Mixed fleet dispatching in truckload relay network design optimization

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Abstract

We propose a mathematical formulation for strategic relay network design and dispatching method selection for full truckload transportation. The proposed model minimizes total transportation and installation costs of a mixed fleet dispatching system combining relay network and point-to-point dispatching. Operational constraints such as maximum driver tour length and load circuity are considered within the variable definition using predefined templates to generate feasible routes. High quality solutions for largely-sized problem instances are obtained in reasonable times. Computational results are analyzed to develop insights about the mixed fleet dispatching system and quantify its benefits over relay network-only and point-to-point dispatching.

Keywords: truckload trucking, relay network design, mixed fleet, dispatching, composite variable

1. Introduction

Driver retention has been and remains a significant problem for full truckload (TL) transportation carriers. The American Transportation Research Institute (2011) reports that driver retention has ranked among the top three concerns for the industry in five of the last seven years, and it has never placed lower than sixth during this period. Driver turnover rates for TL carriers have historically exceeded 100%, and while the reported rate for the third quarter of 2011 is 89%, this value is the highest of the last four years (American Trucking Associations, 2011). In fact, the estimated shortage of truck drivers during 2011 rose to 125,000, exceeding previous estimates (Morris, 2011). Driver turnover not only is a significant expense for the industry due to the estimated hiring and retention costs (approximately $8,200 per driver) (Rodriguez et al., 2000), but also because of the negative effects to the level of service to shippers that results in lost income from demand that cannot be satisfied (Keller and Ozment, 1999). In reality, given that trucking is not a self-contained industry, the shortage of drivers is able to produce negative economic impacts that go far beyond the boundaries of the industry (American Trucking Associations, 2007).

One of the commonly cited reasons for high driver turnover is the point-to-point (PtP) dispatching method TL carriers use to satisfy demand. Long-haul drivers who spend significant time away from home often quit due to a low quality of life perception (Gupta et al., 1996; Lockridge, 2008). In a PtP system, carriers assign a truckload to a single driver who is in charge of transporting it all the way from origin to destination. After the load is delivered, the carrier needs to find a new truckload for the driver with an origin close to the drop-off location in order to minimize empty miles. Finding appropriate backhaul trips for these drivers is very difficult and usually several repositioning moves are needed to return a driver to his or her domicile. Other transportation industries such as less-than-truckload (LTL) and express package shipping that use a hub-and-spoke configuration for their transportation networks do not suffer from the same level of driver turnover (Taylor et al. 1999). In fact, the turnover rate for LTL carriers does not commonly exceed 10% and the value reported for the last quarter of 2011 was only 7% (American Trucking Associations, 2011).

As more truck drivers are needed to satisfy growing freight demand, there is need to evaluate alternative dispatching methods as a means to reduce driver tour lengths and improve driver retention. One alternative dispatching method considers using a network configuration of relay points (RPs) which are physical locations where drivers exchange trailers, allowing drivers to return home more frequently while the truckload continues its transport to its final destination. These TL relay networks essentially divide a load's transportation from origin to destination into several shorter segments between nodes in the transportation network. This helps to increase regularity in the routes for the drivers since now most movements occur between fixed RPs (Üster and Kewcharoenwong, 2011; Üster and Maheshwari, 2007; Vergara and Root, 2012). Essentially, a relay network (RN) is similar to a hub-and-spoke network, except that no sorting or consolidation of truckload freight is required. Also, the strategic design of an RN needs to consider unique operational constraints that make it different from a regular hub-and-spoke network such as limitations on circuity, distances between relay points and number of handlings in a route from origin to destination. Fig. 1 shows a partial relay network for truckload transportation. A review of the literature on TL relay network design is presented in Section 2.

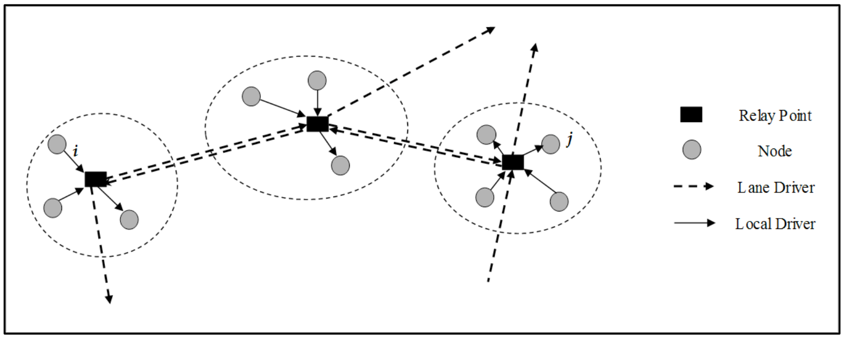

Fig. 1. Relay network for transportation of truckloads.

Previous work on the TL relay network design (TLRND) problem has demonstrated significant potential to improve drivers' jobs. However, these previous studies also suggest that combining the two methods, PtP and RN, into a hybrid system using a mixed fleet will result in a better performance for carriers, drivers and shippers. Interestingly, as described in Section 2, most of the literature focuses on the use of simulation and heuristic approaches for solving this and other mixed fleet dispatching system problems. A general observation from previous work recognizes that hybrid systems consistently outperform the individual methods for freight transportation by truck, but since no exact approaches exist to design such mixed fleet dispatching systems there is not a precise understanding of the benefits of such configurations in the TL industry.

In this paper, we propose a mathematical formulation to solve the integrated problem of strategically designing the relay network and selecting the appropriate dispatching method for truckloads served by a mixed fleet of trucks in a hybrid system that combines PtP and RN dispatching. We call this problem strategic TL relay network design with mixed fleet dispatching or TLRND-MD. The contributions of this work are as follows:

- We develop a prescriptive mathematical model for TLRND-MD using a composite variable model (CVM) formulation. To the best of our knowledge, this is the first prescriptive model that incorporates the selection of the dispatching method for truckloads within the strategic design of a relay network for TL transportation.

- The model presented in this research successfully integrates strategic and tactical decisions while considering several operational constraints using an approach that is similar to the one presented by Vergara and Root (2012), but is different from most previous work in this area. In particular, our model successfully incorporates circuity limitations and limitations on the number of nodes visited, which have been relaxed by previous researchers because of their tractability implications. Furthermore, our model can be used to achieve balanced networks, whereas solution approaches by other researchers have been unable to achieve this.
- An exact solution approach can be used to optimally solve problems of moderate size. We also propose a heuristic solution approach to obtain very high quality solutions for largely-sized problem instances of this problem in reasonable times. Although the model and solution approach presented in this paper generalize the TLRND problem, we are able to solve problem instances with up to 150 nodes whereas other researchers have only be able to solve instances with up to 80 nodes.
- We use our model to quantify the benefit of a hybrid configuration for TL transportation that uses PtP and RN dispatching over an RN-only dispatching system through extensive computational testing. Although practitioners and previous researchers have suggested that hybrid networks will offer improved performance and financial savings, previous research has not quantified this benefit. We explore the effect of several design parameters with respect to performance metrics for carriers, drivers and shippers using randomly generated problem instances and a test case provided by a major TL carrier.

The remainder of the paper is organized as follows. In Section 2, we present a literature review of alternative dispatching methods for freight transportation focusing on mixed fleet systems. A formal problem statement of TLRND-MD and the proposed mathematical formulation for its solution are presented in Section 3. In Section 4, we introduce our solution methodology. The analysis of the computational results obtained for randomly generated problem instances and test case data from a major carrier is presented in Section 5. Finally, conclusions and future research are presented in Section 6.

2. Alternative dispatching methods in freight transportation

Traditional dispatching methods used in the TL industry have focused on the reduction of empty miles between drop-offs and pick-ups for single drivers as a mechanism to reduce dispatching costs. However, this practice and the random fashion in which carriers receive long-haul driving requests make it very difficult to find a sequence of jobs for drivers so that they can return to their home domiciles often. It is estimated that TL drivers typically spend between 14 and 21 days on the road between return trips to their home domiciles (Taylor et al. 1999). This has motivated researchers and practitioners to explore alternative dispatching methods to improve driver job quality and potentially reduce driver turnover rates.

Motivated by the relatively low driver turnover rates in the LTL industry, Taha and Taylor (1994) analyzed the use of hub-and-spoke networks for TL transportation using a simulation approach. They concluded that a network configuration for TL dispatching would reduce driver tour lengths due to the regularization of the duties between the hubs. They observed, however, that this reduction also adds circuity for the loads. In a different study, Taylor et al. (1999) considered the development and analysis of other alternative dispatching methods for a regional implementation. Their simulation of alternative dispatching methods showed significant improvements for both carriers and drivers.

Building on these findings, several other mixed fleet dispatching systems have been analyzed in the literature. Taylor and Whicker (2002) presented a heuristic method and an integer programming approach to select routings and compare various methods of dispatch in a distributed manufacturing setting when considering private fleets. Taylor et al. (2006) considered the combination of traditional PtP dispatching and the use of regional fleets with limited coverage service areas. Taylor et al. (2009) analyzed the use of delivery 'pipelines' with local end-of-line dray movements for some high volume lanes and assessed the effect of these shipments on the rest of system employing regular PtP dispatching. Another 3-way hybrid system integrating regional fleets, delivery 'pipelines' and PtP dispatching in a concurrent operation was explored by Taylor and Whicker (2008). Finally, Taylor and Whicker (2010) studied the use of an extended regional dispatching system using lanes to connect regions of limited service area as they are integrated with a direct PtP dispatching method for some of the truckloads in the system. A general conclusion of these simulation studies is that although operational tradeoffs exist, mixed fleet dispatching systems always outperform a baseline PtP-only system for several metrics that affect carriers, drivers and shippers. Although some general design rules for these hybrid systems are provided, no indication of what constitutes an optimal design is presented in these studies.

