AN ABSTRACT OF THE THESIS OF

Christopher L. Jenks for the degree of Honors Baccalaureate of Science in Industrial Engineering presented on April 8, 2014. Title: Interaction of Design Factors in the Truckload Relay Network Design with Mixed Fleet Dispatching Problem.

Abstract Approved:

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Truckload carriers operating under a Point-To-Point (PtP) dispatching method seek to minimize miles driven with empty loads. This results in driving tours keeping drivers away from their homes for weeks at a time causing high turnover rates industry wide. One proposed solution combines Relay Network dispatching with existing PtP. This design problem is called Truckload Relay Network Design with Mixed-Fleet Dispatching (TLRND-MD). Vergara and Root (2013) attained high quality solutions for large-size network instances of TLRND-MD using an integer programming formulation and a heuristic solution approach. Their model considered several design factors and their experiments looked at the effect of some design factors on model performance and solution quality. However, their experiments ignored the interactions between design factors. This thesis expands on this research via a full factorial experiment, discovering significant interactions between equipment balance restrictions, minimum volume required to open Relay Points (RPs), maximum proportion of PtP loads allowed, and fixed RP installation costs. The ultimate hope of this research is that greater understanding of these interactions will motivate carriers to pursue the implementation of

TLRND-MD systems in practice and improve driver retention. This thesis ends with a discussion of conclusions and ideas for future research.

Key Words: Truckload, Point-to-Point, Relay Network, Mixed Fleet Dispatching, Factorial Experiment

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Interaction of Design Factors in the

Truckload Relay Network Design with Mixed Fleet Dispatching Problem

by

Christopher L. Jenks

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Christopher L. Jenks, Author

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1 INTRODUCTION

1.1 Background and Motivation

For seven of the past eight years, the American Transportation Research Institute (ATRI) has reported driver turnover as being one of the top five concerns for Truckload (TL) freight transportation carriers (ATRI, 2012). Historically, the turnover rate for TL drivers has been at least 100% -- meaning that, on average, every driver employed is replaced within the examined time period (ATA 2013). The high turnover rates are costly for the TL industry. On average, the administrative costs associated with recruiting and training new employees amount to approximately $2.8 billion every year (Rodriquez et al., 2000).

TL carriers utilize Point-to-Point (PtP) dispatching methods, seeking to minimize the number of empty load miles driven to reposition equipment after full truckloads are transported directly from origin to destination. In this system, a single driver is initially assigned to transport a load directly to the destination from the vicinity of the driver's home domicile. When the driver reaches the destination and delivers the load, he or she is often assigned to transport another PtP load originating in the vicinity of the drop-off location to a different destination. This is necessary since backhaul loads are not always available and returning to the driver's home domicile would result in costly empty miles. The resulting tour for the driver can last 2-3 weeks at a time (Shattell et al., 2010). These long driving tours lead drivers to perceive a reduction in their quality of life and are one of the main reasons for the historically high turnover rates.

In contrast, Less-Than-Truckload (LTL) carriers do not suffer from the same issue as TL carriers. LTL trucks are permitted to transport loads at less than full capacity. These partially-filled trucks utilize central hubs in a hub-and-spoke network configuration to consolidate loads and acquire full loads. In this configuration, local drivers transport partial loads between these hubs and the origin or destination of the load, and lane drivers transport loads between the hubs. As a result, the driver turnover rate is much lower among the LTL carriers—reported as only 15% by the American Trucking Association (ATA, 2013).

While ATRI (2013) has recently proposed improved recruitment and training strategies to attract and retain more drivers, TL carriers and researchers have also explored alternative dispatching methods that consider adopting hub-and-spoke configurations that are used in the LTL industry for TL transportation. Over the years, these efforts have ranged from simulation studies to developing mathematical models and heuristic approaches to design and analyze the performance of several alternative dispatching methods as described in Section 2. This document considers one of the most recent implementations, called Truckload Relay Network Design with Mixed Fleet Dispatching (TLRND-MD) which is described next.

1.2 Truckload Relay Network Design with Mixed Fleet Dispatching

According to Vergara and Root (2013), the TLRND-MD problem seeks to minimize the total cost of opening relay points (RPs) and transporting truckloads when operating a combined dispatching system using a relay network (RN) and the PtP dispatching method. Decisions associated with this problem are the dispatching method to be used for different loads and the design of the relay network which involves the locations of relay points and the selection of routes that utilize them.

In this configuration, origin-destination (O-D) pairs in a transportation network represent orders that a customer places with a carrier, for example to ship goods from a Seattle wholesaler to a Portland retailer. For every O-D pair, the number of loads reflects the number of full truckloads that must be transported according to the quantity specified in the customer order. In the PtP network, loads would be transported directly from origin to destination, whereas in an RN the loads would travel via a series of relay points between the origin and destination similar to the “hub-and-spoke” networks attributed to LTL carriers. However, no sorting or consolidation of loads is needed at these relay points.

