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

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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 strategy in which a central entity (such as a third-party logistics firm) seeks to minimize the total system costs of an LTL carrier collaborative that consists of multiple 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 view demand as dynamic, capacities in the proposed LTL multiple-carrier collaborative framework 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 with a branch-and-cut algorithm. The first case examines the effect of one rate-setting behavioral strategy at a time, and the second case examines the effect of multiple rate-setting behavioral strategies simultaneously. Numerical experiments are conducted to seek insights into the computational performance of the TD-MCCP formulations under various network sizes and numbers 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.

The Internet and information communication technologies (ICT) are becoming an integral part of the operations of many trucking companies; the potential for leveraging ICT particularly exists 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. To survive in such an environment, carriers are beginning to explore collaborative strategies to maintain a competitive edge. One manifestation of this shift is the possibility of LTL carrier–carrier collaboration, which seeks to exploit synergies (for example, excess capacity availability) in operations (*1*). The impetus for these smaller carriers to consider cooperative alliances also arises from the need to address emerging concerns, such as the increase in shipper requirements and the role of the Internet and ICT in enhancing competition. Thus, a key operational challenge for carrier–carrier collaborative networks is to address these issues within a cooperative alliance and create win–win situations for all members in the alliance.

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

Carrier collaboration among multiple carriers can be induced from the identification of 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. These rate-setting behavioral strategies can provide insights into the operational characteristics that may lead to a successful collaborative effort. For example, carriers that are trying to establish density between specific facilities or on certain transit corridors may charge reduced rates to provide capacity on 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 in need of capacity, it could first search for carriers that are trying to establish density on various transit corridors. With the advances in the ICT domain, 3PL firms can easily keep track of carriers and update their rate-setting tendencies (rates may also change depending on the economic climate or other unforeseen events).

Each carrier may consider different factors to determine the rate it will charge to fulfill a collaborative shipment request; for example, based on the shipment type, a carrier may charge different rates to ship perishable as opposed to nonperishable goods. In this study, three rate-setting behavioral strategies are considered. First, some carriers may be revenue driven. They will charge higher collaborative rates, independent of the volume the carrier serves; in essence, these carriers will charge a rate based on the current market value for moving a shipment (*2*). Second, some carriers may be volume oriented. They will be more concerned with establishing density on shipment routes between certain terminals; these carriers' rates will typically be set to offset empty hauls (*3*). Third, some carriers may be profit oriented. These carriers will adjust rates through discounts; typically, these carriers' rates will be between those of the volume-oriented and the revenue-driven carriers (*4*). Consideration of these three rate-setting behavioral strategies for the collaborative carrier paradigm enables the viability of an LTL carrier collaborative to be compared with other alternatives, such as short-term leasing.

This paper introduces a framework to study, in a centralized setting, multiple-carrier collaboration among small- to medium-sized LTL carriers with different rate-setting behavioral strategies. 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 for various shipments based on the available collaborative capacities on the 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; the time-dependent collaborative capacities on the network links are known a priori for the entire planning horizon. Therefore, operational aspects related to the variability in link travel time caused by congestion effects are ignored, 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 the transfer facilities. In addition to the rate-setting behavioral strategies, short-term leasing is considered as an option to serve excess demand and is captured through a leasing cost. The performance of the carrier collaborative under the various 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: (*a*) a review of the literature related to the integration of demand and supply concepts for time-dependent multiple-carrier collaborative networks; (*b*) a discussion of the rate-setting cost parameters and the formulation of the TD-MCCP; (*c*) a description of the numerical experiments conducted in this study; (*d*) a summary of experiment results, including sensitivity analyses, an analysis of the effects of the rate-setting behavioral strategies on time-dependent multiple-carrier collaboration, and an estimate of the levels of collaborative capacity utilization; and (*e*) concluding comments.

LITERATURE REVIEW

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

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

Agarwal and Ergun introduced a mechanism design (reverse game-theoretical approach) for service network alliances that allocated the benefits of collaboration in a decentralized setting (*7*). That is, the mechanism determined capacity exchange costs, which in turn were used by the carriers to make routing and capacity exchange decisions. The authors modeled a multicommodity flow game as a linear program for a coalition of carriers and proposed an inverse optimization solution approach to obtain the capacity exchange costs from the perspective of a single carrier. The resulting capacity exchange costs were then shown to be sufficient for the coalition through the compliance of the core property, a cooperative game-theory principle. However, the study assumed that an individual player could route all the demand flow in the network to maximize the total benefit. Agarwal and Ergun applied the above mechanism design to a liner shipping collaborative problem (*8*).