Other types of mixed fleet dispatching systems for freight transportation can be found in the LTL literature. Despite the significant differences between the TL and LTL industries, these studies also show that allowing an alternative method in addition to traditional dispatching is beneficial for reducing cost and improving other performance metrics. In this area, Ronen (1997) explored the effect of combining a private fleet with the use of a common carrier when considering two different objectives: distance minimization and cost minimization. In another study, Liu et al. (2003) developed a heuristic approach to select the dispatching mode for LTL loads in a mixed truck delivery system with both hub-and-spoke and direct shipment between suppliers and customers. They concluded that the mixed delivery system is more effective than pure systems. As evidenced in these studies, further analysis of alternative dispatching systems that use a mixed fleet of trucks is justified based on the potential benefits that can be obtained.

The use of relay networks for TL transportation is one alternative dispatching method to alleviate the driver retention problem. Most of the research in this area has been motivated by the initial work of Taha and Taylor (1994). Hunt (1998) and Ali et al. (2001) explored the development of algorithmic and heuristic approaches to determine the number and location of relay points considering shortest path routes for the truckloads in the network. The first mathematical formulation for the strategic design of TL relay networks was presented by Üster and Maheshwari (2007) and it was modified by Üster and Kewcharoenwong (2011). Their basic model is a combination of the multicommodity network flow formulation and the hub-and-spoke problem. Üster and Maheshwari (2007) presented a heuristic approach to solve a formulation of TLRND that relaxes limitations on truckload circuity and equipment balance. This method was successfully applied in small- to medium-sized problem instances of TLRND. Üster and Kewcharoenwong (2011) then developed an algorithm based in Benders' decomposition to solve larger problem instances of this problem. In most of their computational experiments, the authors explicitly consider the limitation on equipment balance, but relax the truckload circuity constraint which is eventually incorporated through a surrogate later in their experimentation. Relay networks with up to 80 nodes are solved using this approach in reasonable times with an optimality gap of 2.0%.

Vergara and Root (2012) presented an alternative formulation for the strategic design of TL relay networks. The authors proposed a formulation for this problem where operational constraints such as limitations on circuity, local and lane driver tour lengths and number of RPs visited by a load are incorporated within the definition of variables that represent feasible routes for the truckloads. Relay networks with up to 100 nodes are solved to optimality using standard branch-and-cut as implemented in a commercial solver. Moreover, high quality solutions are obtained in reasonable times for largely-sized instances with 150 nodes using only a subset of the variables. This heuristic approach provided very small optimality gaps while significantly reducing computational times and was successfully used to solve a network design problem with test case data provided by a major TL carrier.

More recently, Melton and Ingalls (2012) proposed a prescriptive model for locating RPs while minimizing total costs. Their mixed integer program incorporates driver considerations and includes driver turnover cost in the objective function. The driver turnover percentage is determined using an estimation of the number of drivers required for each origin-destination (O-D) node pair according to the RP locations and the resulting weekly driver mileage. However, this formulation does not consider empty movements to balance equipment and it is only used to solve a small case study for a single O-D pair.

Although these studies show that relay networks have the potential to improve the quality of TL driving jobs, research also suggests that a partial implementation of RNs along with PtP dispatching is likely to result in a system with better performance. Both Üster and Kewcharoenwong (2011) and Vergara and Root (2012) point out that for a non-trivial number of truckloads with origin and destination nodes that are close to each other, highly circuitous routes result when using a relay network. Fig. 2 shows an example – this truckload has origin at node *i* and it is destined to node *j*. It is easy to observe that routing this truckload through the relay network is not as efficient as sending it directly from *i* to *j*. Vergara and Root (2012) also found out that several RPs are only opened for feasibility reasons, especially when truckloads have origin or destination nodes in isolated regions of the transportation network. They observed that the amount of traffic at these RPs is significantly lower than in other parts of the network with higher node density. These isolated truckloads are also good candidates for direct PtP dispatching. Having the option of sending them using this method would result in a reduction in the number of RPs in the network. However, they did not integrate these alternative dispatching decisions in their model and assumed that all truckloads are dispatched through the relay network.

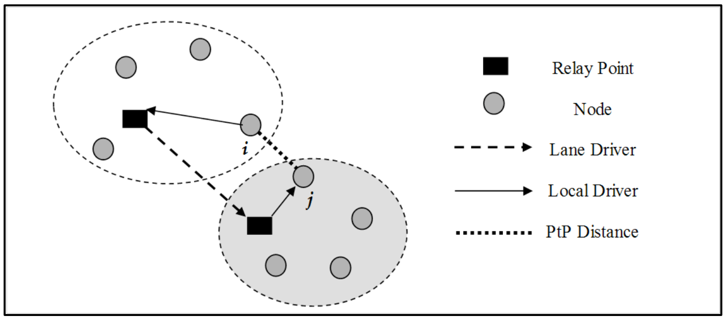

Fig. 2. Highly circuitous route in a relay network for truckload transportation.

The design of relay networks for TL transportation using this mixed fleet dispatching system was analyzed by Üster and Kewcharoenwong (2011) using two approaches. The first is an a priori approach in which first some truckloads of reduced distance (i.e., less than 2/3 of the limitation for local movements) are pre-selected for PtP dispatching and then the relay network is designed for the remaining truckloads. The second approach considers designing the relay network for all truckloads and then selecting truckloads with excessive circuity (e.g. more than 200% circuity) to be dispatched using PtP dispatching. The authors determined that the a priori approach as implemented in their research provided a greater reduction in total costs with more truckloads being dispatched PtP. However, no sensitivity analysis of the values used for selecting truckloads for direct dispatching in both methods is presented in this research. To the best of our knowledge, no prescriptive model exists in the literature to solve this problem in an integrated manner. Our research is intended to fill this existing need.

3. Problem statement and mathematical formulation

3.1. Truckload relay network design with mixed fleet dispatching (TLRND-MD)

Given a set of truckloads (i.e., O-D pairs with associated demand) that need to be transported, the TLRND-MD problem minimizes the total cost of opening RPs and routing truckloads either through the relay network or directly PtP from origin to destination. Fig. 1 shows an example of an RN for TL transportation and Vergara and Root (2012) provide a detailed description of its structure and basic operation. Two types of drivers are required to handle the truckloads that are routed through the RN. *Local drivers* handle the movements from an origin node to an RP or from an RP to a destination node. The distances covered by local drivers must not exceed pre-specified limit, γ_1, so that they can return home nightly. *Lane drivers* are in charge of the movements between RPs. A limitation on distances for lane drivers, γ_2, is imposed to ensure that federal hours-of-service regulations are satisfied in a single movement between two RPs (U.S. Department of Transportation, 2011). Note however that distances for drivers who are responsible of PtP loads are not limited in accordance to current industry practice.

Additional constraints are imposed based on TL carrier requirements. To prevent excessive handling of the RN loads and to ensure timely service to customers, a limitation is imposed on the number of RPs that can be visited between an O-D pair, λ. We also consider a limitation on circuity for the truckloads, β, so that the additional mileage in the RN does not represent a considerable expense for the carriers. In this case, if the shortest path distance between origin and destination for a truckload is d, only those routes that are shorter or equal to $(1 + \beta)d$ are allowed as alternatives to move that truckload. Similarly, in order to reduce the number of empty miles driven and ensure that no node in the RN suffers and excessive deficit or surplus of empty trailers, equipment balance must be enforced at the RPs.

The formulation of TLRND-MD is further complicated by two design considerations that are imposed by TL carriers. First, a minimum volume of freight traffic is desired at the RPs in order to justify their installation. Nodes that do not meet or exceed this threshold cannot be RPs. Second, the proportion of loads that are dispatched direct PtP with respect to the total demand in the system cannot exceed a specified percentage value. This maximum value is set to ensure that the benefits of improved driver retention are actually attained by having most of the driving jobs in regular routes.

3.2. Composite variable formulation for TLRND-MD

In this paper, we present a CVM formulation for TLRND-MD that extends the original formulation presented by Vergara and Root (2012) for the TLRND problem. As in this previous work, our variables are defined as feasible routes for a truckload when it is dispatched using an RN. Limitations on circuity, number of RPs visited, and local and lane distances are enforced when creating feasible routes according to the method described in Section 4.1. This allows us to incorporate the difficult operational constraints for the design of the RN within the variable definition and decompose this problem into several smaller routing problems. Additionally, we introduce a set of decision variables that let the truckloads travel PtP. Using this approach, the selection of dispatching mode for the truckloads and the coordination of the routing decisions for RN loads are handled by the following integer program.

3.2.1. Notation

Based on the definition of our composite variables, the following notation is required for the formulation of the CVM for TLRND-MD.

Sets

R = set of composites r,
T = set of truckloads t,
N = set of nodes k,
R_t = set of composites r for truckload t, $R_t \subset R$,
R_k = set of composites r that visit node k, $R_k \subset R$.

Parameters

c_r = cost of composite r, $\forall r \in R$,
f_k = fixed cost of relay point k, $\forall k \in N$,
p_t = cost of dispatching truckload t using PtP dispatching, $\forall t \in T$,
b_t = demand for truckload t (in number of loads), $\forall t \in T$,
δ = maximum acceptable percentage equipment imbalance,
ρ = maximum proportion of truckloads to be dispatched direct PtP,
v = minimum volume (in number of loads) required to open a RP,
η_{kr} = -1 if node k is the origin relay point of composite r,
1 if node k is the destination relay point of composite r, $\forall k \in N$, $r \in R$,
0 otherwise,
θ_{kr} = 1 if composite r visits relay point k, $\forall k \in N$, $r \in R$,
0 otherwise.

Variables

x_r = number of composites r used, $\forall r \in R$,
y_k = 1 if a relay point is opened at node k, $\forall k \in N$,
0 otherwise.
z_t = number of truckloads t sent direct PtP, $\forall t \in T$.