To successfully transport these loads through the RN, two types of drivers are needed. Local drivers transport loads from the origin to the local RP or from the last RP to the destination. Lane drivers transport loads only between RPs. These local and lane distances cannot be greater than a specified limit—partially set according to Hours of Service (HOS) regulations, but more importantly so that drivers can return to their home domiciles within the same day (for local drivers) or a few days (for lane drivers). This is in stark contrast with the several weeks that drivers can spend on the road in a PtP-only dispatching configuration.

The adaptation of hub-and-spoke models to TL dispatching methods provides the opportunity for TL carriers to reduce driver turnover by benefiting from the resulting comparatively regular routes. Üster and Maheshwari (2007) and Üster and Kewcharoenwong (2011) first proposed a mathematical formulation for the design of relay networks to dispatch loads. Although they noted the potential benefit of a hybrid system, their formulation only considered RN movements and did not include a mixed fleet dispatching approach. Additionally, computational limitations restrict the ability of these mathematical models to incorporate some operational constraints and solve realistically-sized problem instances. The most significant challenges deal with the network sizes that need to be considered when analyzing planning problems for major TL carriers, and also the difficulty to design appropriate routes for the O-D pairs so that the number of additional miles (circuity miles) driven between origin and destination is within a pre-specified limit.

More recently, a mathematical model proposed by Vergara and Root (2013) incorporates both PtP and RP dispatching methods. Their integer programming (IP) formulation uses composite variables to implicitly capture some of the difficult operational constraints and provides solutions for large-sized network instances. The computational experiments presented in this research analyzed the effect of some of the design parameters of the TLRND-MD problem on the performance of the proposed model and solution approach as well as on the characteristics of the resulting dispatching systems. Some of the design parameters that were analyzed include equipment balance requirements, a minimum volume required to open an RP, the maximum proportion of PtP loads allowed in the network, fixed costs associated with installing RPs, and costs associated with repositioning PtP equipment. However, this research did not consider the effect of interactions between these factors on model performance or solution quality.

1.3 Research Objective

The research area concerning the TLRND-MD problem is still relatively novel. Contributors to this field have been able to gauge the main effect of network design parameters and instance size on measures of solution quality and model performance with response variables such as solution cost and computational time, respectively. However, few researchers have considered the impact of interactions between major design factors. The objective of this research is to investigate the effect of the interactions between the design parameters analyzed by Vergara and Root (2013) on the performance of their proposed model and solution approach and the quality of the solutions obtained.

1.4 Expected Contribution

Formal investigation of the interaction effects of some of the design parameters for the TLRND-MD problem can both reinforce existing knowledge and also provide new insights into the TLRND-MD problem and the proposed solution approach presented by Vergara and Root (2013).

For instance, a thorough understanding of the interaction effects of design parameters on metrics such as overall solution costs and the quantity of RPs to open can be helpful to organizations seeking to determine the time and financial resources required to implement a hybrid RN. Also, performance metrics such as computational time can provide an understanding of the time resources required by the proposed modeling and solution method. Given a company's customer portfolio and network size, this could help decision-makers decide how to best utilize their planning resources. In all, this research should provide a better understanding of the feasibility of a hybrid dispatching system for

TL transportation and assess the usefulness of the method proposed by Vergara and Root (2013) to solve this type of problems in practice.

1.5 Organization of this Document

The remaining portions of this document are organized as follows. In Section 2, a literature review related to the evolution of alternative dispatching methods using relays will be discussed. In Section 3, a methodology for investigating the interaction effects between design parameters of the TLRND-MD problem will be described. In Sections 4 and 5, the results of the experiments and their analysis will be presented, respectively. Lastly, in Section 6 conclusions about this research will be discussed along with areas for future research.

2 LITERATURE REVIEW

2.1 Alternative Dispatching Methods for TL Transportation using Relays

2.1.1 Multi-Zone Dispatching

One of the first attempts to develop a modeling approach for the Truckload Relay Network Design (TLRND) problem was developed by Üster and Maheshwari (2007) as a hub-and-spoke implementation to TL dispatching, called multi-zone dispatching. Their model utilized relay points as described earlier and considered constraints on local driver tour length, lane driver tour length, percentage circuity, and load imbalance. However, their mathematical formulation encountered significant difficulties obtaining optimal solutions due to the size of the problem. Subsequently, they relaxed the circuity and load imbalance constraints and developed a tabu search-based heuristic solution approach. They later assessed percentage circuity and load imbalance by calculating their values from the proposed solution.

Using the heuristic approach, the authors were able to obtain near-optimal solutions for (small) networks of up to 35 nodes in size. One of the conclusions drawn in this research was that circuity and load imbalance could be controlled via the tour length constraints, and that changes in local driver tour length had greater impact than changes to lane driver tour length.

