. There are two key differences between the previous studies and this study. First, this study addresses the effect of rate-setting behavior over a multi-carrier collaboration network by simultaneously considering a leasing alternative. By exploring the effect of rate-setting behavior on collaborative transactions between carriers, it provides the ability to capture those rate-setting behavioral strategies that lead to the largest reductions in operational costs for the collaborative system. Second, we study the problem from the context of the LTL small- to medium-sized carrier industry which operates over a network of warehouse, depots, and/or distribution centers. That is, this industry operates on a point-to-point network structure which has two key advantages. First, carriers do not have to digress to potentially-distant intermediate terminal locations, leading to faster trips. Second, they save carriers additional transfer and transit costs because they bypass consolidation terminals (4, 9). This network structure is especially attractive because synergies in the form of excess capacity can be exploited.

To the best of our knowledge, this is the first study to model a multiple carrier collaboration problem for the small- to medium-sized LTL industry. In addition, this work differentiates itself from the previous literature by analyzing three real-world rate-setting behavioral strategies. Addressed from a planning perspective, the TD-MCCP represents a starting point for studying the effects of rate-setting behavioral strategies in a centralized carrier collaboration network. That is, while this planning-focused TD-MCCP represents congestion effects through holding costs and assumes prior knowledge of the time-dependent collaborative capacities, it also provides a starting point to address multiple carrier collaborative paradigms in an operational context for the small- to medium-sized LTL. For example, a rolling horizon method (10, 11) can be used to operationally deploy the dynamic multiple LTL carrier collaborative problem, as better estimates of the available collaborative capacities and demand can be obtained closer to real-time.
MATHEMATICAL MODEL OF THE TD-MCCP

Problem Description and Assumptions

The TD-MCCP seeks to determine a time-dependent collaborative network routing strategy for a central entity (such as a 3PL firm) that minimizes the total collaborative system cost for the set of collaborating carriers which provide or consume some collaborative capacity. Hence, a carrier in this system is classified as either requiring (consuming) capacity or providing capacity. A carrier may either acquire some excess capacity from a collaborative partner for some segments of a route to meet demand requirements, or it may provide excess capacity to collaborative partners for some portions of their routes in order to offset deadheading costs. The operational networks of the various collaborating carriers can be completely identical geographically or overlap in some segments relative to the carrier of interest.

The collaborative rate structure for a capacity-providing carrier is represented by one of the following strategies: (i) a rate that is purely revenue-driven, (ii) a rate that is volume-oriented, or (iii) a rate that is profit-oriented. If a collaborative opportunity cannot be identified on a transit corridor based on the collaborative rate structures, a leasing alternative is considered. The leased capacity from the leasing alternative can be shared by multiple carriers (which require additional capacity) that share the same transit corridor, if it is cheaper to do so. It is assumed that the costs to lease capacity are divided in proportion to the shipment amounts of the carriers using that capacity on a transit corridor.

The following assumptions are made in the TD-MCCP: (i) a shipment is not split to multiple carriers during a transfer, (ii) a shipment is not split to multiple truck routes (arcs) of the same carrier during a transfer, and (iii) a shipment is not split to multiple truck routes (arcs) of the same leasing alternative during a transfer. Further, the TD-MCCP assumes that the collaborating carriers subscribe to the following provisions: (i) all carriers first utilize their available capacity before committing excess capacity, (ii) the costs associated with loading/unloading a shipment (transfers) and the costs associated with the holding of a shipment at a transfer location (collaborative holding costs) are divided equally between the carriers involved in that collaborative opportunity.

Problem Formulation for a Single Rate-Setting Behavioral Strategy

This section describes the mathematical programming formulation of the TD-MCCP for the single rate-setting behavioral strategy case. The notation, constraints, and objective function are discussed, followed by the characterization of the formulation properties.