3.2.2. Model formulation

The mathematical formulation for TLRND-MD is as follows.

$$\min \sum_{r \in R} c_r x_r + \sum_{t \in T} p_t z_t + \sum_{k \in N} f_k y_k \tag{1}$$

subject to

$$\sum_{r \in R_t} x_r + z_t = b_t \qquad \forall\, t \in T \tag{2}$$

$$\sum_{r \in R_t} \theta_{kr} x_r \leq b_t y_k \qquad \forall\, t \in T, k \in N \tag{3}$$

$$\sum_{r:\eta_{kr}=-1} x_r - \sum_{r:\eta_{kr}=1} x_r \leq \delta \sum_{r:\eta_{kr}=-1} x_r \quad \forall\, k \in N \tag{4}$$

$$\sum_{r:\eta_{kr}=1} x_r - \sum_{r:\eta_{kr}=-1} x_r \leq \delta \sum_{r:\eta_{kr}=1} x_r \quad \forall\, k \in N \tag{5}$$

$$\sum_{r\in R} \theta_{kr} x_r \geq v y_k \quad \forall\, k \in N \tag{6}$$

$$\sum_{t\in T} z_t \leq \rho \sum_{t\in T} b_t \tag{7}$$

$$x_r \text{ integer} \quad \forall\, r \in R \tag{8}$$

$$y_k \in \{0,1\} \quad \forall\, k \in N \tag{9}$$

$$z_t \text{ integer} \quad \forall\, t \in T \tag{10}$$

The objective function (1) minimizes the total cost of routing truckloads through the RN, the cost of dispatching loads PtP, and the fixed cost of installation of the RPs. Constraint (2) requires that a routing for each truckload is selected either using an RN route (i.e. a composite) and/or dispatching the load directly from origin to destination. In either case, total demand for all truckloads has to be satisfied. Constraint (3) enforces that selected routes can visit relay points in the network only if they are open. Constraints (4) and (5) enforce relay network balance by requiring that a maximum permissible imbalance at each node be satisfied considering the difference between outgoing and incoming flows for RN loads. Note that a value of $\delta = 0$ enforces perfect balance for RN loads at every node in the transportation network; this is the only case in which constraints (4) and (5) will be binding simultaneously. Note that since PtP loads are dispatched using a different fleet, they are not included in these constraints. To account for the balance of PtP loads, we include a repositioning cost into the estimation of the cost of sending a load direct from origin to destination, p_t. In particular, we recognize that additional miles must be traveled to achieve balance in the PtP network. This allows the model to accurately tradeoff the increased travel required to reposition PtP movements and the cost of opening and rebalancing trailers in the RN. Constraint (6) requires the volume at each open RP to meet or exceed a pre-specified threshold, v. Constraint (7) requires that the proportion of truckloads dispatched direct PtP with respect to the total demand does not exceed a given limitation set by the TL carrier. Finally, constraints (8), (9) and (10) enforce integrality for all decision variables.

4. Solution methodology

4.1. Generation of composite variables

An enumeration based procedure using *templates* is used to generate composite variables for our formulation of TLRND-MD presented in Section 3.2.2. A template is a predefined routing pattern that represents an alternative for moving truckloads from origin to destination through a series of intermediate nodes. Since the number of RPs that can be visited in a route is limited to λ=3 due to TL carrier requirements, we can enumerate all feasible routes with three or fewer stops that satisfy constraints on circuity and distances for local and lane drivers. Even with this limitation on the number of RPs that can be visited, the number of composite variables required for our formulation is very large. Fig. 3 shows all template types that were considered in this research. In this figure, squares represent RPs and circles represent non-RP origin and destination nodes. Note that no templates with a total of two nodes from which only one is an RP are considered here. This is because these alternatives connect nearby O-D; such truckloads would be moved PtP rather than through the RN (see Fig. 2).

Note that since we enforce the important operational constraints associated with circuity and distance limitations by checking the feasibility of the routes that are generated with this approach, there is no need to incorporate them as constraints in the mathematical formulation for TLRND-MD.

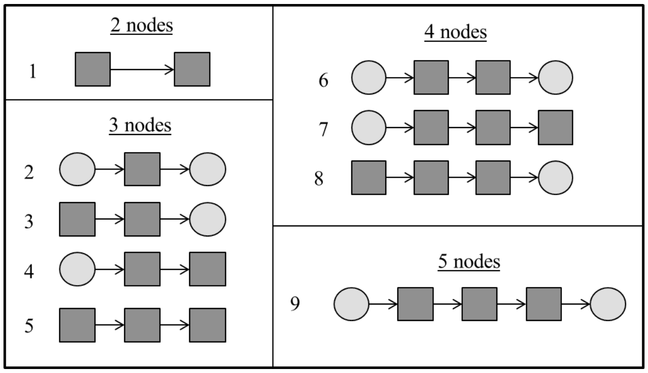

Fig. 3. Template types used for composite variable generation.

4.2. Heuristic solution method

Exact solutions for some instances of TLRND-MD can be obtained using standard branch-and-cut as implemented in CPLEX. Preliminary testing with the formulation showed that the number of composite variables needed significantly affects the tractability of the model. However, this testing also revealed that optimal solutions for this problem do not usually consider composites generated for some of the template types that are presented in Fig. 3. This presented an opportunity to reduce the number of variables significantly. Analyzing the usage of each template type in the optimal solutions found during our preliminary testing using 10 replications of 50 node networks and three different levels of demand density that were generated using an approach similar to the one used by Vergara and Root (2012), we found out that only 0.12% of the composites used were generated using template types 5, 7, 8 and 9. Moreover, an analysis of the truckloads that are dispatched PtP in this preliminary testing showed that most of these loads have shorter lengths of haul as compared to those transported through the RN.

These observations led us to develop a heuristic approach to obtain high quality solutions to TLRND-MD. The idea behind this heuristic approach is to modify our composite variables generation so that only a reduced subset of high quality variables is created and added to the model. This model is then solved using CPLEX until a pre-specified optimality tolerance is satisfied. In this research we use a similar approach to the one implemented by Vergara and Root (2012) (i.e., elimination of template types that produce variables that are not commonly used in optimal solutions), but we enhance it by further reducing the number of composites in the model by avoiding the creation of variables for truckloads that have O-D pair distances below a given threshold. The assumption is that these truckloads will be dispatched using the direct PtP method and no alternative routes (i.e., composites) are required for them. Since we observed that template types 5, 7, 8 and 9 are rarely used, the heuristic we implemented considers only the remaining templates with two or less RPs shown in Fig. 3 (i.e., types 1, 2, 3, 4 and 6).

We also observed in our preliminary testing that truckloads with O-D pair distances below 100 miles seem to be dispatched primarily using PtP (87.7%) rather than routing them through the relay network (12.3%); we therefore preprocessed the solutions to ensure such loads would travel PtP. Although we are not able to guarantee that optimal solutions will be obtained with this heuristic approach, our computational results showed that we are still able to obtain very high quality solutions while significantly improving the performance of the model. The average and worst case optimality gaps observed for 50 node networks are 0.1% and 0.3% respectively, while there is a significant reduction in the number of composites generated for the model that exceeds 86%. The reduction in problem size results in a considerable reduction in CPU times of almost 90%. These improvements allow us to solve largely-sized problem instances in reasonable times. Further results are presented in Section 5.3.2.

5. Computational results

Computational testing of our formulation and solution approach for TLRND-MD uses a baseline scenario and seven alternative cases based on modifications to the original design parameters established. One of the purposes of our computational experiments is to observe the effect of parameter changes on the design of the RNs (i.e., number of RPs opened and dispatching method selected for the truckloads) and performance metrics for drivers, carriers and shippers. Different network sizes and freight densities are considered through randomly generated problem instances. Additionally, we compare the results obtained for the mixed fleet dispatching system with those of a pure RN implementation and a PtP-only dispatching system. These results are presented in Sections 5.3.1 to 5.3.3. Finally, to assess the performance of our proposed formulation in a realistic scenario, we include the analysis of a test case provided by a major TL carrier in Section 5.3.4.

5.1. Experimental design

In order to determine the influence of design parameters on the solutions obtained for TLRND-MD and the performance of our model, a baseline and several alternative scenarios are defined by varying parameter values. The results obtained for each scenario are averaged over 10 replications of 50, 100 and 150 node networks that were randomly generated using the approach that is presented in Section 5.2.

The baseline scenario was established to assess the effect of allowing truckloads to be dispatched either PtP or through the RN without enforcing a limitation on the maximum proportion of PtP loads allowed (ρ=1.0) or requiring a minimum volume of truckload traffic to open an RP (ν=0). Note that the results for the mixed fleet dispatching system are to be compared to an RN-only system where perfect balance is required for RN loads (δ=0). Also, repositioning costs of PtP loads are estimated to be one quarter of the actual cost of transportation (Alam et al., 2007); for this reason, we inflate transportation costs 25% for these loads. Finally, the fixed cost of installation of a relay point is assumed to be \$10,000. Discussions with a major TL carrier indicate that installing RPs requires very little capital investment since exchanging trailers between drivers at these locations does not require the use of expensive equipment and infrastructure. Exact and heuristic results obtained for this scenario are presented in Sections 5.3.1 and 5.3.2 respectively.

In each scenario, the value of one of the parameters was modified relative to the baseline scenario to evaluate the effect of the corresponding parameter on the solutions obtained while the remaining parameters were held constant. This sensitivity analysis is presented in Section 5.3.3. We explored the effect of the repositioning cost for PtP loads, a limitation on the proportion of loads that are dispatched PtP and the requirement for a minimum level of truckload traffic required to open an RP. We also analyzed the effect of allowing imbalance at the nodes for truckloads dispatched through the RPs to assess the effect of enforcing equipment balance. Finally, we studied the effect of a higher fixed cost of installation for the RPs.

For system parameters, we used values similar to those used in Vergara and Root (2012) to solve TLRND. A limitation of 25% circuity (β) above the shortest path distance was imposed when generating feasible RN routes for a truckload. Similarly, the distances covered by local (γ_1) and lane (γ_2) drivers were limited to 150 miles and 600 miles respectively. Note that changes to these parameters affect the number of variables that are generated and consequently affect the tractability of our model. Finally, the rates per mile charged for local and lane movements were set to \$1.00 and \$1.30 respectively.