In the context of the carrier collaboration problem addressed in this paper, 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 but not the carriers' rate-setting behavioral 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 multicarrier collaboration network and simultaneously considers a leasing alternative. Exploring the effect of rate-setting behavior on collaborative transactions between carriers can identify those rate-setting behavioral strategies that lead to the largest reductions in operational costs for the collaborative system. Second, this study examines the problem from the context of the LTL small- to medium-sized carrier industry, which operates over a network of warehouses, depots, and 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, which results in faster trips. Second, carriers are saved from additional transfer and transit costs because consolidation terminals are bypassed (*4, 9*). This network structure is especially attractive because synergies, in the form of excess capacity, can be exploited.

To the best of the authors' 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 through the analysis of three real-world rate-setting behavioral strategies. Addressed from a planning perspective, the TD-MCCP represents a starting point from which to study the effects of rate-setting behavioral strategies in a centralized carrier collaboration network. That is, although 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 from which to address multiple-carrier collaborative paradigms in an operational context for the small- to medium-sized LTL industry. For example, a rolling horizon method can be used to 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 (*10, 11*).

TD-MCCP MATHEMATICAL MODEL

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 system cost for the carriers that 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 acquire excess capacity from a collaborative partner for some segments of a route to meet demand, or a carrier may provide excess capacity to collaborative partners for some portions of their routes to offset deadheading costs. The operational networks of the collaborating carriers can be geographically identical or can overlap in only some segments.

The collaborative rate structure for a capacity-providing carrier is represented by one of the following strategies: (*a*) rates that are revenue driven, (*b*) rates that are volume oriented, or (*c*) rates that are 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 that require additional capacity and 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 that use that capacity on a transit corridor.

The following assumptions are made in the TD-MCCP: (*a*) a shipment is not split between multiple carriers during a transfer, (*b*) a shipment is not split between multiple truck routes (arcs) of the same carrier during a transfer, and (*c*) a shipment is not split between multiple truck routes (arcs) of the same leasing alternative during a transfer. Furthermore, the TD-MCCP assumes that the collaborating carriers subscribe to the following provisions: (*a*) all carriers utilize their available capacity before committing excess capacity, and (*b*) the costs associated with loading and 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 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") that 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 the corridors that head to facility $i \in N$ are depicted as $a \in \Gamma^{-1}(i)$. A shipment $k \in K$ from a carrier that requires capacity $\tilde{q} \in \tilde{Q}$ may be served by a transit corridor $a \in A$ through a capacity-providing carrier $q' \in Q'$ that operates on this corridor in time interval $t \in T$. Fixed transshipment facilities $i \in N$ and collaborative carriers $\tilde{Q}$, $Q' \subset Q$ form the collaborative network. A shipment $k \in K$ will enter the collaborative network through an origin facility $[O(k)]$ and exit through a destination facility $[D(k)]$. For a shipment $k \in K$, its origin facility $[O(k)]$ and its destination facility $[D(k)]$ constitute its origin–destination pair.

Parameters

Each shipment $k \in K$ from a carrier requiring capacity $\tilde{q} \in \tilde{Q}$ has an associated volume ($d_{k\tilde{q}}$). The available collaborative capacity (unused volume) of a collaborative carrier $q' \in Q'$ for transit corridor $a \in A$ for time interval $t \in T$ is $w_{aq't}$. If a collaborative carrier $q' \in Q'$ does not provide service for a transit corridor $a \in A$ in time interval $t \in T$, then it is assumed that the available collaborative capacity ($w_{aq't}$) is 0. The leased capacity provided on transit corridor $a \in A$ in time interval $t \in T$ is L_{at}. If capacity is not requested through the leasing alternative on transit corridor $a \in A$ in time interval $t \in T$, it is assumed that the leased capacity (L_{at}) is 0. The cost of acquiring a unit of capacity (volume) by a carrier $\tilde{q} \in \tilde{Q}$ that requires capacity from a carrier $q' \in Q'$ that provides capacity on transit corridor $a \in A$ is the collaborative rate $\delta_{a\tilde{q}q'}$. The travel time of a shipment through transit corridor $a \in A$ is τ_a.