2.1.2 Truckload Relay Network Dispatching

This first mathematical model developed by Üster and Maheshwari (2007) for multi-zone dispatching was re-introduced with some changes by Üster and Kewcharoenwong (2011) for Truckload Relay Network Design (TLRND) problem. Unlike their prior heuristic approach, an exact approach was implemented to obtain optimal solutions by incorporating circuity using a surrogate constraint. This was accomplished via an algorithmic technique that utilized Bender's cuts to filter for feasible solutions. By fixing the values of the decision variables to satisfy restrictions on tour distances and load balance, they could filter infeasible solutions with excessively large network costs, and then re-incorporate these constraints into the problem with post-priori methods. Their model was able to obtain optimal solutions for RP-only networks with sizes of up to 80 nodes using this exact solution approach.

While not able to incorporate all parameters explicitly into their latest model, Üster and Kewcharoenwong (2011) presented some useful insights. The authors observed that solution time increased with smaller allowance on equipment imbalance and circuity allowances as expected. Additionally, they observed that increasing allowable lane tour length decreased solution time—suggesting that allowing a proportion of loads to be dispatched PtP may offer reduced solution times. Lastly, their research demonstrated significant cost savings of up to 11% and reductions in driver tour time by at least 50% on average with RP networks.

More recently, progress has been made in the development of mathematical models to solve the TLRND problem and its extensions. Vergara and Root (2012) considered both exact and heuristic-based approaches using a composite variable formulation to solve the TLRND problem. In their formulation, composite variables represent feasible truck routes, so many of the operational constraints that were traditionally relaxed due to tractability issues were able to be implicitly incorporated into the formulation. These composites were generated using templates meant to represent node-RP combinations of two, three, four, and five nodes as illustrated in Figure 1.

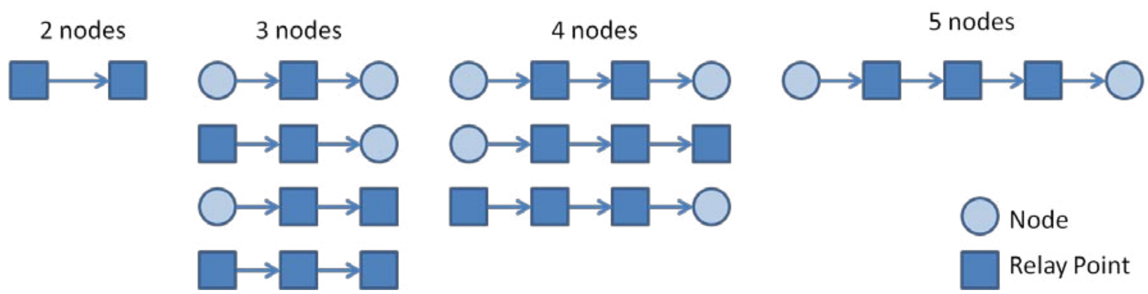


Figure 1: Templates for Composite Variable Generation (Vergara and Root, 2012)

An exact approach using branch-and-price was first attempted on this composite variable formulation. While able to obtain optimal solutions for networks of up to 100 nodes, tractability issues were found in several test cases due to the size of the problem. For this reason, using the data from optimal solutions obtained, the authors developed a heuristic using a reduced the number of composites in the model (> 86% reduction) by eliminating templates rarely used in optimal solutions. With this heuristic method, they were able to obtain high quality solutions with worst-case optimality gaps no greater than 1% for networks with up to 150 nodes. Additionally, the heuristic was able to provide solutions faster (> 90% reduction in setup time) and a test case for a major TL carrier was solved in less than an hour demonstrating the potential of this method for more realistic instances of the TLRND problem. Based on the computational results obtained, this research reinforced some of the insights presented in previous studies with respect to the potential of a hybrid system for total cost reduction given the large number of RPs needed and the low volume handled by some of those RPs which were only open for feasibility purposes. These findings motivated the study of the hybrid dispatching approach that is the subject of this thesis.

2.1.3 Truckload Relay Network with Mixed Fleet Dispatching

Based on their previous research, Vergara and Root (2013) studied the design of a hybrid dispatching system using both RN and PtP dispatching (mixed fleet dispatching networks). The difference with respect to the previous dispatching method that considered exclusively dispatching through the RN is based on the addition of PtP dispatching as an alternative to the RN (Figure 2). The TLRND-MD network has the additional possibility of dispatching via the PtP route, indicated by the finely-dotted line.