5.2. Random network problem generation

Similar to the approach used in Vergara and Root (2012), our computational tests used random instances of complete networks with 50, 100 and 150 nodes to assess the effect of network size on model performance. These are networks that have arcs connecting every pair of nodes in both directions, and consequently have the highest network density possible. Although practical transportation networks are sparser, these instances allow us to test the worst case performance of our formulation since the number of composites (i.e., feasible routes for the truckloads through the RN) that will be generated using the approach described in Section 4.1 is expected to be very large. Nodes are uniformly distributed in a squared area that represents the regional service area of a major TL carrier (i.e., 600 miles × 600 miles), and distances between node pairs are computed using the Euclidean norm as a surrogate to actual over the road miles. Ten network problems of each size were generated to reduce random effects.

To test the performance of our model with different truckload flow densities, the number of lanes in the network (i.e., O-D node pairs) with freight traffic was also modified by randomly selecting 10%, 20% and 40% of all O-D pairs to have truckload flows. This means that for a network with 100 nodes, we selected 990, 1,980 and 3,960 O-D node pairs to have truckload flows. Moreover, to represent lanes with different freight volume, a randomly generated integer number between 10 and 20 was used to establish the number of truckloads required between each selected O-D node pair. The latter is similar to the approach used by Üster and Kewcharoenwong (2011).

5.3. Results

We implemented our formulation and solution approach using Python 2.6 and solved the computational experiments with CPLEX 12.1 on a 3.20 GHz Intel® Xeon® workstation with 6 GB of RAM.

5.3.1. Exact solution results

Table 1 shows the results obtained for the baseline scenario with 50 node networks using CPLEX 12.1 (i.e., a standard branch-and-cut method). The values presented in Table 1 are averages for ten replications of problems with the same freight density. As observed in this table, freight density affects the size of the problem by increasing the number of variables and constraints in the formulation. In turn, the increase in problem size directly affects the time required for the solution. Setup times correspond to the time required to generate composites and build the mathematical model that is then solved by CPLEX using the time shown in the last column of this table (i.e., Solution Time). Although increases in problem size increase total CPU time, optimal solutions are obtained for high freight density problems in very reasonable times (i.e., less than 5 minutes in the worst case).

From this table, note that as freight density increases the number of RPs that are opened increases while the proportion of loads that are dispatched PtP decreases. This is the result of having more traffic in the system and consequently better opportunities for relayed movements. More importantly, the proportion of loads that are dispatched PtP never exceeds 20% and is almost half of that number for higher freight density problems. This means that most of the demand will be satisfied by RN drivers, and thus driver retention will generally improve for the TL carrier.

Table 1

Exact results for 50 node networks (baseline scenario).

# O-D Pairs	# Composites	# Constraints	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
245	30,743.5	3,471.4	1,650,991	15.1	19.58%	45.83	6.07
490	64,077.7	6,894.0	3,148,072	19.9	13.65%	94.22	6.42
980	127,566.0	13,660.1	6,040,305	25.6	10.43%	197.27	8.87

One of the objectives of the present study was to determine the benefit of a mixed fleet dispatching system over RN-only and PtP-only systems. Table 2 shows the comparison of these two other dispatching methods with the mixed fleet system. The values between parentheses are the differences observed with the mixed fleet results.

Table 2

Comparison RN-only and PtP-only systems with mixed fleet dispatching (50 node networks).

	Mixed Fleet		RN-only		PtP-only	
# O-D Pairs	Solution Value ($)	# RPs Open	Solution Value ($)	# RPs Open	Solution Value ($)	# RPs Open
245	1,650,991	15.1	1,694,802 (+2.65%)	24.0 (+8.9)	1,913,915 (+15.82%)	N/A
490	3,148,072	19.9	3,164,872 (+0.53%)	28.7 (+8.8)	3,884,885 (+23.40%)	N/A
980	6,040,305	25.6	6,018,572 (-0.36%)	32.5 (+6.9)	7,734,080 (+28.06%)	N/A

Results for the pure RN implementation were obtained using the heuristic approach presented by Vergara and Root (2012) to solve TLRND. Note that there are 73% fewer variables and 33% more constraints in the RN-only problems as compared to the mixed fleet instances solved to optimality. The solution values for the PtP system were computed considering a repositioning cost of 25% over the lane rate per mile for all truckloads when they are dispatched directly from origin to destination. Note that the mixed fleet system provides significant savings as compared to the PtP-only system, and those savings increase as freight density increases. This is due largely to the need to reposition the equipment for the next pick-up of a PtP load which adds empty miles to the transportation costs in this system. Repositioning is significantly easier and less expensive in a relay network configuration since loads flow between a limited number of points and can be repositioned more easily. Also, given the savings observed note that the solutions for the mixed fleet dispatching system are still cheaper than using the PtP-only method even when the fixed cost of installation of RPs increases from its baseline of $10,000 to up to $17,000, $37,000 and $66,000 respectively for problems with 10%, 20% and 40% freight density.

In contrast, although there is no significant difference in the total cost as compared to the RN-only method, using the mixed fleet system results in relay networks with considerably fewer RPs. This reduction in the number of RPs represents other operational advantages to the carriers in terms of managing fewer driver domiciles and increased utilization of each of the RPs that is installed. Note, however, that another byproduct of the mixed fleet system is increased circuity for the truckloads that travel through the relay network since fewer RPs are open.

Although the cost of a mixed-fleet network will always be less than or equal to a network that transports loads using only RN- or PtP-movements, we point out that for 40% network density (980 O-D pairs), the cost of RN-only movements is slightly less than the cost for a mixed fleet network. This difference arises because of the way costs are computed for each of the different types of networks. For the RN-only case, loads that are moved between two nodes that are less than the local distance limitation apart are charged the unit cost per mile for local movements ($1). In the case of the mixed fleet problems, since no template exists for these local movements, the loads are dispatched PtP or using the template for RN lane movement between an origin and a destination (Template 1). As such, the cost for these truckloads ($1.30/mile) always exceeds the cost that would be incurred if they were dispatched through the relay network as local movements ($1/mile). This causes the difference in the costs, which is quite small (<0.5%).

Moreover, although the mixed fleet dispatching system seems to provide overall benefits to the carriers, it is also important to look at performance metrics for drivers and customers. A measure of importance to drivers is the *average length of haul* defined as the average one-way driving distance covered in a single leg between two nodes. A reduced average length of haul allows the creation of shorter driving duties (i.e., driving jobs that initiate and terminate at a driver's domicile). This means more frequent returns to domiciles for the drivers and consequently, an improvement in quality of life that leads to lower driver turnover. Similarly, a metric that interests shippers is *service time* defined as the estimated time to deliver a truckload from origin to destination. In a PtP system, service time is estimated by considering the distance between origin and destination for the truckload, average speed for the vehicles, and hours-of-service regulations for the drivers. Given the long distances that are usually covered by TL carriers, some loads are commonly delayed while drivers stop to rest in compliance with federal safety regulations. On the other hand, truckloads that are dispatched on the RN can be immediately transferred to a different driver assuming there are available drivers at the RP and continue to their final destination. It is important to determine expected and worst case service times for RN loads and PtP loads in the mixed fleet system in order to guarantee appropriate service to all customers.

Fig. 4 shows the results for average length of haul and Fig. 5 presents the average and worst case service times observed for the three alternative dispatching systems under study.

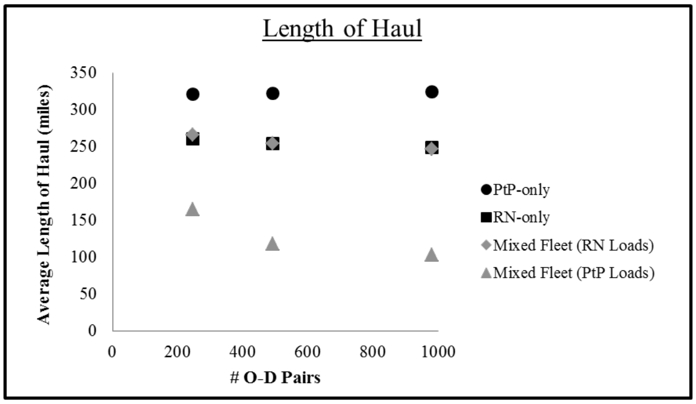

Fig. 4. Length of haul results for alternative dispatching systems (50 node networks).

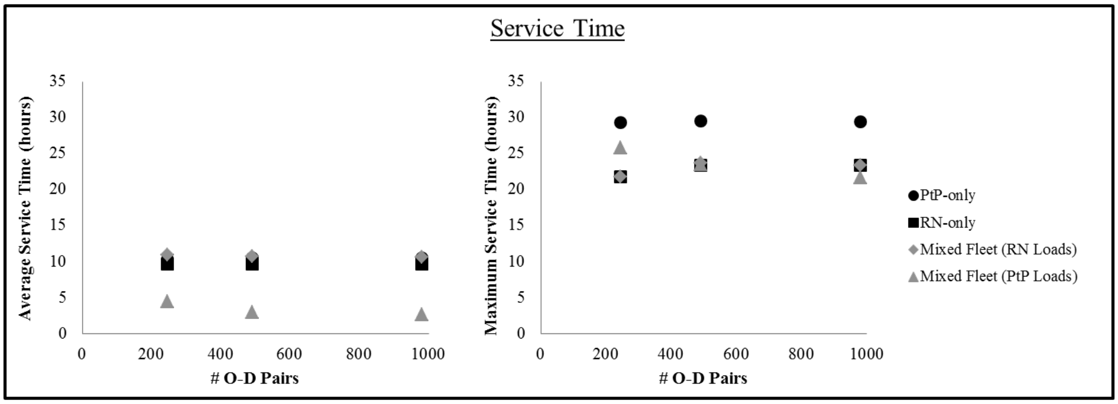

Fig. 5. Service time results for alternative dispatching systems (50 node networks).