**Sets**

Let a shipment \( k \in K \) be served in a time interval \( t \in T \) of the planning horizon by a set of fixed transshipment facilities \( i \in N \) (labeled facilities or nodes) which are interconnected by transit corridors \( a \in A \) (labeled arcs). The transit corridors \( a \in A \) that originate from facility \( i \in N \) are depicted as \( a \in \Gamma(i) \) and those heading to facility \( i \in N \) as \( a \in \Gamma^{-1}(i) \). A shipment \( k \in K \) from a carrier requiring capacity \( q \in Q \) may be served by a transit corridor \( a \in A \) through a capacity-providing carrier \( q \in Q \) operating in this corridor in time interval \( t \in T \). Fixed transshipment facilities \( i \in N \) and collaborative carriers \( Q, \hat{Q} \subseteq Q \) form the collaborative network. A shipment
In equation (1), \( C_{TC} \) represents the transfer cost per shipment, \( r_a \) represents the length of transit corridor \( a \in A \), and \( d_{kq} \) represents the total shipment volume. \( \alpha \) and \( \beta \) represent positive monetary values that depend on the shipment characteristics (12).

The volume-oriented carrier will charge a rate to offset the empty haul trip (deadheading trip):

\[
\delta_{aqq} = \frac{C_{TC}}{d_{kq}} + \frac{(\alpha r_a + \beta d_{kq})}{d_{kq}}
\]  

In equation (2), \( \rho \) represents a positive monetary value that depends on empty haul characteristics (for example, cost of driver, insurance, and fuel).

The profit-oriented carrier will charge a rate based on amount of volume shipped:

\[
\delta_{aqq} = \frac{C_{TC}}{d_{kq}} + \frac{\left(\frac{\alpha + \rho}{2}\right) r_a + \beta d_{kq}}{d_{kq}}
\]  

For equation (3), we assume that the \( \delta_{aqq} \) will use the average of the monetary value parameters corresponding to the transit corridor length for equations (1) and (2).

A leasing cost \( \phi_a \) is assessed if a collaborative transaction fails to occur for a transit corridor \( a \in A \) with demand that needs to be serviced. The leasing cost is as follows:

\[
\phi_a = T_k() + D_k() + U_k()
\]
where the function $T_k(\cdot)$ represents the costs associated with acquiring the short-term lease(s) for the additional capacity (vehicle size, rental, insurance, number of days, number of trucks, and fuel expenses), $D_k(\cdot)$ represents the costs associated with the driver(s) (wage per hour), and $U_k(\cdot)$ represents the costs associated with handling the loads (loading/unloading, equipment, duration costs) ($I$).

We assign a holding cost $\vartheta_i$ per time interval for each time interval a shipment in a facility $i \in N$ is not transshipped immediately (as in cross-docking operations) and held in the same facility for the next time interval. The holding costs $\vartheta_i$ are assumed to vary for each facility $i \in N$. They are obtained using the ranges specified in Kawamura (13) on the value of time per unit of shipment for LTL carriers. The holding costs are divided equally between the collaborating carriers related to that transfer (see Problem Description and Assumptions).

**Variables**

If a shipment $k \in K$ is served through transit corridor $a \in A$ for a capacity-requiring carrier $q \in \bar{Q}$ by a capacity-providing carrier $\hat{q} \in \hat{Q}$ in time interval $t \in T$, we define $Y_{kaq}t$ to take the value 1, and 0 otherwise. This variable represents the collaborative capacity transaction between the carriers.

If a shipment $k \in K$ belonging to capacity-requiring carrier $q \in Q$ is held in facility $i \in N$ in time interval $t \in T$, we define $X_{kaqt}$ to take the value 1, and 0 otherwise. We note here that holding of shipments at facilities is not, in general, a cost-effective solution. However, in our time-dependent collaborative network, holding of shipments may be either required for establishing the feasibility of transshipment or may allow optimal routing of shipments in later uncapacitated periods.

If a shipment $k \in K$ is served through transit corridor $a \in A$ for a capacity-requiring carrier $q \in \bar{Q}$ in time interval $t \in T$ through leasing, we define $Z_{ka}t$ to take the value 1, and 0 otherwise. We note here that leasing of capacity is not, in general, cost-effective. However, in our collaborative network, leasing of capacity may be required to meet demand requirements.