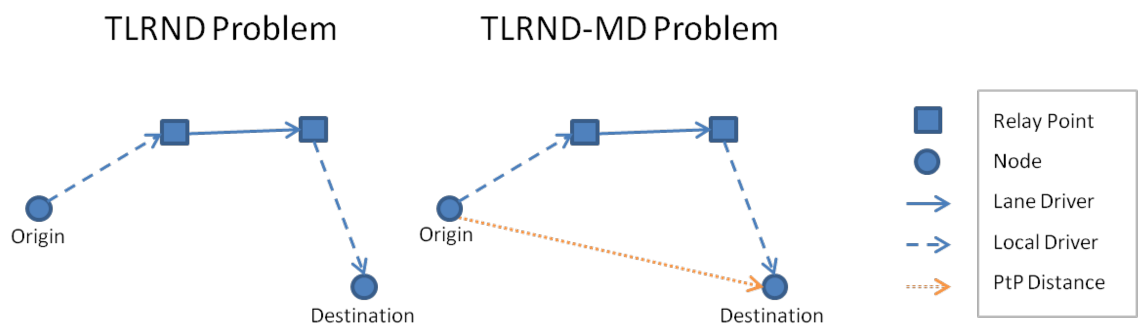


Figure 2: TLRND (RP-only) network contrasted with TLRND-MD (hybrid) network

The solution approach for TLRND-MD considered first the generation of feasible paths for the loads as composite variables, and then the solution of an integer programming problem to determine the appropriate dispatching method for loads and the selection of feasible paths and relay points to open in the relay network. Using a heuristic solution method, high quality solutions were obtained for significantly larger network sizes of up to 150 nodes. Computational experimental results using this approach showed that a mixed fleet dispatching system outperforms both RN-only and PtP-only systems.

One of the key insights obtained from this research was that the number of composite variables generated for the model significantly affected its performance as the network size increased. The subsequent increases in average computational time (from 38 to more than 1,900 seconds for 50 and 100 node networks, respectively) could be attributed to the increased network size which results in a larger number of potential locations to open RPs. Additionally, the authors noted that truckloads dispatched with O-D pair distances less than 100 miles were primarily dispatched PtP. They modified their previous composite variable generation methodology to dispatch such loads PtP. This resulted in fewer composite variables generated in the setup of the model, thus resulted in significant computational time reductions. Worth noting is that the computational experiments completed by Vergara and Root (2013) considered the effect of changing design parameters one-at-a-time only. The research in Vergara and Root (2013) provides the basis for the analysis presented in this thesis.

2.1.4 Importance of Design Parameters for TLRND-MD

Ultimately, developing a robust and scalable method for solving the TLRND-MD problem is important in making this dispatching method applicable for TL operations. While the approach of Vergara and Root (2013) was able to successfully attain high quality solutions for large-sized problem instances, the authors didn't analyze the effect of interactions between some of the design parameters used in their experimentation. Different levels for the design factors were considered one-at-a-time, varying the level of a single factor while fixing the levels of the remaining factors—this is a problem because the interactions between the different factors was not explicitly analyzed in terms of their effects on solution quality and model performance. Knowledge of these interactions would develop a better understanding of the characteristics of TL dispatching that affect the application of relay networks and the solution approach proposed by Vergara and Root (2013) in practice.

3 METHODOLOGY

We will use the mathematical model and solution approach presented by Vergara and Root (2013) to investigate the interaction effects between design parameters of the TLRND-MD problem. The parameters to be considered are: equipment imbalance allowed in the network, maximum proportion of PtP loads allowed, minimum volume required to open an RP, and the financial parameters concerning repositioning costs of PtP loads and fixed installation costs of opening RPs. Certain parameters such as network size and O-D pair density have been studied in Vergara and Root (2013) and therefore will not be investigated here.

This section is split into four subsections. First, a formal definition of the TLRND-MD problem is given. Second, the most recent implementation of the composite variable generation and mathematical model developed by Vergara and Root (2013) is briefly described. Third, a rationale is given for the selection of the design parameters and response variables that are considered in this analysis. Finally, the design and execution of the experiment is discussed to provide an overview of how the results were obtained and analyzed.

3.1 Definition of the TLRND-MD Problem

In this section, a formal definition of the TRLND-MD problem presented by Vergara and Root (2013) and the corresponding terminology are discussed briefly.

3.1.1 Problem Definition

Vergara and Root (2013) provide a succinct definition of the TLRND-MD problem. “Given a set of truckloads 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 subject to operational constraints."

3.1.2 Terminology of the TLRND-MD Problem

In a relay network configuration for TL transportation, two types of drivers are required for local (between origin or destination nodes and RPs) and lane (between RPs) movements (Vergara and Root, 2013). To comply with federal Hours-of-Service (HOS) regulations, local drivers are not permitted to travel distances greater than a pre-specified maximum local distance (γ_1), and lane drivers are not permitted to travel distances greater than a maximum allowed lane distance (γ_2). A per-mile rate is applied to local and lane miles driven to compute the transportation costs in the system.

Additional operational limitations are imposed to limit the number of RPs visited between origin and destination and the total length of the route in excess of the shortest path distance (circuity, β) between the O-D pairs to prevent excessive handling of loads and excessive mileage costs, respectively. For example, if the shortest distance between the origin and destination is SD_{OD}, then only routes with distance less than $SD_{OD}(1+\beta)$ are allowed in the RN (Vergara and Root, 2013).

Further, a minimum volume of loads (ν) passing through a node are required to justify the installation of an RP at that location. Each RP has a corresponding setup cost (f_k) that is given as an amortized amount of the fixed costs of installation for the planning horizon under analysis.