Once again, the PtP-only dispatching system shows the worst performance of the three with the highest average length of haul and worst case service times observed. The comparison between the RN-only and mixed fleet dispatching systems shows that there is no significant difference between the metrics obtained for truckloads that are shipped through the relay network. However, an advantage of the mixed fleet system can be observed for those truckloads that are sent PtP. The reduced average length of haul for these loads allows the creation of short duties for the drivers who are responsible for these movements. As a result, even if they are not assigned to relayed movements, it is very likely that they will be able to return home more frequently. Also, average service times for PtP loads in the mixed fleet dispatching system are below the average service times observed for RN loads since many of the truckloads dispatched PtP travel only short distances between origin and destination nodes.

Finally, it is important to note that the strength of our formulation was analyzed by solving these problem instances using the LP relaxation of our model. The average and worst case optimality gaps obtained were 0.03% and 0.22% respectively. In fact, our formulation proved to be better as freight density increased. This is an indication that the CVM formulation has very good lower bounds even when problem size increases, allowing us to obtain high-quality solutions quickly.

5.3.2. Heuristic solution results

Since the number of variables ultimately affects our model's tractability, we decided to implement the heuristic method presented in Section 4.2 to solve the 50 node network instances and test the performance of the heuristic approach in terms of solution quality and efficiency. Table 3 shows the results obtained using the heuristic. The values between parentheses correspond to the differences observed relative to the exact solutions presented in Table 1. As shown in this table, the significant reduction in the number of composite variables and constraints in the model allows us to obtain very high quality solutions efficiently. The reduction in setup times is a direct result of the reduction in problem size.

Based on the performance of the heuristic, we used this method to solve larger problem instances with more nodes and freight traffic to assess the effect of network size and freight density. The results for 100 and 150 node networks are presented in Table 4.

Table 3

Heuristic results for 50 node networks (baseline scenario).

# O-D Pairs	# Composites	# Constraints	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
245	4,096.2 (-86.68%)	2,381.7 (-31.39%)	1,652,401 (+0.09%)	15.2 (+0.1)	20.21% (+0.63)	5.06 (-88.96%)	2.17 (-64.33%)
490	8,351.9 (-86.97%)	4,628.9 (-32.86%)	3,151,178 (+0.10%)	19.7 (-0.2)	14.50% (+0.85)	9.58 (-89.83%)	1.73 (-73.10%)
980	16,828.7 (-86.81%)	9,182.2 (-32.78%)	6,047,650 (+0.12%)	25.3 (-0.3)	11.52% (+1.09)	18.66 (-90.54%)	2.17 (-75.49%)

Table 4

Results for 100 and 150 node networks (baseline scenario).

Nodes	# O-D Pairs	# Composites	# Constraints	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
100	990	55,684.7	16,170.5	5,902,860	29.4	10.09%	70.12	118.68
	1,980	109,663.5	31,688.8	11,152,766	39.3	9.24%	143.56	51.08
	3,960	219,354.3	63,079.8	21,970,931	50.6	8.57%	312.50	46.71
150	2,235	265,290.2	51,505.2	12,310,993	55.6	8.30%	408.82	266.40
	4,470	532,480.1	102,724.4	23,906,718	68.7	8.02%	992.13	165.51
	8,940	1,065,642.4	204,741.7	47,230,483	76.9	8.00%	2,722.20	253.09

These results show that while the number of composites in the model directly affects setup times, solution times are mostly determined by the size of the networks (i.e., number of nodes). However, setup time is still the most important fraction of total CPU time. The largest problem instances with 150 nodes and 8,940 O-D pairs with truckload flows are built and solved in less than 55 minutes in the worst case. This is quite acceptable considering that this is a strategic design problem. It is interesting to note that solution times seem to be higher for problems with the same number of nodes but lower freight density. This may be an indication that as more truckload traffic exists more common routes can be defined and it is easier to design the relay network. Another observation from these results is that the fixed cost of installation of the RPs is not a significant fraction of the total cost. This is clearly the case for problems with 150 nodes and 2,235 O-D node pairs. This indicates that transportation costs account for most of the expense for the carriers. Also, similar to the results obtained for 50 node networks, the number of open RPs increases and the proportion of loads dispatched PtP decreases as freight demand increases for networks of the same size. However, the rate of decrease for the proportion of loads dispatched PtP seems to be decreasing as well with problem size.

Comparing these results to those obtained for RN-only and PtP-only dispatching systems we observed similar results to those obtained for 50 node networks. Both RN-only and mixed fleet systems outperform traditional PtP dispatching, and although the objective function values are very close for the network-based systems, we noticed a greater reduction in the number of RPs required in the mixed fleet dispatching system as the size of the network increases requiring around 13 fewer RPs in 100 node networks and up to 30 fewer RPs in 150 node networks. Certainly, this represents an advantage for the mixed fleet dispatching system, particularly as the cost of relay point installation increases as discussed later in Section 5.3.3.5.

5.3.3. Sensitivity analysis for carrier parameters

The results analyzed so far correspond to the baseline scenario presented in Section 5.1. Appendix A shows the results in detail for the scenarios that explore the effects of repositioning costs for PtP loads, the proportion of PtP loads permitted, the minimum volume required to open a relay point, the percentage of imbalance allowed in the relay network, and the fixed cost of installation of RPs. These results are analyzed in the following subsections.

5.3.3.1. Effect of repositioning cost for PtP loads

In two alternative scenarios, we considered modifications to the repositioning cost applied to loads that are dispatched PtP. The scenario called *Low PtP Repositioning Cost* tests a repositioning cost that is less than the average percentage of empty miles (10%) for TL carriers while the scenario called *High PtP Repositioning Cost* considers a cost that doubles the baseline cost (50%). A repositioning cost of zero was not used since additional moves to balance equipment for the PtP fleet will always be needed in practice. Table A.1 and Table A.2 in Appendix A show the results for these two scenarios.

In the low PtP cost case, we observed a reduction in solution values and number of RPs that are required in the relay network. However, the reduction in total cost is not significant and never exceeds 2%. A greater effect is observed in the proportion of truckloads that are shipped PtP, especially for 50 node networks and low freight density. This is an indication that with the lower repositioning cost, some truckloads are better served PtP since circuity and rebalancing miles can be avoided in the RN. The increase in the proportion of loads moved PtP is less significant for bigger instances since having more truckloads in the system requires routing a higher proportion of truckloads through the RN to obtain balance at the nodes. In terms of the performance of our model, there is a prevalent reduction in solution times which seems to show that it is generally easier to select the dispatching method when the transportation cost for PtP loads is less expensive and closer to the cost for RN loads.

Looking at the results for the high PtP cost case, we noticed a similar behavior but in the opposite direction. Changes to solution values and number of open RPs are observed but they are only marginal (the highest increase in solution value does not exceed 2%). The effect of the higher repositioning costs on solution times is less clear and seems to range from higher CPU times for largely-sized problems with 150 nodes to lower CPU times for smaller instances. These results indicate that even assessing a very high repositioning cost seems to result in a mixed fleet dispatching system that has advantages over a pure RN dispatching method in terms of fewer RPs open and comparable total costs.

Fig. 6 shows the effect of varying the repositioning cost for PtP loads from 10% to 50% on solution values and number of open RPs for instances with 100 nodes and 10% freight density. As observed in the graph located on the left side of Fig. 6, the savings associated with the mixed fleet system as compared to an RN-only system decrease as the repositioning cost for PtP loads increases. Note that when the repositioning cost is 50% over the cost of transportation, the cost of a mixed fleet system exceeds that of an RN. The main reason for this is that in our approach we pre-process truckloads with distances shorter than 100 miles to be dispatched PtP in the mixed fleet dispatching system, and thus the transportation cost for these truckloads always exceeds the cost that would be incurred if they are dispatched through the relay network as local movements. On the other hand, it can also be observed in the graph located on the right side of Fig. 6 that the hybrid configuration consistently requires fewer RPs in the network than an RN-only system.

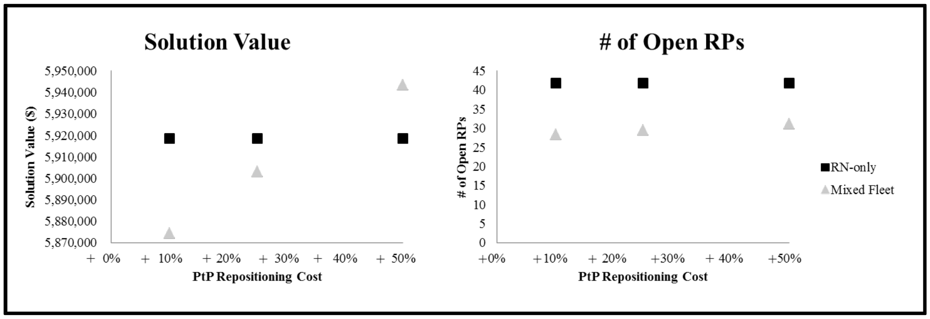

Fig. 6. Differences between RN-only and mixed fleet as PtP repositioning cost varies.

5.3.3.2. Effect of maximum proportion of PtP loads

TL carriers believe that limiting the proportion of loads traveling PtP represents the best compromise between overall driver retention (given that most loads are dispatched through the relay network and shorter tour lengths are possible) and reduced circuity (i.e., additional miles driven) for the truckloads. In the baseline scenario we did not impose a restriction on this value. For the scenario called *Limited Proportion of PtP Loads*, we used a value of $\rho = 0.1$ to limit the proportion of loads that are sent PtP to 10%. The results obtained are presented in Table A.3 in Appendix A.