**Constraints**

Next, we formulate the constraint set of the TD-MCCP. It consists of two sets of constraints. The first set of constraints (4a, 4b, and 4c) model the independent transshipment of shipments through the time-dependent carrier collaborative network. The second set of constraints (5 and 6) establishes upper bounds on the available collaborative capacity (in terms of volume) and the available capacity from leasing. The constraints are as follows:

\[- \sum_{a \in \Theta(k)} \left( \sum_{q \in \bar{Q}} Y_{kaq}t \right) + Z_{ka}t \right) - X_{ka}t = -1 \quad \forall i \in O(k), k \in K, q \in \bar{Q}, t \in T \quad (4a)\]

\[\sum_{a \in \Theta^{-1}(i)} \left( \sum_{q \in \bar{Q}} Y_{kaq}(t-\tau_a) \right) + Z_{ka}(t-\tau_a) \right) + X_{ka}(t-\tau_a) = \sum_{a \in \Theta^{-1}(i)} \left( \sum_{q \in \bar{Q}} Y_{kaq}t \right) + Z_{ka}t \right) + X_{ka}t \quad \forall i \in N \setminus \{O(k), D(k)\}, k \in K, q \in \bar{Q}, t \in T, t \geq \tau_a \quad (4b)\]
The objective function of the TD-MCCP problem seeks to minimize the total system collaborative costs for the multiple carrier coalition and is represented as:

\[\text{Min } P = \sum_{k \in K} \sum_{a \in A} \sum_{q \in Q} \sum_{t \in T} \delta_{aqk} d_{aqk} Y_{aqk} + \sum_{k \in K} \sum_{a \in A} \sum_{q \in Q} \sum_{t \in T} \phi_a d_{aqk} Z_{aqk} + \sum_{k \in K} \sum_{q \in Q} \sum_{t \in T} \theta_t d_{aqk} X_{aqkt}\] (10)

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It consists of three parts. The first term represents the collaborative capacity transaction costs, the second term represents the capacity leasing costs, and third term denotes the holding constraints and ensures the node flow propagation conservation for the capacity transaction decisions; at most one decision unit of capacity transaction is propagated at a node/facility. It consists of three node flow propagation conservation constraints (4a), (4b), and (4c), which correspond to the origin, intermediate, and destination nodes/facilities in the network, respectively.

Constraint set (4a) corresponds to the origin nodes (facilities). It states that at most one unit of flow may enter an origin facility, and that it will either be serviced to the next facility by a collaborative carrier or a leasing alternative, or remain in the same facility for that time interval. Constraint set (4b) is the mass balance equation at intermediate nodes representing the non-origin and non-destination facilities. The shipments at an intermediate facility may arrive from upstream facilities through a collaborative carrier or a leasing alternative, or may be held at that facility in the previous time interval. They can either be shipped out of the facility to a downstream facility or remain in the same facility for that time interval. Constraint set (4c) corresponds to the destination nodes. A shipment may originate from an upstream facility that reaches the destination facility in this time interval through a collaborative carrier or a leasing alternative, or be held at the destination facility in the previous time interval. This shipment either exits from the network at this destination facility or is held in it for this time interval.

Constraint (5) represents the collaborative capacity constraint; it ensures that the capacity acquired from a capacity-providing carrier (left-hand side of (5)) is at most its available capacity (right-hand side of (5)) on that transit corridor for that time interval. Constraint (6) represents the leasing capacity constraint; it ensures that the leasing capacity acquired by the capacity-requiring carrier (left-hand side of (6)) is less than the available leasing capacity (right-hand side of (6)) on that transit corridor for that time interval.

Constraint sets (7), (8) and (9) represent the 0-1 integrality conditions for the decision variables.

**Objective Function**

The objective function of the TD-MCCP problem seeks to minimize the total system collaborative costs for the multiple carrier coalition and is represented as:
costs at the facilities. The overall collaborative capacity transaction costs are obtained as the summation of the product of the collaborative capacity transaction rate \( \delta_{aqq} \), the demand \( d_{kq} \), and \( Y_{kaqt} \) (the decision on whether a time-dependent collaborative capacity transaction between carriers occurs on a transit corridor). The overall leasing costs are obtained as the summation of the product of the leasing costs \( \phi_a \), the demand \( d_{kq} \), and \( Z_{kaqt} \) (the decision on whether a capacity-requiring carrier leases capacity on a transit corridor in this time interval). The overall holding costs are obtained as the summation of the product of the holding costs \( \phi_i \) for that facility, the demand \( d_{kq} \), and \( X_{kqit} \) (the decision on whether the shipment is held by this facility for a capacity-requiring carrier in this time interval). It should be noted that all capacity-providing carriers are assumed to have the same rate-setting behavioral strategy here. Hence, equation (10) subject to constraints (4) through (9) represents the formulation of the TD-MCCP.