For the purpose of this study, $\delta_{a\tilde{q}q'}$ is represented through three functional forms that correspond to the three rate-setting behavioral strategies discussed earlier. The revenue-driven carrier will charge a rate equal to the line-haul cost defined by Hernández and Peeta (*1*):

$$\delta_{a\tilde{q}q'} = \frac{C_{\mathrm{TC}}}{d_{k\tilde{q}}} + \frac{\left(\alpha \tilde{r}_a + \beta d_{k\tilde{q}}\right)}{d_{k\tilde{q}}} \qquad (1)$$

where

C_{TC} = transfer cost per shipment,
$\tilde{r}_a$ = length of transit corridor $a \in A$,
$d_{k\tilde{q}}$ = total shipment volume, and
α and β = 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):

$$\delta_{a\tilde{q}q'} = \frac{C_{\mathrm{TC}}}{d_{k\tilde{q}}} + \frac{\left(\rho \tilde{r}_a\right)}{d_{k\tilde{q}}} \qquad (2)$$

where ρ represents a positive monetary value that depends on empty-haul characteristics (for example, the cost of the driver, the insurance, and the fuel).

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

$$\delta_{a\tilde{q}q'} = \frac{C_{\mathrm{TC}}}{d_{k\tilde{q}}} + \frac{\left(\frac{\alpha + \rho}{2}\right)\tilde{r}_a + \beta d_{k\tilde{q}}}{d_{k\tilde{q}}} \qquad (3)$$

In Equation 3, it is assumed that the $\delta_{a\tilde{q}q'}$ will use the average of the monetary value parameters corresponding to the transit corridor length for Equations 1 and 2.

A leasing cost (ϕ_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:

$$\phi_a = T_k(\cdot) + D_k(\cdot) + U_k(\cdot) \qquad (4)$$

where

$T_k(\cdot)$ = costs associated with acquiring short-term leases for the additional capacity (e.g., vehicle size, rental, insurance, number of days, number of trucks, and fuel expenses),
$D_k(\cdot)$ = costs associated with the drivers (wage per hour), and

$U_k(\cdot)$ = costs associated with handling the loads (e.g., loading and unloading, equipment, and duration costs) (*1*).

A holding cost (ϑ_i) is assigned for each time interval that a shipment in a facility $i \in N$ is not transshipped immediately (as with cross-docking operations) and is held in the same facility for the next time interval. The holding costs (ϑ_i) are assumed to vary for each facility $i \in N$ and are obtained by use of the ranges specified by Kawamura on the value of time per unit of shipment for LTL carriers (*13*). The holding costs are divided equally between the collaborating carriers related to that transfer (see the section on project assumptions).

Variables

If a shipment $k \in K$ is served through transit corridor $a \in A$ for a capacity-requiring carrier $\tilde{q} \in \tilde{Q}$ by a capacity-providing carrier $q' \in Q'$ in time interval $t \in T$, then $Y_{ka\tilde{q}q't}$ takes the value 1; otherwise it takes the value 0. This variable represents the collaborative capacity transaction between the carriers.

If a shipment $k \in K$, belonging to capacity-requiring carrier $\tilde{q} \in \tilde{Q}$, is held in facility $i \in N$ in time interval $t \in T$, then $X_{k\tilde{q}it}$ takes the value 1; otherwise it takes the value 0. Holding shipments at facilities is not, in general, a cost-effective solution. However, in this study's time-dependent collaborative network, shipments may be held to establish the feasibility of transshipment or to allow the optimal routing of shipments in later time periods.

If a shipment $k \in K$ is served through transit corridor $a \in A$ for a capacity-requiring carrier $\tilde{q} \in \tilde{Q}$ in time interval $t \in T$ through leasing, then $Z_{ka\tilde{q}t}$ takes the value 1; otherwise it takes the value 0. The leasing of capacity is not, in general, cost-effective. However, in this study's collaborative network, the leasing of capacity may be required to meet demand requirements.

Constraints

The constraint set of the TD-MCCP consists of two sets of constraints. The first set (Constraints 5*a*, 5*b*, and 5*c*, shown in Equations 5*a*, 5*b*, and 5*c*) models the independent transshipment of shipments through the time-dependent carrier collaborative network. The second set [Constraints 6 and 7 (Equations 6 and 7)] establishes the upper bounds on the available collaborative capacity, in terms of volume, and the available capacity from leasing. The constraints are as follows:

$$-\sum_{a\in\Gamma(i)}\left(\left(\sum_{q'\in Q'}Y_{ka\tilde{q}q't}\right)+Z_{ka\tilde{q}t}\right)-X_{k\tilde{q}it}=-1 \qquad \forall i\in O(k),k\in K,\tilde{q}\in\tilde{Q},t\in T \qquad (5a)$$