The limitation on the proportion of PtP loads in the mixed fleet system proved to be more restrictive for the smaller networks with 50 nodes, especially when freight density is low. In these cases, the limitation on the proportion of PtP loads results in the need for more RPs to handle more traffic through the RN. However, since the fixed cost of installation of RPs is not a significant portion of the total cost, solution values do not change significantly. The observed worst case increase in solution value just barely exceeds 1%. It is also important to note that there are some infeasible instances for which no solution can be obtained using our heuristic approach. The reason for this is that since we pre-select truckloads with O-D node pair distance below 100 miles, the proportion of PtP loads that will exist in the system is already higher than the limitation imposed by the model. The exact solution approach or a heuristic method without pre-processing of PtP loads will be able to find solutions for these problems.

In terms of the performance of our formulation when this restriction is imposed, we observed that with a few exceptions, solution times are significantly higher than those observed in the baseline case. Note, however, that setup times continue to be the most significant portion of total CPU times and the largest instances are still solved in less than 54 minutes in average. This is just 4 minutes longer than in the baseline case.

5.3.3.3. Effect of minimum volume required to open a relay point

A design parameter that interests TL carriers is the establishment of a minimum volume required to justify opening and operating an RP. For this reason, we considered values of v = 2% and v = 5% of the total truckload demand to require moderate and high truckload volume respectively. A value of zero for this parameter was used in the baseline scenario, so that even locations with low truckload traffic were allowed to serve as RPs. Table A.4 and Table A.5 in Appendix A show the results for moderate and high truckload volume required to open an RP in respective order. In both scenarios, we observed that the limitation on RP volume becomes restrictive as the size of the network and freight density increase. The moderate volume requirement only starts to affect problems with 100 nodes and 40% freight density. A reduction in the number of open RPs along with a significant increase in solution times are observed for these instances. However, total costs increase only slightly as a result of this constraint. It is clear that as the size of the network increases to 150 nodes, this limitation becomes very restrictive affecting the performance of our formulation and requiring longer solution times. Although instances with 20% freight density are still solved by CPLEX, problems with higher freight density (i.e., 40%) cannot be completely solved and CPLEX stopped due to lack of memory as more nodes in the branch-and-cut tree are needed. Interestingly, we noticed that for the majority of the time required to solve the model, it maintains the initial feasible solution found with all truckloads dispatched PtP. When the first mixed fleet solution is found, the optimality gap drops substantially (typically to <1%) and a final solution is found relatively soon after. For the largest instances that we were able to solve, we observed a worst case solution time of 86 minutes on top of the time required to setup the problem.

The same general behavior is observed in the high volume requirement scenario. This means reductions in the number of open RPs and increased solution times are observed for instances in which the constraint becomes restrictive. However, since the limitation is stricter in this case, its effect is more significant and starts to be noticed in smaller instances as compared to the previous case (i.e., fewer RPs and longer solution times are observed for 50 node networks with 40% freight density). Still, high quality solutions for mixed fleet dispatching designs are able to be obtained for problems with up to 150 nodes and 10% freight density. After the problem is setup, these instances can be solved in less than 4 hours and 15 minutes in the worst case with an average solution time of 2 hours and 40 minutes. Once again, memory issues prevent us from solving larger problem instances with 20% and 40% freight density. In general, these results are an indication that this parameter is very important for the design of mixed fleet dispatching systems of considerable size since it can limit significantly the number of open RPs in the network, and has implications both on the solutions obtained and the tractability of our model.

Fig. 7 shows the differences in solution values and number of open RPs between an RN-only system when this limitation is enforced and the mixed fleet dispatching system for problems with 100 nodes and 10% freight density. Note that as the minimum volume required to open an RP increases the savings associated with the mixed fleet system become more apparent as fewer RPs are needed and more loads can be dispatched PtP.

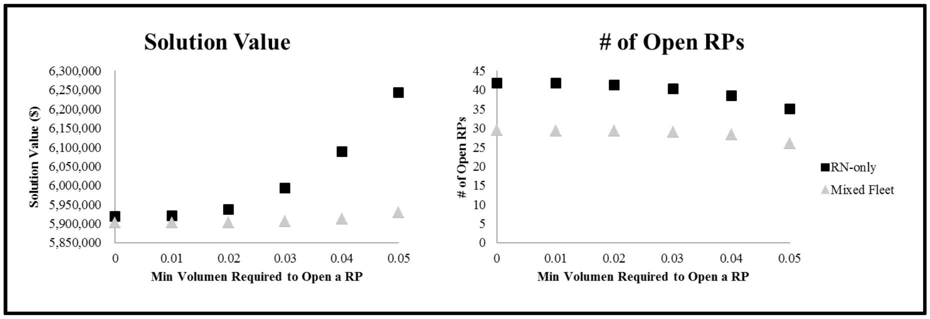

Fig. 7. Differences between RN-only and mixed fleet as minimum volume required to open RPs varies.

5.3.3.4. Effect of equipment balance for relay network loads

The baseline scenario requires perfect balance for the loads that are dispatched through the relay network. We decided to relax this limitation and allow some imbalance at the nodes in the network to analyze the effect of this operational constraint on the performance of our model and the solutions obtained. The results for a maximum percentage imbalance allowed of $\delta = 0.3$ are presented in Table A.6 of Appendix A.

No significant differences are observed for the solution values as compared to the baseline scenario with perfect balance. However, we note a slight increase in the number of RPs that are open in networks with 150 nodes. This increment in the number of facilities in the RN is not accompanied by a significant change in the proportion of loads that are dispatched PtP.

More importantly, we were able to determine that balance comes at a cost in terms of CPU time. As observed in these results, with the exception of the small networks with less freight density, allowing some imbalance at the nodes in the RN results in solution times that are significantly faster than the baseline scenario. Nonetheless, since setup times are once again the most important portion of total CPU time, the overall benefits are not as significant. The average total CPU time for the largest instances is only reduced in 3 minutes, decreasing from 50 minutes in the perfect balance case to 47 minutes when this constraint is relaxed.

The effect of equipment imbalance at the nodes in the relay network in terms of solution values and number of open RPs can be observed in Fig. 8. This figure also shows the differences between the mixed fleet dispatching system and an RN-only system as this limitation varies from requiring perfect balance to allowing 100% imbalance. We observe that the savings associated with the mixed fleet configuration remain consistent across the different levels of allowed imbalance at the nodes.

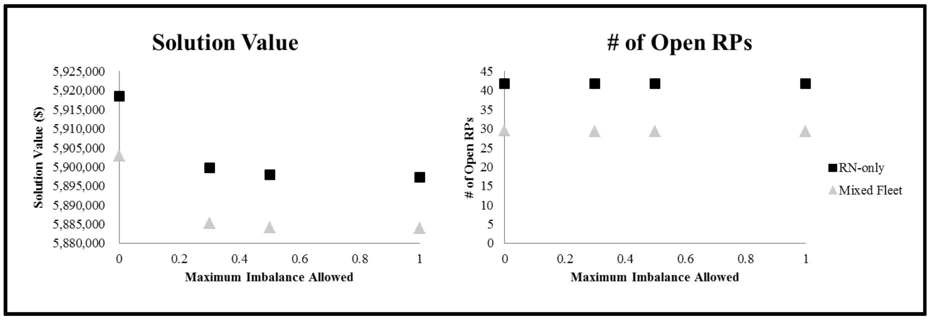

Fig. 8. Differences between RN-only and mixed fleet as maximum imbalance allowed varies.

5.3.3.5. Effect of fixed cost of installation of relay points

TL carriers that operate nationally have difficulty estimating appropriate installation and operation costs for their facilities given the differences in land and labor costs across regions in the U.S. The value of $10,000 used in the baseline scenario is relatively low, but is justified by the fact that RPs do not need expensive equipment and infrastructure to operate. However, in this scenario we considered a fixed cost of installation for the RPs that is ten times higher (i.e., $100,000) to test the performance of our model and determine how this parameter affects the characteristics of the solutions obtained. The results for a higher fixed cost of installation of $100,000 are presented in Table A.7 of Appendix A.

We observe that the higher fixed cost of installation results in PtP-only solutions for problems with 50 nodes and freight densities of 10% and 20%. In these cases, as the capital investment to open RPs becomes more significant, the reduced truckload volume is insufficient to justify opening RPs as the expense associated with their installation cannot be outweighed by the reduction in transportation costs.

Solutions with a mixed fleet configuration begin to occur for instances with 50 nodes and 40% freight density. The higher fixed cost of installation results in mixed fleet systems with significantly fewer RPs. This consequently affects the proportion of loads that are dispatched PtP and solution values. The reduced number of RPs becomes more significant as the number of nodes and freight density increase. This reduction goes from 16 to 47 fewer RPs with respect to the baseline case. Solution values increase significantly but never exceed a 25% increase over the baseline scenario. As the instance sizes grow, this objective function increase becomes less significant. In the same way, the increase in the proportion of loads that are dispatched PtP is more significant for smaller instances. In these cases, the proportion of loads dispatched PtP is almost two times higher than in the baseline scenario.

The higher fixed cost of installation also affects solution times significantly. The increase in solution times always exceeds 750% with respect to the baseline scenario as observed for instances with 50 nodes and 40% freight density. As the number of nodes and freight density increase this increase is even more significant. The largest instances solved without running into memory issues are those with 150 nodes and 20% freight density. The worst case solution time observed for these problems is 3 hours and 2 minutes with an average solution time of 2 hours and 46 minutes.

Fig. 9 shows that as the fixed cost of installation of the RPs increases the differences between RN-only and mixed fleet dispatching become more apparent from an economic perspective. For a fixed cost of $100,000, the savings associated with the hybrid configuration ascend to 20.5% with respect to the pure RN system. In addition, it can be observed that as fixed cost increases the number of open RPs in the RN-only system converges to a value required for feasibility reasons. Since loads can also be dispatched PtP in the mixed fleet system, the number of open RPs continue to decrease as higher fixed costs of installation are considered.