**Properties**

This section discusses some properties of the proposed TD-MCCP formulation.

**Classification** The proposed formulation of the TD-MCCP belongs to the class of binary (0-1) multi-commodity minimum cost flow problems. This is because, constraints (4a), (4b), and (4c) are mass balance constraints on which “flow” (transaction decisions) propagate. The classification is further substantiated by the structure of the physical network in which the collaborative carriers operate; that is, the static nodes of the time-expanded network are the fixed transshipment facilities (for example, warehouses, depots, and/or distribution centers) and the static arcs are transit corridors corresponding to the collaborative carriers. It can be noted that constraints (4a), (4b), and (4c) can be written independently for each shipment. Constraint set (5) and (6) are the equivalent collaborative capacity constraints and leasing capacity constraints respectively, which bind the rest of the formulation together.

As a result of this mathematical structure, exact methods such as branch-and-cut can be applied to modestly-sized problem instances (14), as illustrated in the current study where small-to medium-sized LTL carriers operate under modest collaborative network sizes. For larger problem instances (such as larger operating networks), a Lagrangian relaxation method can be used to solve the multi-commodity minimum cost problem through the relaxation of the capacity constraint sets (5) and (6). In relaxing these constraint sets, independent multiple minimum cost flow problems can be solved. However, due to the (0-1) binary nature of the TD-MCCP formulation, this implies solving independent shortest path problems. Other mathematical decomposition methods have also been proposed for this class of problems (15, 16).

**The TD-MCCP Corresponding Graphs are Acyclic** The acyclic property is characteristic of time-expanded graphs. It is proved by contradiction. Assume that there is a directed cycle in the graph structure. The directed cycle will allow a flow to pass either from an \( X_{kqit} \), \( Y_{kaqt} \), or \( Z_{kaqt} \) arc twice in time interval \( t \in T \). However, the flow entering any \( X_{kqit} \), \( Y_{kaqt} \), or \( Z_{kaqt} \) arc arrives from previous time intervals and exits at later time intervals, which are exclusively connected by adjacent \( X_{kqit} \), \( Y_{kaqt} \), or \( Z_{kaqt} \) arcs following the single direction that time flows. Therefore, a flow can never go back in time in order to re-enter the same \( X_{kqit} \), \( Y_{kaqt} \), or \( Z_{kaqt} \) arcs in time interval \( t \in T \). This contradicts the initial assumption and completes the proof.

The physical interpretation is that there is no path in the corresponding graphs of the TD-
MCCP allowing a decision unit of capacity transaction to return back in time. This property allows the implementation of the reaching shortest path algorithm for acyclic networks \((15)\), which has a running time complexity of \(O(|A|)\).

**Total Unimodularity** The TD-MCCP formulation is characterized by the total unimodularity, which guarantees that the optimum decision variable values are integers. This property enables the circumvention of much slower integer programming solution algorithms through the use of more efficient linear programming techniques.

The property of total unimodularity aids in the solution of our problem in the following ways. First, the branch-and-cut algorithm in GAMS/CPLEX is used which solves the linear program without the integer constraints to obtain the optimal solution. Here, the unimodularity property precludes the need for utilizing the cutting plane algorithm. Second, the unimodularity property helps in the context of the decomposition (as discussed earlier) of larger problem instances involving large networks (for example, larger LTL collaboration operations) to multiple independent shortest path problems. Hence, for each independent shortest path problem, the integrality constraints can be dropped and the problem can be solved using linear shortest path algorithms (like the reaching shortest path algorithm) to obtain integer 0-1 solution sets which satisfy the original integrality constraints.