Finally, restrictions on the maximum percentage of equipment imbalance allowed at the nodes of the network (δ) and the maximum percentage of loads dispatched PtP (ρ) are enforced to minimize empty miles driven and guarantee that most drivers benefit from shorter tours and support better driver retention, respectively (Vergara and Root, 2013).

3.2 TLRND-MD Composite Variable Model Implementation

This subsection is subdivided into two subsections. We first introduce the mathematical model proposed by Vergara and Root (2013) for the TLRND-MD problem (Section 3.2.1). Later, we discuss some of the most important aspects associated with the implementation of the composite variable generation approach and solution methodology (Section 3.2.2).

3.2.1 TLRND-MD Mathematical Model (Vergara and Root, 2013)

The mathematical model and notation developed by Vergara and Root (2013) are presented next as a reference.

3.2.1.1 Notation

Sets

$R = set\ of\ composites\ r,$

$T = set\ of\ truckloads\ (O - D\ pairs)\ t,$

$N = set\ of\ nodes\ k,$

$R_t = set\ of\ composites\ r\ for\ truckload\ t, R_t \subset R,$

$R_k = set\ of\ composites\ r\ that\ visit\ node\ k, R_k \subset R,$

Parameters

$c_r = cost\ of\ composite\ r, \forall r \in R,$

$f_k = fixed\ cost\ of\ relay\ point\ k, \forall k \in N,$

$p_t = cost\ of\ dispatching\ truckload\ t\ using\ PtP\ dispatching, \forall t \in T,$

$b_t = demand\ for\ truckload\ t\ (in\ number\ of\ loads), \forall t \in T,$

$\delta = maximum\ acceptable\ percentage\ equipment\ imbalance,$

$\rho = maximum\ proporton\ of\ truckloads\ to\ be\ dispatched\ direct\ PtP,$

$v = minimum\ volume\ (in\ number\ of\ loads)\ required\ to\ open\ an\ RP,$

$n_{kr} = -1\ if\ node\ k\ is\ the\ origin\ relay\ point\ of\ composite\ r,$

$1\ if\ node\ k\ is\ the\ destination\ relay\ point\ of\ composite\ r, \forall k \in N, \forall r \in R,$

$0\ otherwise,$

$\theta_{kr} = 1\ if\ \ composite\ r\ used, \forall r \in R,$

$0\ otherwise.$

Variables

$x_r = number\ of\ composites\ r\ used, \forall r \in R,$

$y_k = 1\ if\ \ relay\ point\ k\ is\ opened, \forall k \in N,$

$0\ otherwise,$

$z_t = number\ of\ truckloads\ sent\ direct\ PtP, \forall t \in T.$

3.2.1.2 Formulation

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

$s.t.$

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

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

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

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

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

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

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

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

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

The objective function (1) minimizes the total cost of transportation of the RN and PtP loads, and the costs of opening RPs. Constraint (2) requires that all truckloads are dispatched PtP or via the RN. Constraint (3) requires that every load dispatched through the RN is assigned to an RP that is open. Constraints (4) and (5) enforce incoming and outgoing equipment balance at each RP, requiring the difference in balance not to exceed the allowable imbalance, δ. Constraint (6) enforces the minimum volume requirement to open an RP at nodes that exceed the minimum load volume, ν. Constraint (7) requires that the number of loads dispatched PtP be less than the maximum percentage of the total load demand, ρ. Lastly, constraints (8), (9), and (10) enforce variable type constraints on all decision variables.

3.2.2 Solution Methodology and Implementation

The solution of the mathematical model presented in Section 3.2.1 requires (1) an algorithm to generate the composite variables for the IP problem, and (2) an IP solver to solve the TLRND-MD problem using these composite variables.

Generation of the composite variables is the most computationally intensive portion of the solution method. The algorithmic approach discussed here is based on the revised implementation by Vergara and Root (2013). Here, a series of templates are applied to each O-D pair as a means of enumerating feasible RN routes satisfying limitations on the number of nodes visited, local distances between RPs and the origin or destination, lane distances between RPs, and circuity (β). Figure 3 shows the templates used and Figure 4 illustrates how the operational constraints are enforced thru these templates.

Vergara and Root (2013) originally utilized nine templates based on a limitation of a maximum of 3 RP nodes for any O-D pair, and considered only lane movements for cases with 2 nodes. Under-utilization of four of these templates in optimal solutions for some preliminary tests allowed them to come up with a heuristic solution approach based on the reduction in the number of composites by only considering the five templates in Figure 3 (templates with less than 2 RPs).