$$\sum_{a\in\Gamma^{-1}(i)}\left(\left(\sum_{q'\in Q'}Y_{ka\tilde{q}q'(t-\tau_a)}\right)+Z_{ka\tilde{q}(t-\tau_a)}\right)+X_{k\tilde{q}i(t-1)} = \sum_{a\in\Gamma(i)}\left(\left(\sum_{q'\in Q'}Y_{ka\tilde{q}q't}\right)+Z_{ka\tilde{q}t}\right)+X_{k\tilde{q}it}$$
$$\forall i\in N\setminus\{O(k),D(k)\},k\in K,\tilde{q}\in\tilde{Q},t\in T,t\geq\tau_a \qquad (5b)$$

$$\sum_{a\in\Gamma^{-1}(i)}\left(\left(\sum_{q'\in Q'}Y_{ka\tilde{q}q'(t-\tau_a)}\right)+Z_{ka\tilde{q}(t-\tau_a)}\right)+X_{k\tilde{q}i(t-1)}=1 \qquad \forall i\in D(k),k\in K,\tilde{q}\in\tilde{Q},t\in T,t\geq\tau_a \qquad (5c)$$

$$\sum_{k\in K}\sum_{\tilde{q}\in\tilde{Q}}d_{k\tilde{q}}Y_{ka\tilde{q}q't}\leq w_{aq't} \qquad \forall a\in A,q'\in Q',t\in T \qquad (6)$$

$$\sum_{k\in K}\sum_{\tilde{q}\in\tilde{Q}}d_{k\tilde{q}}Z_{ka\tilde{q}t}\leq L_{at} \qquad \forall a\in A,t\in T \qquad (7)$$

$$Y_{ka\tilde{q}q't}\in\{0,1\} \qquad \forall a\in A,k\in K,\tilde{q}\in\tilde{Q},q'\in Q',t\in T \qquad (8)$$

$$X_{k\tilde{q}it}\in\{0,1\} \qquad \forall k\in K,\tilde{q}\in\tilde{Q},i\in N,t\in T \qquad (9)$$

$$Z_{ka\tilde{q}t}\in\{0,1\} \qquad \forall a\in A,k\in K,\tilde{q}\in\tilde{Q},t\in T \qquad (10)$$

Constraint Set 5 represents the mass balance 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 or facility. The set consists of three node-flow propagation conservation constraints: Constraints 5*a*, 5*b*, and 5*c*, which correspond to the origin, intermediate, and destination nodes or facilities in the network, respectively.

Constraint 5*a* corresponds to the origin nodes (facilities). It states that, at most, one unit of flow may enter an origin facility; the unit will be taken to the next facility by a collaborative carrier or a leasing alternative or will remain in the same facility for that time interval. Constraint 5*b* is the mass balance equation at intermediate nodes that represent the nonorigin and nondestination facilities. The shipments at an intermediate facility may arrive from upstream facilities through a collaborative carrier or a leasing alternative, or the shipments may have been held at that facility in the previous time interval. They can either be shipped to a downstream facility or remain in the same facility for that time interval. Constraint 5*c* corresponds to the destination nodes. A shipment may originate from an upstream facility and reach the destination facility in this time interval through a collaborative carrier or a leasing alternative, or the shipment may have been held at the destination facility in the previous time interval. The shipment either exits from the network at this destination facility or is held at the facility for this time interval.

Constraint 6 represents the collaborative capacity constraint; it ensures that the capacity acquired from a capacity-providing carrier (left-hand side of Equation 6) is, at most, its available capacity (right-hand side of Equation 6) on that transit corridor for that time interval. Constraint 7 represents the leasing capacity constraint; it ensures that the leasing capacity acquired by the capacity-requiring carrier (left-hand side of Equation 7) is less than the available leasing capacity (right-hand side of Equation 7) on that transit corridor for that time interval.

Constraints 8, 9, and 10 (Equations 8, 9, and 10) represent the 0–1 integrality conditions for the decision variables.