Third, the total unimodularity property implicitly addresses the three key assumptions for precluding the splitting of shipments, as stated earlier. Constraints (4a), (4b), and (4c), along with integrality constraints (7), (8) and (9), intrinsically ensure that a shipment is not split to multiple carriers during a transfer in a time period, that a shipment is not split to multiple truck routes (arcs) of the same carrier during a transfer in a time period, and that shipment is not split to multiple truck routes (arcs) of the same leased alternative during a transfer in a time period. Therefore, the following constraints, which would otherwise be required, are redundant, respectively:

\[
\sum_{q \in \tilde{Q}} Y_{kaqt} \leq 1 \quad \forall a \in A, k \in K, q \in \tilde{Q}, t \in T \tag{11}
\]

\[
\sum_{a \in U(k)} Y_{kaqt} \leq 1 \quad \forall k \in K, i \in N, q \in \tilde{Q}, q \in \tilde{Q}, t \in T \tag{12}
\]

\[
\sum_{a \in U(i)} Z_{kaqt} \leq 1 \quad \forall k \in K, i \in N, q \in \tilde{Q}, t \in T \tag{13}
\]

**Multiple rate-setting behavioral extension**

As shown earlier, equation (10) assumes that the carriers exhibit the same rate-setting behavioral strategy. To analyze all three rate-setting behaviors in a single formulation, the rate setting behavioral strategies are introduced in the TD-MCCP as an index \(u \in U\) associated to the carrier providing capacity \(q_u \in \tilde{Q}_u\). The formulation for the multiple rate-setting behavioral strategy case is represented through a straightforward extension of equations (4) through (8). The acyclic property characterized for time-expanded graphs (see The TD-MCCP Corresponding Graphs are Acyclic) and the total unimodularity property (see Total Unimodularity) hold for this extension as well due to the separability of each shipment.
STUDY EXPERIMENTS

The study experiments analyze the performance of the TD-MCCP model under the three individual rate-setting behavioral strategies (all carriers in the collaborative system assume the same rate-setting behavior) and the case where all three are simultaneously considered (each carrier in the collaborative system portrays one rate-setting behavior from among the three proposed, leading to a mix of rate-setting behaviors in the collaborative) for various numbers of shipments and network sizes. The performance is measured in terms of the computational time required to solve the problem formulation to optimality. In addition, experiments are conducted to explore the benefits of the collaboration in a time-dependent setting as a means of increasing capacity utilization.

Data Generation

The data for this study was simulated, and closely follows the industry ranges introduced in Hernandez and Peeta (2010) for: (i) the rates for each of the three rate user classes (equations (1-3)), (ii) the costs to acquire a lease of additional capacity, (iii) the origin-destination demand for multiple shipments, and (iv) the collaborative capacities. A diesel fuel price of $2.79 per gallon is assumed.

Solution and Implementation Details

The computing environment consists of a DELL XPS machine with an Intel Core™ 2 Duo processor T8300, under the Windows Vista™ operating system with 2.40GHz and 4GB of RAM. The TD-MCCP problem was solved using the branch-and-cut algorithm in GAMS/CPLEX optimization software version 22.9 with ILOG CPLEX 11.0.

The TD-MCCP binary (0-1) multi-commodity minimum cost flow problem representation is solved utilizing the branch-and-cut algorithm (16, 17) in GAMS/CPLEX. The branch-and-cut algorithm is used because the scope of the operations in this study represents that of the small- to medium-sized LTL carrier industry. That is, these LTL carriers can be classified as either local (within state operations) or regional (operations between two or more states in a region), and may at most be associated with a dozen or so transfer facilities (4). Hence, their network sizes are modest. As discussed earlier, for larger and more complex LTL collaborative carrier operations, decomposition methods are expected to be more suitable due to the added complexity that larger operating networks and number of shipments introduce.

Experiment Setup

The experimental set up consists of six collaborating carriers for the TD-MCCP problem. The additional problem parameters take values according to the following ranges: network size in terms of the number of nodes (12 and 20) and the number of shipments per carrier (1, 3, and 5). The 12-node network is a representation of a U.S. Midwest LTL network as shown in Figure 1(a), and the 20-node network was randomly generated using MATLAB (see Figure 1(b)). As the data is simulated, ten randomly generated data sets consistent with the small- to medium-sized LTL industry observed ranges are created for each test scenario (in terms of network size and number of shipments). For each network size and number of shipments per carrier scenario,
the collaborative rates and leasing costs are identical in the randomly generated data. However, the demand and collaborative capacities are different for all cases.