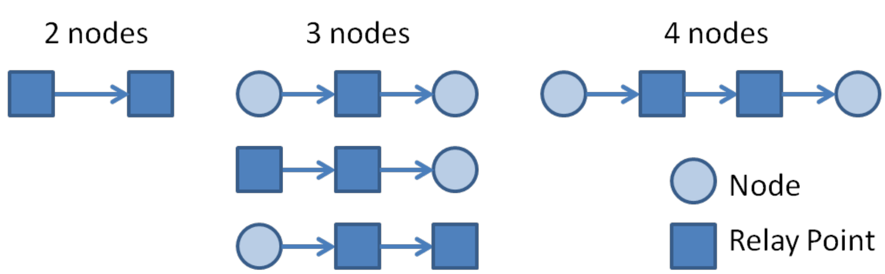


Figure 3: Reduced set of seven templates (Vergara and Root, 2013)

In addition to enforcing the limitation on the number of RPs allowed to be visited, each of the five templates in Figure 3 incorporates limitations on circuity and also local and lane distances, as illustrated in Figure 4.

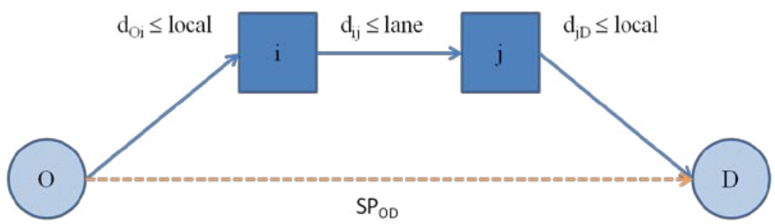


Figure 4: Composite Variable Generation based on Circuity and Distance Constraints

Assume that an O-D pair has shortest path distance, SP_{OD}. If both the distance from origin to destination through the RN is less than $(1+\beta)SP_{OD,}$ and the distances between nodes are less than local or lane distances (configuration determined by template), then the path is added as a composite variable into the mathematical model presented in Section 3.2.1. In this way, the circuity constraint is included implicitly in the definition of the variables as opposed to being included as a constraint in the mathematical model.

Further reduction of composites was also implemented as preliminary testing demonstrated that 87.7% of O-D pairs with distances of less than 100 miles were dispatched PtP. In their composite variable generation algorithm, Vergara and Root (2013) were able to further reduce the number of composites by dispatching PtP all O-D pairs with distances less than 100 miles. For example, as illustrated in Figure 5, pair O-D_1 is always dispatched PtP because it has a distance of 60 miles, whereas composite variables representing feasible routes are generated for the loads to be dispatched between the pair O-D_2 that has a distance of 130 miles (only one feasible route is shown in Figure 5). The model will select one of those feasible routes to satisfy the demand between O-D_2.

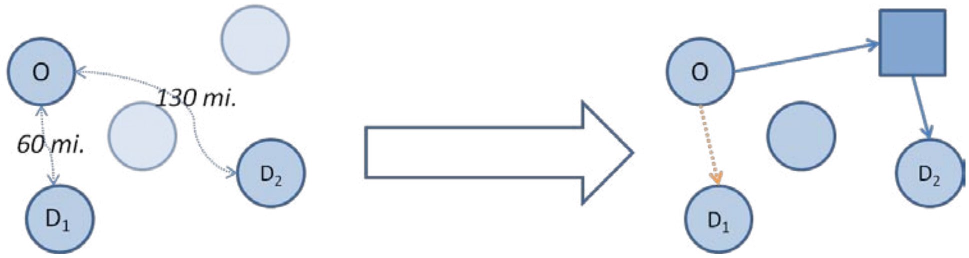


Figure 5: Composite Generation and Reduction Method (Vergara and Root, 2013)

The general programming language of choice for writing these algorithms was Python 2.7 for its object-based environment and just-in-time compilation capabilities. CPLEX was chosen as the mathematical programming solver, as it is powerful, well-supported, and offers Python modules that can be used in the code to call CPLEX functions and solve the IP formulation via traditional branch-and-cut methods.

Random networks were generated by locating nodes in a bounded region. Coordinates for the location of nodes were generated randomly in Python 2.7 according to a uniform distribution U(0, L), where L signifies the length of the sides of a square area. Complete networks were obtained by connecting all nodes in the network with an arc for each pair of nodes. Distances between nodes were computed using the Euclidian norm. Likewise, the O-D pairs and loads were randomly, uniformly, and independently generated using Python 2.7.

3.3 TLRND-MD Design Parameters and Response Variables for Study

This subsection discusses the design parameters and response variables selected for this study. Design parameters such as the equipment imbalance allowed, maximum proportion of PtP loads allowed, minimum volume required to open an RP, and financial parameters are presented in subsections 3.3.1 through 3.3.4. Parameters that were fixed in this study due to computational limitations are discussed in subsection 3.3.5. Finally, the response variables selected for interaction effects analysis are discussed in subsection 3.3.6.

3.3.1 Equipment Imbalance Allowed

Since TL carriers seek to minimize empty miles driven while repositioning equipment to serve new loads, equipment balance must be considered at the RPs. Equipment balance is synonymous to the terms “material balance” and “load balance” in this paper.