Objective Function

The objective function of the TD-MCCP seeks to minimize the total system collaborative costs for the multiple-carrier coalition and is represented as

$$\min P=\sum_{k\in K}\sum_{a\in A}\sum_{\tilde{q}\in\tilde{Q}}\sum_{q'\in Q'}\sum_{t\in T}\delta_{a\tilde{q}q'}d_{k\tilde{q}}Y_{ka\tilde{q}q't}+\sum_{k\in K}\sum_{a\in A}\sum_{\tilde{q}\in\tilde{Q}}\sum_{t\in T}\phi_a d_{k\tilde{q}}Z_{ka\tilde{q}t} +\sum_{k\in K}\sum_{\tilde{q}\in\tilde{Q}}\sum_{i\in N}\sum_{t\in T}\vartheta_i d_{k\tilde{q}}X_{k\tilde{q}it} \qquad (11)$$

The function consists of three parts. The first term represents the collaborative capacity transaction costs; the second term represents the capacity leasing costs; the third term denotes the holding costs at the facilities. The overall collaborative capacity transaction costs are obtained as the summation of the product of the collaborative capacity transaction rate ($\delta_{a\tilde{q}q'}$), the demand ($d_{k\tilde{q}}$), and the decision on whether a time-dependent collaborative capacity transaction between carriers occurs on a transit corridor ($Y_{ka\tilde{q}q't}$). The overall leasing costs are obtained as the summation of the product of the leasing costs (ϕ_a), the demand ($d_{k\tilde{q}}$), and the decision on whether a capacity-requiring carrier leases capacity on a transit corridor in that time interval ($Z_{ka\tilde{q}t}$). The overall holding costs are obtained as the summation of the product of the holding costs (ϑ_i) for that facility, the demand ($d_{k\tilde{q}}$), and the decision on whether the shipment is held by this facility for a capacity-requiring carrier in this time interval ($X_{k\tilde{q}it}$). All capacity-providing carriers are assumed to have the same rate-setting behavioral strategy. Hence, Equation 11, subject to Constraints 5 through 10, 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) multicommodity minimum cost-flow problems. This is because Constraints 5*a*, 5*b*, and 5*c* are mass balance constraints on which flow (transaction) decisions propagate. The classification is further substantiated by the structure of the physical network on 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 distribution centers), and the static arcs are the transit corridors that correspond to the collaborative carriers. Constraints 5*a*, 5*b*, and 5*c* can be written independently for each shipment. Constraints 6 and 7 are the equivalent collaborative capacity constraints and leasing capacity constraints, respectively, that 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 problems (*14*), as illustrated by the current study in which small- to medium-sized LTL carriers operate under modest collaborative network sizes.

For larger problems (such as larger operating networks), a Lagrangian relaxation method can be used to solve the multicommodity minimum cost problem through the relaxation of capacity Constraints 6 and 7. Through the relaxation of these constraints, independent multiple minimum cost-flow problems can be solved. However, the (0–1) binary nature of the TD-MCCP formulation implies the solving of independent shortest-path problems. Other mathematical decomposition methods have also been proposed for this class of problems (*15*, *16*).

Acyclic Corresponding Graphs The acyclic property of the TD-MCCP corresponding graphs 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 from an $X_{k\tilde{q}it}$, a $Y_{ka\tilde{q}q't}$, or a $Z_{ka\tilde{q}t}$ arc twice in time interval $t \in T$. However, the flow entering any $X_{k\tilde{q}it}$, $Y_{ka\tilde{q}q't}$, or $Z_{ka\tilde{q}t}$ arc, which are exclusively connected by adjacent $X_{k\tilde{q}it}$, $Y_{ka\tilde{q}q't}$, or $Z_{ka\tilde{q}t}$ arcs, must arrive from a previous time interval and exit at a later time interval. Therefore, a flow can never go back in time in order to reenter the same $X_{k\tilde{q}it}$, $Y_{ka\tilde{q}q't}$, or $Z_{ka\tilde{q}t}$ arcs in time interval $t \in T$. This contradicts the initial assumption and completes the proof.

The physical interpretation is that no path in the corresponding graphs of the TD-MCCP will allow a decision unit of capacity transaction to return back in time. This property allows the reaching shortest-path algorithm for acyclic networks to be implemented (*15*); the algorithm has a running time complexity of $O(|A|)$.

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

The property of total unimodularity aids in the solution of the problem presented in this paper 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 the cutting-plane algorithm. Second, the unimodularity property helps in the decomposition of larger problems involving large networks (for example, larger LTL collaboration operations) into multiple independent shortest-path problems. Hence, for each independent shortest-path problem, the integrality constraints can be dropped and the problem can be solved with linear shortest-path algorithms (like the reaching shortest-path algorithm) to obtain integer 0–1 solution sets that satisfy the original integrality constraints.