**FIGURE 1** Physical representation of: (a) the 12-node network representing the U.S. Midwest, and (b) the randomly generated 20-node network

<table>
<thead>
<tr>
<th>Node ID</th>
<th>State</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iowa</td>
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<tr>
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<td>Chicago</td>
</tr>
<tr>
<td>3</td>
<td>Indiana</td>
<td>Indianapolis</td>
</tr>
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<td>Toledo</td>
</tr>
<tr>
<td>5</td>
<td>Missouri</td>
<td>Springfield</td>
</tr>
<tr>
<td>6</td>
<td>Illinois</td>
<td>East St. Louis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lexington-</td>
</tr>
<tr>
<td>7</td>
<td>Kentucky</td>
<td>Fayette</td>
</tr>
<tr>
<td>8</td>
<td>West Virginia</td>
<td>Charleston</td>
</tr>
<tr>
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<td>Littlerock</td>
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<tr>
<td>10</td>
<td>Mississippi</td>
<td>Jackson</td>
</tr>
<tr>
<td>11</td>
<td>Tennessee</td>
<td>Knoxville</td>
</tr>
<tr>
<td>12</td>
<td>North Carolina</td>
<td>Charlotte</td>
</tr>
</tbody>
</table>
ANALYSIS OF RESULTS

The TD-MCCP is addressed under a time-dependent planning horizon, and insights can be obtained on how different rate-setting behavioral strategies affect the ability of a carrier to increase operational efficiency through the sharing of capacity in a collaborative manner. From the central entity’s perspective, collaborative transactions can only be made if the collaborative capacity costs for the system minimize the total shipment routing costs for the collaborative. As an alternative to collaborative capacity, the central entity also considers the leasing of capacity as an option to aid carriers requiring capacity for part of or the entire shipment route. The leasing alternative can potentially be viable in the multiple carrier case as the costs are shared by the relevant carriers acquiring this capacity in the collaborative, and due to the notion that the sustained demand can exist due to the multiple carriers involved. The leased capacity can be shared amongst the carriers whose shipments share the same transit corridor. As stated in Section 3, the costs associated with this leased capacity are divided (by the central entity) proportionally to the shipment amounts of the various carriers. Hence, the leasing alternative is considered as a strategy to meet demand requirements of the system by the central entity.

Single Rate-Setting Behavioral Strategy Results

To determine the rate-setting behavioral strategies that lead to an increase in operational efficiency through reduced system cost, we compare the performance of the revenue-generating, volume-oriented, and profit-oriented rate-setting behavioral strategies separately. That is, we assume that all collaborative carriers exhibit one rate-setting behavior. The parametric sensitivity analysis and the corresponding numerical results are summarized in Table 1 for each rate-setting behavioral strategy solved separately. Table 1 illustrates that the overall trend for each network size indicates that, in general, the costs for each rate-setting behavioral strategy increase as the number of shipments increase. The exception to this trend is the profit-oriented strategy for the 3 shipments per carrier scenario for the 12-node network which has higher costs compared to the 5 shipments per carrier scenario in Table 1. This is because the randomly generated rates were, on average, lower for the 3 shipments scenario resulting in an increase in collaborative capacity acquisition by the system. The leasing alternative, in many instances, entailed much higher costs, especially under the 5-shipment scenario. This is because as the number of shipments increase, the leasing alternative becomes more attractive in some instances as multiple carriers requiring capacity are able to share the cost burden associated with the leased capacity.
TABLE 1 Comparison of the System Performance Under the Individual Rate-Setting Behavioral Strategies

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>Number of Arcs</th>
<th>Number of Shipments per Carrier</th>
<th>Revenue-Generating Costs</th>
<th>Volume-Oriented (Leasing Costs)</th>
<th>Profit-Oriented (Leasing Costs)</th>
<th>Total System Cost for Each Rate-Setting Behavior Scenario Including Holding Costs (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>29</td>
<td>1</td>
<td>1214 (13543)</td>
<td>6123 (4720)</td>
<td>4343 (9002)</td>
<td>16004 (11759) (14473)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>5374 (56850)</td>
<td>27738 (19335)</td>
<td>21449 (36220)</td>
<td>66984 (50674) (62081)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10382 (105527)</td>
<td>48870 (40716)</td>
<td>17095 (85543)</td>
<td>114099 (96863) (110975)</td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td>1</td>
<td>2156 (25684)</td>
<td>14953 (8694)</td>
<td>7026 (19280)</td>
<td>30878 (26227) (29177)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2976 (66321)</td>
<td>38265 (23323)</td>
<td>9531 (68482)</td>
<td>76234 (67753) (85822)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>14338 (131778)</td>
<td>61602 (59827)</td>
<td>44919 (92171)</td>
<td>160041 (133001) (150155)</td>
</tr>
</tbody>
</table>
Further, as seen in Table 1, the overall costs (which include the holding costs) for a collaborative system with a volume-oriented rate-setting behavioral strategy are lower than either those of the revenue-generating or profit-oriented carrier systems. This is because the volume-oriented carriers with excess capacity charge rates that are equal to the costs associated with moving empty (see equation (2)), leading to much lower costs than either the revenue-generating carriers, profit-oriented carriers, or the leasing alternative. The costs to move empty usually serve as a base for carriers when they consider serving a shipment (3).