For simplicity, the model presented by Vergara and Root (2013) assumes equipment balance for local loads. This is a sound assumption because the movements are bi-directional. For example, as illustrated in Figure 6, trailers are either dropped off at or picked up from RPs by local drivers that satisfy demand or initiate supply at the origin or destination.

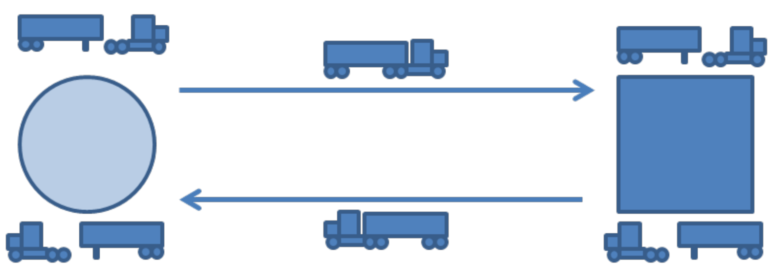


Figure 6: Equipment Balance is Assumed for Local Loads

On the other hand, the model explicitly incorporates equipment imbalance for lane loads as part of the formulation, so that a limitation on the percentage of imbalance allowed could be used as a design parameter of the RN. As illustrated in Figure 7, a large number of full trailers may depart one RP and then subsequently accumulate in excess at another RP. This has the tendency to create “surplus or deficit” conditions throughout the RN if balance is not enforced.

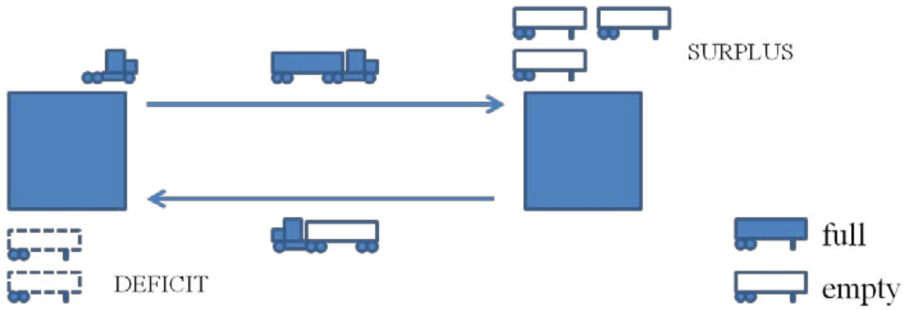


Figure 7: Equipment Imbalance for Lane Loads

Üster and Kewcharoenwong (2011) noted that the inclusion of load balance in their model affected the tractability of their formulation and consequently solution time. They observed that as the limitations on load balance were relaxed the solution times decreased. Vergara and Root (2012) also observed that enforcing balance in the model increased solution time; however they also noted that load balance had a marginal effect on solution cost. They hypothesized that the network configuration actually facilitates attaining balance in the network regardless of having a strict limitation on the equipment imbalance allowed. For these reasons, we select equipment imbalance allowed as one of the design parameters that will be analyzed in this research to be able to assess its impact when considering variations of other design parameters.

3.3.2 Maximum Proportion of PtP Loads Allowed

We are also interested on analyzing the effects of the maximum proportion of PtP loads allowed in the network. Üster and Kewcharoenwong (2011) noted that decreased solution times could be attained by allowing larger tour length distances by relaxing the circuity constraint in their formulation. Further, Vergara and Root (2013) demonstrated that allowing some proportion of PtP loads to exist in a hybrid version of the RN could improve solution cost.

While a pure RN might help carriers benefit from improved driver retention due to regular and shorter routes, this is not necessarily practical for all carriers. Having an understanding of how the proportion of PtP loads affects network performance could help carriers to plan for the implementation of RN designs in practice. The proportion of PtP loads allowed in the network is part of a tradeoff between additional route length (circuity) for the load and decreased tour length for the driver, but also influences per-mile dispatching costs. Loads that are not sent PtP can be sent through the RN, but this can result in highly circuitous routes for the loads dispatched and more RPs in the network. These trade-offs are important and this is the reason why this design parameter is included in our analysis.

3.3.3 Minimum Volume Required to Open an RP

Minimum volume required to open an RP arises from the need to justify the expense of installation. As such, there is an important tradeoff between the minimum volume required to open an RP and the total fixed cost of installation of RPs. Generally, the number of RPs opened in the network will decrease as the minimum volume required for opening an RP increases. The value of this parameter could significantly affect the extent to which a carrier may be able to implement a mixed fleet dispatching system using RPs. These tradeoffs are very important for carriers, and for this reason we have included this parameter in our analysis.

3.3.4 Financial Parameters

There are two different costs that are considered as financial parameters.

First, since existing TL infrastructure is not already equipped to handle the increased traffic at RPs, the fixed cost of installing RPs must be considered. In addition, the PtP dispatching repositioning costs (per mile) are included in the objective function of the model presented by Vergara and Root (2013) as a surrogate for enforcing balance for the equipment used in this type of service.