Third, the total unimodularity property implicitly addresses the three key assumptions that preclude the splitting of shipments, as stated earlier. Constraints 5*a*, 5*b*, and 5*c*, along with Constraints 8, 9, and 10, intrinsically ensure that, in a time period, (*a*) a shipment is not split between multiple carriers during a transfer; (*b*) a shipment is not split between multiple truck routes (arcs) of the same carrier during a transfer; and (*c*) a shipment is not split between multiple truck routes (arcs) of the same leased alternative during a transfer. Therefore, the following constraints, which would otherwise be required, are redundant:

$$\sum_{q' \in Q'} Y_{ka\tilde{q}q't} \leq 1 \qquad \forall a \in A, k \in K, \tilde{q} \in \tilde{Q}, t \in T \tag{12}$$

$$\sum_{a \in \Gamma(i)} Y_{ka\tilde{q}q't} \leq 1 \qquad \forall k \in K, i \in N, q' \in Q', \tilde{q} \in \tilde{Q}, t \in T \tag{13}$$

$$\sum_{a \in \Gamma(i)} Z_{ka\tilde{q}t} \leq 1 \qquad \forall k \in K, i \in N, \tilde{q} \in \tilde{Q}, t \in T \tag{14}$$

Multiple Rate-Setting Behavioral Extension

Equation 11 assumes that all 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 with the carrier providing capacity ($q'_u \in Q'_u$). The formulation for the multiple rate-setting behavioral strategy case is represented through a straightforward extension of Equations 5 through 10. The acyclic property characterized for time-expanded graphs and the total unimodularity property hold true 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 in which all three strategies are considered simultaneously (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 were simulated and closely follow the industry ranges introduced in Hernández and Peeta for (*a*) the rates for each of the three rate user classes (Equations 1–3); (*b*) the costs to acquire a lease of additional capacity; (*c*) the origin–destination demand for multiple shipments; and (*d*) the collaborative capacities (*1*). A diesel fuel price of $2.79 per gallon is assumed.

Solution and Implementation Details

The computing environment consisted of a Dell XPS machine with an Intel Core 2 Duo processor T8300, under the Windows Vista operating system, with 2.40 GHz and 4 GB of RAM. The TD-MCCP was solved by use of the branch-and-cut algorithm in the GAMS/Cplex optimization software (Version 22.9) with ILOG Cplex 11.0.

The TD-MCCP binary (0–1) multicommodity minimum cost-flow problem representation was solved by utilizing the branch-and-cut algorithm in GAMS/Cplex (*16, 17*). The branch-and-cut algorithm was used because the scope of the operations in this study represented that of the small- to medium-sized LTL industry. That is, these LTL carriers could be classified as either local (within-state operations) or regional (operations between two or more states in a region) and might be associated with a dozen or so transfer facilities (*4*). Hence, the 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 numbers of shipments introduce.

Experiment Setup

The experimental setup consists of six collaborating carriers for the TD-MCCP. The additional problem parameters take values according to the following ranges: (*a*) network size in terms of the number of nodes (12 and 20) and (*b*) the number of shipments per carrier (one, three, and five). The 12-node network is a representation of a U.S. Midwest LTL network, shown in Figure 1*a*, and the 20-node network was randomly generated using MATLAB (see Figure 1*b*). As the data are simulated, ten randomly generated data sets, consistent with observed ranges in the small- to medium-sized LTL industry, are created for each test scenario (in terms of network size and number of shipments). For each 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.

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 to aid carriers that require capacity for part of or the entire shipment route. The leasing alternative can be viable in the multiple-carrier case as the costs are shared by the carriers that acquire this capacity and because sustained demand can exist due to the multiple carriers involved. The leased capacity can be shared among the carriers whose shipments share the same transit corridor. As stated in the section on the TD-MCCP mathematical model, the costs associated with this leased capacity are divided by the central entity in proportion to the shipment amounts of the various carriers. Hence, the leasing alternative is considered by the central entity to meet the demand requirements of the system.

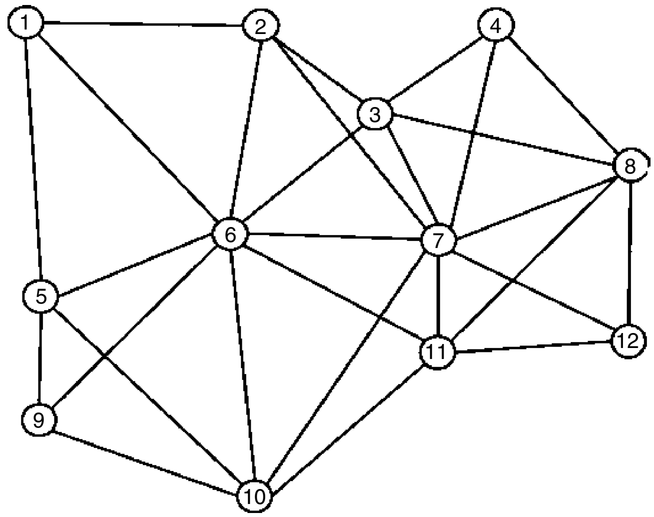
Single Rate-Setting Behavioral Strategy Results