Multiple Rate-Setting Behavioral Strategy Results

In the real-world, not all carriers exhibit the same rate-setting behavioral strategy, leading to a collaborative system which contains a mix of carriers exhibiting one of the three rate-setting behavioral strategies. For our six-carrier collaborative system, two carriers each were assigned to the volume-oriented, profit-oriented, and revenue-generating behavioral categories. The parametric sensitivity analysis and the corresponding numerical results for the TD-MCCP under this mixed scenario of rate-setting behaviors are summarized in Table 2. It illustrates that the overall trend for each network size and number of shipments scenario indicates that the costs increases as the number of shipments increase. Further, the costs associated with the volume-oriented rate-setting carriers were significantly larger than those of the revenue-generating and profit-oriented carriers. The larger share of costs for the volume-oriented carriers is because the centralized system seeks to utilize as much of the volume-oriented capacity as possible due to its lower rate. In comparison to the rate-setting behavior classes, the leasing alternative represents a substantial portion of the overall system costs. This illustrates that the leasing alternative was utilized quite frequently due to the greater affordability provided to multiple carriers requiring capacity for specific transit corridors. The affordability is result of the capacity-requiring carriers proportionally splitting the costs to acquire the capacity, thereby reducing the relative cost burden for the associated individual carriers. The results also indicate that the leasing alternative is a viable option, especially as the number of shipments increase. This is due to instances of scarcity of affordable collaborative capacity in the multiple carrier system in the associated numerical experiments.
<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>Number of Arches</th>
<th>Total Costs ($)</th>
<th>Total Leasing Costs ($)</th>
<th>Total Holding Costs ($)</th>
<th>Revenue-Generating ($)</th>
<th>Volume-Oriented ($)</th>
<th>Profit-Oriented ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>55</td>
<td>133532</td>
<td>60337</td>
<td>13246</td>
<td>4822</td>
<td>52119</td>
<td>16254</td>
</tr>
<tr>
<td>12</td>
<td>29</td>
<td>93739</td>
<td>49814</td>
<td>8024</td>
<td>2538</td>
<td>32198</td>
<td>9191</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70183</td>
<td>26915</td>
<td>5165</td>
<td>2851</td>
<td>30810</td>
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<td>133532</td>
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<td>4822</td>
<td>52119</td>
<td>16254</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>16096</td>
<td>4465</td>
<td>1462</td>
<td>766</td>
<td>8282</td>
<td>2583</td>
</tr>
</tbody>
</table>

TABLE 2 Comparison of the System Performance Under the Mix of Multiple Rate-Settings Behavioral Strategies
Capacity Utilization

Table 3 details the average capacity utilization under the mix of multiple rate-setting behavioral strategies. The volume-oriented carriers, on average, incur the largest increase in capacity utilization across all scenarios indicating that this rate strategy can leverage empty movements through a collaborative network to create win-win situations. To illustrate this further, on average, 85% of the volume-oriented capacity is utilized for all network size and number of shipments scenarios. It indicates that the volume-oriented rate-setting behavioral strategy is a dominant collaboration-inducing strategy for a centralized multiple carrier collaborative network. That is, a carrier collaborative stands to gain from such a strategy in terms of reduced costs for the carriers requiring capacity and increased operational efficiency for carriers seeking to reposition capacity.