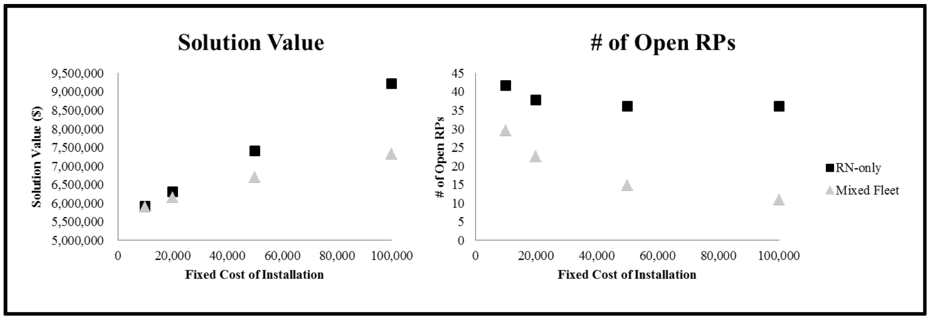

Fig. 9. Differences between RN-only and mixed fleet as fixed cost of RPs varies.

5.3.3.6. Discussion of sensitivity analysis results

In our computational experiments, we observed that with the exception of minimum volume required to open an RP and fixed cost of installation, changes to the design parameters for TLRND-MD result in solutions with very similar total costs. However, it is important to note that although the solutions obtained are very similar from an economic perspective, they are all different in terms of the configuration of the mixed fleet dispatching system obtained with our model since different nodes are selected as RPs and varying proportions of loads that are dispatched PtP. This highlights the importance of our prescriptive model since very different solutions with very similar solution values can be obtained when making changes to several design parameters of this problem.

The most significant changes in solutions obtained and model performance are observed for the scenarios in which we enforce a limitation on the minimum volume required to open an RP and the scenario with a higher fixed cost of installation. Consequently, TL carriers need to consider these two parameters very carefully when designing mixed fleet dispatching systems.

5.3.4. Test case results

To test the performance of our model with realistically-sized problem instances, we used test case data provided by J.B. Hunt Transportation Services, one of the largest TL carriers in the United States. Origins and destinations for truckloads in the eastern half of the U.S. were aggregated at the three-digit zip code level resulting in a network with 623 nodes where a node is placed on the centroid of the aggregated origins and destinations. These nodes are connected by a total of 83,734 arcs. This is an arc density of 21.61% which is significantly lower than the arc density of 100% of the complete networks used in our previous experiments. The distances on the arcs are over the road miles between connected nodes in the transportation network. A total of 1,386 O-D node pairs with truckload flows are included in this problem instance. Also, we considered limitations on the distance allowed for local drivers of γ_1 = 225 miles and distance allowed for lane drivers of γ_2 = 450 miles. All other problem parameters were not modified in the experimental design. Table 5 shows the results for the baseline scenario of TLRND-MD described in Section 5.1. This table also presents the values observed for RN-only and PtP-only dispatching methods to compare them to the mixed fleet dispatching system.

As observed in this table, the mixed fleet dispatching system has the lowest solution value of the three configurations. The difference is more significant with respect to the PtP-only system that has a total cost that is 22.56% higher. On the other hand, the cost of the pure RN system is only 1.9% higher than the mixed fleet method. The most noticeable difference between RN-only and mixed fleet dispatching relates to the number of open RPs. Allowing some truckloads to be dispatched PtP results in a considerable reduction of 34 RPs or 25% fewer facilities than in the RN-only alternative. As previously mentioned, this reduction translates into operational advantages for carriers such as fewer drivers' domiciles to manage and increased utilization. This reduction in the number of RPs needed is accomplished by shipping close to 92% of the truckloads through the relay network while the rest is dispatched PtP.

Table 5
Results for test case (623 nodes and 1,386 O-D pairs with truckload demand).

Dispatching Method	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Average Length of Haul (miles)	Average Service Time (hours)	Maximum Service Time (hours)	Setup Time (secs)	Solution Time (secs)
Mixed Fleet	19,613,127	102	8.42%	310.15 (RN) 748.62 (PtP)	18.94 (RN) 29.99 (PtP)	35.39 (RN) 64.62 (PtP)	9,894.34	1,648.86
RN-only	19,986,727	136	0.00%	314.73	19.25	35.70	11,577.23	1,025.67
PtP-only	24,038,329	0	100.00%	638.08	25.37	64.62	N/A	N/A

Average length of haul and service times for the majority of the truckloads in the mixed fleet system (i.e., loads that are shipped through the relay network) are comparable to those in the RN-only method and are considerably better than in traditional PtP dispatching. Unfortunately, the small portion of loads that are dispatched PtP in the mixed fleet system show relatively high average length of haul and service times. In contrast to the previous experiments, there is a higher proportion of direct shipments that cover longer distances. This mostly occurs when a direct shipment is used to satisfy demand at isolated nodes in the network.

In terms of the performance of our formulation of TLRND-MD and the heuristic solution approach developed in this research, setup times continue to dominate total CPU time. The large number of composite variables that are generated (i.e., close to 2 million composites) requires approximately 2.5

hours of setup time to build the model. Fortunately, CPLEX takes less than 28 minutes to solve the problem with an optimality gap of 1.0%. The solution of this test case shows that our approach can be used to obtain high quality solutions for largely-sized problem instances that are likely to appear in practical settings.

6. Conclusions

This paper makes several contributions to the literature. First, this paper presents a prescriptive model for the design of a mixed fleet dispatching system for TL transportation. This method combines direct shipments from origin to destination with the use of a network configuration of relay points. To the best of our knowledge, this is the first prescriptive model for such systems. Previously, Üster and Maheshwari (2007), Üster and Kewcharoenwong (2010) and Vergara and Root (2012) presented formulations for relay network design in TL transportation, but did not integrate the alternative dispatching decisions within their formulations.

A second contribution is that our model is able to solve realistically-sized problems, and incorporates constraints such as circuity that have been relaxed or enforced through surrogates in previous research. We propose a composite variable model that implicitly considers several operational constraints within the definition of variables that represent feasible routes for truckloads through the relay network. The selection of the dispatching mode and routing for the truckloads is handled by an integer programming model that is used to obtain high quality solutions for largely-sized problem instances.

Another contribution is that using this model, we can substantiate the claim from both TL carriers and researchers that mixed fleet networks show significant promise and are more likely to be successful in practice than an RN alone. Our results show that from a cost perspective the differences between relay networks and mixed fleet dispatching systems are minor when fixed cost of installation of the RPs is low with an average difference of only around 2% in the best case. However, as the fixed cost of installation increases, mixed fleet dispatching systems show more significant savings over a pure RN system. In addition, mixed fleet network configurations always require fewer relay points which may offer other advantages over RN-only solutions in terms of higher utilization of facilities and fewer domiciles to manage. Note that our methodology can be used to assess whether these findings are true for other network topologies and demand patterns. In addition, our experiments show that both systems – RN-only and mixed fleet – outperform the traditional PtP-only dispatching system in total costs and other performance metrics of interest such as average length of haul and service times for the truckloads.

Our results suggest that truckloads that have origin and destination nodes close to one another are good candidates for PtP dispatching. Similarly, truckloads that either have the origin or the destination node in an isolated area are best served PtP. When the proportion of truckloads shipped directly is usually small, TL carriers can expect to improve the quality of the majority of driving jobs by using this alternative dispatching method while reducing the number of RPs required in the network.

In our research, we also observed that changes to several design parameters of the mixed fleet systems result in alternative configurations with different RPs and varying proportions of truckloads shipped PtP. However, these changes seem to only minimally affect the solution values (i.e., total costs) obtained. A general observation across different scenarios is that dispatching through the relay network is preferable for a higher proportion of the truckloads as network size and freight density increase.

Also, we determined that the performance of our CVM formulation for TLRND-MD is consistent across several scenarios with the exception of cases where very strict limitations are imposed on the minimum volume required to open an RP and when higher fixed costs of installation for RPs are considered. Extended solution times are required for larger problem instances in these cases. Moreover, the heuristic approach developed in this research was successfully used to obtain a solution for a practical problem provided by a major TL carrier in reasonable time, especially considering that this is an integrated strategic design problem.

There are some challenges that need to be addressed as part of future work such as explicitly incorporating a balance constraint for truckloads that are dispatched PtP instead of using a repositioning cost as a surrogate. Another important area for future research is to assess whether or not mixed fleet dispatching systems can significantly outperform RN-only configurations for certain network topologies, or whether our observations that for low fixed costs of installation of the RPs the cost implications of a mixed fleet dispatching system are not significant extend to all types of network configurations. If secondary performance metrics beyond total cost can be identified to assess the value of mixed fleet dispatching systems, the use of a multi-objective optimization approach may be justified for this problem based on the effect of alternative dispatching systems on metrics that interest not only carriers but also affect drivers and shippers.

In addition, we would like to explore other methods for the generation of the composite variables that are used in our formulation. A method to generate the composites in parallel for different truckloads will help to reduce setup times even further, especially for largely-sized problems.

Finally, driver considerations and timing for the truckloads should be incorporated in order to develop efficient schedules for the drivers. The benefits of this and other alternative dispatching systems in terms of driver retention will only be attainable as long as TL carriers are able to construct driving duties that bring drivers home more frequently.