To determine the rate-setting behavioral strategies that lead to an increase in operational efficiency through reduced system cost, the performance of the revenue-generating, volume-oriented, and profit-oriented rate-setting behavioral strategies are considered separately. That is, it is assumed 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. 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 increases. The exception to this trend is the profit-oriented strategy for the three-shipments-per-carrier scenario for the 12-node network, which has higher costs than the 12-node network, five-shipments-per-carrier scenario. This is because the randomly generated rates were, on average, lower for the three-shipment 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 five-shipment scenario. This is because, as the number of shipments increases, the leasing alternative becomes more attractive in some instances as multiple carriers that require capacity are able to share the cost burden associated with the leased capacity.

Furthermore, as seen in Table 1, the overall costs (which include the holding costs) for the collaborative system with a volume-oriented rate-setting behavioral strategy are lower than the overall costs 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), which leads to much lower costs than those for 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 making a shipment (*3*).

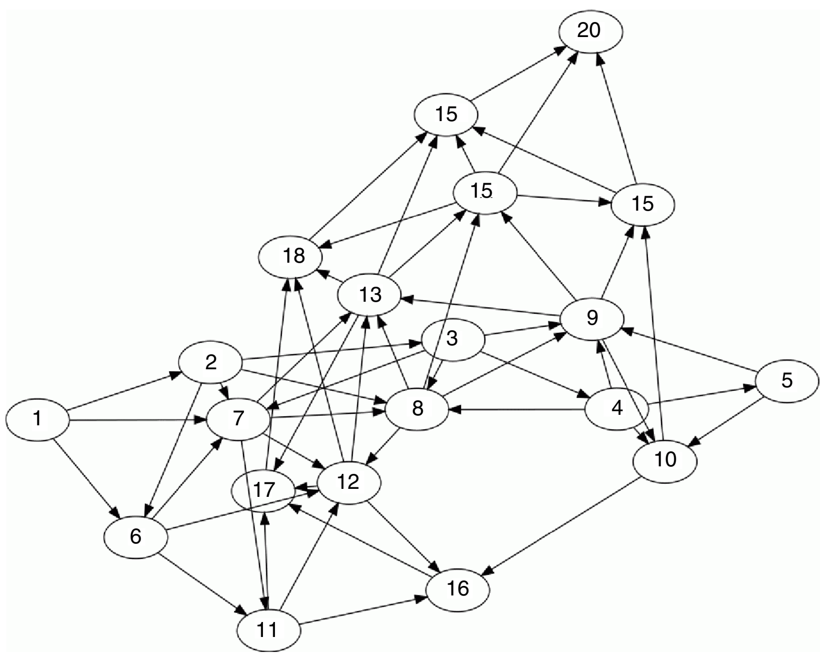
Multiple Rate-Setting Behavioral Strategy Results

In the real world, not all carriers exhibit the same rate-setting behavioral strategy, which leads to a collaborative system with a mix of carriers that exhibit one of the three rate-setting behavioral strategies. For the six-carrier collaborative system, two carriers were assigned to each of the behavioral categories: volume oriented, profit oriented, and revenue generating. The parametric sensitivity analysis and the



Node ID	State	City
1	Iowa	Des Moines
2	Illinois	Chicago
3	Indiana	Indianapolis
4	Ohio	Toledo
5	Missouri	Springfield
6	Illinois	East St. Louis
7	Kentucky	Lexington–Fayette
8	West Virginia	Charleston
9	Arkansas	Littlerock
10	Mississippi	Jackson
11	Tennessee	Knoxville
12	North Carolina	Charlotte

(a)



(b)

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

TABLE 1 Comparison of System Performance Under Individual Rate-Setting Behavioral Strategies