**TABLE 3 Average Capacity Utilization Ratio Under the Mix of Multiple Rate-Setting Behavioral Strategies**

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>Number of Arcs</th>
<th>Number of Shipments per Carrier</th>
<th>Revenue-Generating</th>
<th>Volume-Oriented</th>
<th>Profit-Oriented</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>29</td>
<td>1</td>
<td>1%</td>
<td>89%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.5%</td>
<td>85%</td>
<td>14.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>2%</td>
<td>78%</td>
<td>20%</td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td>1</td>
<td>1%</td>
<td>87%</td>
<td>12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1%</td>
<td>86%</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>3%</td>
<td>82%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Computational Experience

Table 4 summarizes the CPU computational time results for the branch-and-cut algorithm for each problem instance. The computational time for each instance increases with the number of shipments for a network size, and with the network size itself. Optimality for each scenario was achieved through the branch-and-cut approach in a few seconds, indicating that the branch-and-cut algorithm is an appropriate solution technique for the TD-MCCP instances analyzed, and in general for the typical scale of small- to medium-sized LTL operations.
TABLE 4 Branch-and-Cut Computational Time Results for the 12-Node and 20-Node Networks

<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>Number of Arcs</th>
<th>Number of Shipments per Carrier</th>
<th>Revenue-Generating (Seconds)</th>
<th>Volume-Oriented (Seconds)</th>
<th>Profit-Oriented (Seconds)</th>
<th>Mix of Behavioral Classes (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>29</td>
<td>1</td>
<td>1.98</td>
<td>1.99</td>
<td>1.94</td>
<td>2.13</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.17</td>
<td>3.2</td>
<td>3.19</td>
<td>3.2</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.56</td>
<td>3.47</td>
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<tr>
<td>20</td>
<td>55</td>
<td>1</td>
<td>5.22</td>
<td>5.25</td>
<td>5.22</td>
<td>5.27</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>7.33</td>
<td>7.7</td>
<td>6.97</td>
<td>7.86</td>
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<td></td>
<td></td>
<td>5</td>
<td>9.44</td>
<td>10.3</td>
<td>9.73</td>
<td>9.42</td>
</tr>
</tbody>
</table>

In summary, the study experiments provide insights into the various rate-setting behavioral strategies and their ability to induce collaboration in a centralized LTL carrier collaborative network. The results suggest that the attractiveness of the multiple carrier collaboration paradigm increases with the volume-oriented rate-setting strategy. Further, a volume-oriented strategy has the potential to increase the capacity utilization of carriers seeking to minimize empty-haul trips. Finally, the leasing alternative can serve as a viable option for a centralized collaborative effort when the costs to lease the capacity are fairly allocated amongst the users.

CONCLUDING COMMENTS

A time-dependent centralized multiple carrier collaboration problem (TD-MCCP) is introduced that provides a planning mechanism to analyze the benefits of a centralized multiple carrier collaboration system. It addresses the operational issue of dead-heading by leveraging excess capacity from the perspective of small- to medium-sized LTL trucking firms, synergized by novel opportunities provided through advances in ICT and e-commerce. A binary (0-1) multicommodity minimum cost flow formulation of the TD-MCCP problem was presented for two sets of rate-setting behavioral strategies involving the capacity-providing carriers. The first studied the effect of a single rate-setting behavioral strategy for the collaborative system, by considering each of the three strategies separately. The second addressed the effect of a mix of multiple rate-setting behavioral strategies in the collaborative system. The corresponding formulations were shown to exhibit the total unimodularity property which reduced the complexity of the TD-MCCP problem through the elimination of redundant constraints. A branch-and-cut algorithm for solving integer programs was used to solve the problem formulation for network sizes consistent with the small- to medium-sized LTL industry. The computational results indicated that the branch-and-cut algorithm is an effective and sufficient solution approach for the problem formulation.

The study results indicated that the time-dependent centralized multiple carrier collaboration paradigm can increase capacity utilization for member carriers under a volume-oriented rate-setting strategy, thereby generating the potential to offset costs for empty-haul trips.
In addition, the leasing alternative can potentially serve as a viable alternative when collaborative capacity is either not available or affordable. This is because the costs to acquire the leased capacity under a centralized multiple collaborative system can be allocated fairly amongst the carriers sharing the relevant capacity. A key implication of this study is that carrier collaboration can become a critical strategy for LTL carriers to remain competitive by decreasing their operational costs.
REFERENCES