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Appendix A

Table A.1

Results for Low PtP Repositioning Cost.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,619,427 (-2.00%)	12 (-3.2)	30.66% (+10.45)	5.05 (-0.18%)	2.74 (+26.64%)
	490	3,121,304 (-0.95%)	18.2 (-1.5)	18.14% (+3.64)	9.59 (+0.18%)	1.54 (-11.04%)
	980	6,006,667 (-0.68%)	23.5 (-1.8)	13.73% (+2.21)	18.68 (+0.15%)	1.28 (-40.99%)
100	990	5,874,232 (-0.48%)	28.3 (-1.1)	11.20% (+1.11)	70.24 (+0.17%)	75.59 (-36.31%)
	1,980	11,108,342 (-0.40%)	38.0 (-1.3)	9.67% (+0.44)	143.56 (-)	36.51 (-28.52%)
	3,960	21,895,843 (-0.34%)	49.6 (-1.0)	8.78% (+0.21)	311.47 (-0.33%)	41.68 (-10.77%)
150	2,235	12,265,220 (-0.37%)	54.1 (-1.5)	8.57% (+0.27)	408.61 (-0.05%)	262.11 (-1.61%)
	4,470	23,814,251 (-0.39%)	64.3 (-4.4)	8.20% (+0.18)	991.97 (-0.02%)	159.89 (-3.40%)
	8,940	47,085,717 (-0.31%)	75.4 (-1.5)	8.13% (+0.13)	2,723.96 (+0.06%)	230.97 (-8.74%)

Table A.2

Results for High PtP Repositioning Cost.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,684,057	17.4	15.63%	5.06	2.87
		(+1.92%)	(+2.2)	(-4.58)	(+0.11%)	(+32.66%)
	490	3,185,633	21.2	12.89%	9.60	1.69
		(+1.09%)	(+1.5)	(-1.62)	(+0.28%)	(-2.32%)
	980	6,098,415	27.0	10.43%	18.71	2.38
		(+0.84%)	(+1.7)	(-1.09)	(+0.26%)	(+9.43%)
100	990	5,943,406	31.0	9.29%	70.10	111.78
		(+0.69%)	(+1.6)	(-0.80)	(-0.03%)	(-5.82%)
	1,980	11,219,937	41.0	8.87%	143.58	35.51
		(+0.60%)	(+1.7)	(-0.36)	(+0.02%)	(-30.47%)
	3,960	22,089,934	52.6	8.32%	312.18	34.77
		(+0.54%)	(+2.0)	(-0.25)	(-0.10%)	(-25.57%)
150	2,235	12,366,688	54.0	8.13%	408.94	415.61
		(+0.45%)	(-1.6)	(-0.17)	(+0.03%)	(+56.01%)
	4,470	24,033,820	71.0	7.88%	990.13	168.19
		(+0.53%)	(+2.3)	(-0.14)	(-0.20%)	(+1.62%)
	8,940	47,465,632	79	7.89%	2,720.51	262.92
		(+0.50%)	(+2.1)	(-0.11)	(-0.06%)	(+3.88%)

Table A.3

Results for Limited Proportion of PtP Loads.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)	# of Infeasible Instances
50	245	1,669,985	21.6	10.00%	4.93	3.72	3
		(+1.06%)	(+6.4)	(-10.21)	(-2.52%)	(+71.77%)	
	490	3,174,001	27.4	10.00%	9.41	4.56	2
		(+0.72%)	(+7.7)	(-4.50)	(-1.78%)	(+164.25%)	
	980	6,044,016	28.6	9.98%	18.30	4.52	1
		(-0.06%)	(+3.3)	(-1.54)	(-1.91%)	(+107.97%)	
100	990	5,907,329	30.6	9.64%	70.14	200.65	0
		(+0.08%)	(+1.2)	(-0.45)	(+0.02%)	(+69.07%)	
	1,980	11,115,816	39.9	9.10%	143.64	40.81	0
		(+0.03%)	(+0.6)	(-0.14)	(+0.06%)	(-20.10%)	
	3,960	21,971,203	50.5	8.57%	312.16	45.33	0
		(+0.001%)	(-0.1)	(-)	(-0.11%)	(-2.95%)	
150	2,235	12,323,958	57.7	8.31%	408.79	353.18	0
		(+0.11%)	(+2.1)	(+0.01)	(-0.01%)	(+32.58%)	
	4,470	23,962,971	73.8	7.96%	990.58	246.20	0
		(+0.24%)	(+5.1)	(-0.06)	(-0.16%)	(+148.75%)	
	8,940	47,100,056	74.8	8.06%	2,747.40	477.65	1
		(-0.28%)	(-2.1)	(+0.06)	(+0.93%)	(+188.73%)	

Table A.4

Results for Moderate Volume Required to Open an RP.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,652,414 (+0.001%)	15.3 (+0.1)	20.17% (-0.04)	5.08 (+0.39%)	2.82 (+30.59%)
	490	3,151,213 (+0.001%)	19.7 (-)	14.53% (-0.03)	9.64 (+0.65%)	1.65 (-4.40%)
	980	6,047,985 (+0.006%)	25.2 (-0.1)	11.61% (+0.09)	18.79 (+0.74%)	1.82 (-16.26%)
100	990	5,902,990 (+0.002%)	29.2 (-0.2)	10.08% (-0.01)	71.40 (+1.83%)	104.77 (-11.72%)
	1,980	11,156,163 (+0.03%)	38.8 (-0.5)	9.39% (+0.15)	144.11 (+0.39%)	50.58 (-0.95%)
	3,960	22,001,047 (+0.14%)	46.4 (-4.2)	9.00% (+0.43)	311.57 (-0.30%)	154.75 (+231.29%)
150	2,235	12,291,190 (-0.16%)	45.5 (-10.1)	9.01% (-0.71)	411.20 (+0.58%)	833.83 (+213.00%)
	4,470	23,939,619 (+1.38%)	55.3 (-13.5)	8.81% (+0.80)	989.78 (-0.24%)	2,228.59 (+1,246.48%)
	8,940[a]	---	---	---	2,747.40 (+0.93%)	---

[a] CPLEX out of memory while exploring branch-and-cut tree

Table A.5

Results for High Volume Required to Open an RP.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,653,791 (+0.08%)	15.0 (-0.2)	20.57% (+0.36)	5.07 (+0.18%)	2.84 (+31.12%)
	490	3,153,772 (+0.08%)	19.2 (-0.5)	14.79% (+0.29)	9.57 (-0.10%)	2.32 (+34.47%)
	980	6,065,296 (+0.29%)	22.6 (-2.7)	12.74% (+1.22)	18.79 (+0.69%)	7.47 (+243.62%)
100	990	5,928,106 (+0.43%)	25.9 (-3.5)	11.26% (+1.18)	71.48 (+1.94%)	527.51 (+344.47%)
	1,980	11,278,022 (+1.12%)	28.6 (-10.7)	11.12% (+1.88)	143.46 (-0.07%)	4,553.36 (+8,815.00%)
	3,960	22,443,812 (+2.15%)	29.3 (-21.3)	11.01% (+2.44)	310.16 (-0.75%)	6,387.58 (+13,574.75%)
150	2,235	12,450,410 (+1.13%)	28.9 (-26.7)	10.65% (+2.34)	410.54 (+0.42%)	9,651.55 (+3,522.95%)
	4,470[b]	---	---	---	987.66 (-0.45%)	---
	8,940[b]	---	---	---	2,720.42 (-0.93%)	---

[b] CPLEX out of memory while exploring branch-and-cut tree

Table A.6

Results for Some Imbalance Allowed at Nodes for RN Loads.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,633,912 (-1.12%)	15.1 (-0.1)	16.90% (-3.31)	5.06 (+0.06%)	5.97 (+175.77%)
	490	3,133,419 (-0.56%)	19.5 (-0.2)	13.88% (-0.62)	9.56 (-0.16%)	2.26 (+30.74%)
	980	6,025,640 (-0.36%)	25.0 (-0.3)	11.13% (-0.39)	18.68 (+0.12%)	0.91 (-58.36%)
100	990	5,885,231 (-0.30%)	29.2 (-0.2)	10.16% (+0.07)	70.08 (-0.06%)	27.54 (-76.80%)
	1,980	11,132,782 (-0.18%)	39.8 (+0.5)	9.18% (-0.06)	143.82 (+0.19%)	11.92 (-76.65%)
	3,960	21,958,981 (-0.05%)	50.7 (+0.1)	8.55% (-0.02)	312.41 (-0.03%)	12.96 (-72.25%)
150	2,235	12,323,958 (+0.11%)	57.7 (+2.1)	8.32% (+0.02)	408.95 (+0.03%)	73.59 (-72.38%)
	4,470	23,957,141 (+0.21%)	74.4 (+5.7)	7.91% (-0.11)	990.57 (-0.16%)	32.35 (-80.45%)
	8,940	47,245,013 (+0.03%)	79.5 (+2.6)	7.97% (-0.03)	2,729.60 (+0.27%)	56.75 (-77.58%)

Table A.7

Results for High Fixed Cost of Installation of RPs.

Nodes	# O-D Pairs	Solution Value ($)	# RPs Open	Proportion of PtP Loads	Setup Time (secs)	Solution Time (secs)
50	245	1,913,915 (+15.83%)	0.0 (-15.2)	100.00% (+79.79)	4.17 (-17.58%)	5.01 (+131.19%)
	490	3,884,855 (+23.28%)	0.0 (-19.7)	100.00% (+85.50)	7.90 (-17.54%)	9.50 (+450.05%)
	980	7,329,919 (+21.20%)	9.5 (-15.8)	31.84% (+20.32)	15.45 (-17.21%)	18.60 (+755.86%)
100	990	7,321,420 (+24.03%)	10.8 (-18.6)	27.66% (+17.58)	70.33 (+0.30%)	1,011.92 (+752.63%)
	1,980	13,069,119 (+17.18%)	14.6 (-24.7)	18.26% (+9.02)	143.75 (+0.14%)	2,843.32 (+5,466.92%)
	3,960	24,551,334 (+11.74%)	19.8 (-30.8)	13.72% (+5.15)	309.66 (-0.91%)	4,253.72 (+9,006.51%)
150	2,235	14,334,604 (+16.44%)	16.2 (-39.4)	16.16% (+7.86)	408.19 (-0.15%)	4,297.87 (+1,513.31%)
	4,470	26,584,614 (+11.20%)	22.3 (-46.5)	12.26% (+4.24)	1,003.10 (+1.11%)	9,942.02 (+5,906.82%)
	8,940[c]	---	---	---	2,732.72 (+0.39%)	---

[c] CPLEX out of memory while exploring branch-and-cut tree

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