			Cost Comparison for Rate-Setting Behavior and Leasing Alternative ($)			Total System Cost for Each Rate-Setting Behavior Scenario Including Holding Costs ($)		
Number of Nodes	Number of Arcs	Number of Shipments per Carrier	Revenue Generating (Leasing Costs)	Volume Oriented (Leasing Costs)	Profit Oriented (Leasing Costs)	Revenue Generating	Volume Oriented	Profit Oriented
12	29	1	1,214 (13,543)	6,123 (4,720)	4,343 (9,002)	16,004	11,759	14,473
		3	5,374 (56,850)	27,738 (19,335)	21,449 (36,220)	66,984	50,674	62,081
		5	10,382 (105,527)	48,870 (40,716)	17,095 (85,543)	114,099	96,863	110,975
20	55	1	2,156 (25,684)	14,953 (8,694)	7,026 (19,280)	30,878	26,227	29,177
		3	2,976 (66,321)	38,265 (23,323)	9,531 (68,482)	76,234	67,753	85,822
		5	14,338 (131,778)	61,602 (59,827)	44,919 (92,171)	160,041	133,001	150,155

TABLE 2 Comparison of System Performance Under Multiple Rate-Setting Behavioral Strategies

Number of Nodes	Number of Arcs	Number of Shipments per Carrier	Total Costs ($)	Total Leasing Costs ($)	Total Holding Costs ($)	Total System Cost per Rate-Setting Behavior Class: Revenue Generating ($)	Volume Oriented ($)	Profit Oriented ($)
12	29	1	16,096	4,465	1,462	766	8,282	2,583
		3	70,183	26,915	5,165	2,851	30,810	9,608
		5	93,739	49,814	8,024	2,538	32,198	9,191
20	55	1	29,528	13,917	3,402	1,028	11,116	3,467
		3	75,439	35,881	8,087	2,323	25,111	7,831
		5	133,532	60,337	13,246	4,822	52,119	16,254

corresponding numerical results for the TD-MCCP under this mixed scenario of rate-setting behaviors are summarized in Table 2. The overall trend for each network-size and number-of-shipments scenario indicates that the costs increase as the number of shipments increases. Furthermore, the costs associated with the volume-oriented 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 that require capacity for specific transit corridors. This affordability is the result of the capacity-requiring carriers proportionally splitting the costs to acquire the capacity, and 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 increases. This is due to instances of scarcity of affordable collaborative capacity in the multiple-carrier system in the associated numerical experiments.

Capacity Utilization

Table 3 details the average capacity utilization under the mix of rate-setting behavioral strategies. The volume-oriented carriers, on average, incur the largest increase in capacity utilization across all scenarios, which indicates that this rate strategy can leverage empty movements through a collaborative network to create win–win situations. On average, 85% of the volume-oriented capacity is utilized for all the 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 that require capacity and increased operational efficiency for carriers that seek to reposition capacity.

Computational Experience

Table 4 summarizes the computational time results for the branch-and-cut algorithm for each problem instance. The computational time increases with the increase in network size and also within each network size as the number of shipments increases. Optimality for each scenario was achieved through the branch-and-cut approach in a few seconds, which indicates 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.

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. Furthermore, a volume-oriented strategy has the potential to increase the capacity utilization of carriers that seek 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 among the users.

CONCLUDING COMMENTS

A TD-MCCP was introduced that provided a planning mechanism to analyze the benefits of a centralized multiple-carrier collaboration system. The mechanism addressed the operational issue of

TABLE 3 Average Capacity Utilization Ratio Under Multiple Rate-Setting Behavioral Strategies

Number of Nodes	Number of Arcs	Number of Shipments per Carrier	Average Capacity Utilization (%): Revenue Generating	Volume Oriented	Profit Oriented
12	29	1	1	89	10
		3	0.5	85	14.5
		5	2	78	20
20	55	1	1	87	12
		3	1	86	13
		5	3	82	15

TABLE 4 Branch-and-Cut Computational Time Results for the 12-Node and 20-Node Networks

Number of Nodes	Number of Arcs	Number of Shipments per Carrier	CPU Time (s) Revenue Generating	Volume Oriented	Profit Oriented	Mix of Behavioral Classes
12	29	1	1.98	1.99	1.94	2.13
		3	3.17	3.2	3.19	3.2
		5	3.5	3.5	3.56	3.47
20	55	1	5.22	5.25	5.22	5.27
		3	7.33	7.7	6.97	7.86
		5	9.44	10.3	9.73	9.42

deadheading 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 was presented for two sets of rate-setting behavioral strategies that involved 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 mixed 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 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 was 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 not available or unaffordable. This is because the costs to acquire the leased capacity under a centralized multiple-collaborative system can be allocated fairly among the carriers that share 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.

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