Fixed installation costs of RPs take into account the increased administrative, utility, labor, and other site costs that are incurred with the designation of a location as a relay point; higher installation costs discourages or limits the rate of development of an RP network. On the other hand, PtP repositioning costs take into account the cost of fuel, maintenance, driver wages, and related costs incurred on a per-mile basis for every empty mile driven. This is reflected as an inflation rate per mile, and has the opposite effect of installation costs; increased repositioning costs encourage expanding the RN. The impact of the two types of costs is worth investigating since they can affect the characteristics of the solutions obtained and performance of the model proposed by Vergara and Root (2013).

3.3.5 Other Design Parameters

Other design parameters such as network size (number of nodes in the network), O-D pair density (the number of O-D pairs with demand for transportation), and number of loads per O-D pair primarily affect the computational performance of the model and solution approach as all of them play significant roles in the feasibility of finding a solution and greatly impact the computational resources required to solve those that are feasible. In this research, we make the assumption that these parameters will change very little, if at all, for a carrier with regular customers under contract. The effect of these parameters has been already analyzed by Vergara and Root (2013), so for the purposes of this computational experiment a fixed network size, O-D pair density, and load density will be chosen. The instances to be used will be fixed based on the values observed by Vergara and Root (2013), such that computational run time for most base case instances is approximately 5 minutes. This corresponds to networks of 100 nodes with 20% O-D pair density under "base" conditions according to Vergara and Root (2013). These base conditions and their values are summarized in Table 1.

Table 1: Base Conditions for Instances Used in Computational Experiments

Base Condition	**Value**
Local dist. (miles)	150
Lane dist. (miles)	600
Circuity (β)	0.25
Local per-mile cost ($)	1
Lane per-mile cost ($)	1.3
Percent Imbalance allowed	0
Min volume required to open RP	0
PtP limit (%)	1
PtP repositioning costs (as a per-mile surcharge)	0.25
Fixed cost of installing RPs (multiplier of $10,000)	1

3.3.6 Response Variables for Interaction Effects Analysis

Response variables have been selected to assess the impact of the interactions between design factors on model performance and solution quality. Model performance can be measured by the computational run time. Run time has implications in operational strategy decisions, as the run time can determine if the algorithm is used more as a real-time, monthly, quarterly, or yearly tool.

Solution quality refers to the characteristics of the solutions obtained for the TLRND-MD problem. The two responses used are the overall solution cost and the number of RPs opened. Overall solution cost is the most straight-forward method of communicating the benefits of alternative dispatching methods over current dispatching methods. The number of RPs opened can provide a good idea of the administrative load required to implement the solution. At the very least, the number of RPs opened can paint a clearer picture to planners about how the changes to the network might be implemented and what time scale might be required to do so. Additional characteristics of the solutions such as the proportion of PtP loads versus RN loads and the distribution of the locations of RPs are not explicitly considered in this research.

3.4 Development of the Experimental Design

This section presents the considerations taken to design the experiment to analyze the interactions between the design factors discussed in section 3.3, and it is divided in five subsections. First, the justification for choosing a factorial experiment design is discussed in subsection 3.4.1. Then, the levels chosen for each of the design factors is discussed in subsection 3.4.2. Interactions of interest are presented as four specific cases in subsection 3.4.3. Finally, in subsections 3.4.5 and 3.4.6, we describe how the experiment will be executed and the results analyzed, respectively.

3.4.1 Justification for Factorial Experiment Design

Up to now, the primary method of investigating the effects of the design factors on the model performance and solution quality measures has been the traditional "pick and fix one-at-a-time" approach. While this may hint at interrelationships between variables, it does not have the capability to effectively investigate higher order interactions. Additionally, this approach cannot incorporate multiple response variables simultaneously, and has very limited ability to reduce the set of design factors by elimination. In comparison, a factorial experiment would be much better suited to these purposes as an analysis tool.

Traditional “pick and fix one-at-a-time” approaches are used as a means of estimating main effects with factors at specific combinations and levels. However, this does not give the experimenter the capacity to sufficiently extrapolate findings to different levels of factors. To use an example in chemistry, a mix of four chemicals may behave in equilibrium with the concentration of one chemical fixed at a specific level—but when this level changes, the chemicals may interact very differently and produce unexpected results. Factorial experiments offer the capability to investigate these unknown interactions between factors, and are especially effective at incorporating both multiple factors and multiple responses. Further, fractional factorial designs allow the reduction of the size of the problem (number of treatments) for those with especially large numbers of factors and responses (Box et al., 2005).

In this research, there are many factors and many responses present simultaneously. We consider five primary design factors (equipment imbalance allowed, minimum volume required to open an RP, maximum proportion of PtP loads allowed, fixed costs of installation of RPs, and PtP repositioning costs) and two categories of responses (model performance and solution quality metrics). A full factorial design with five factors each at two levels would require 2^5 (32) treatments, with $32*n$ total runs (where n is the number of replications—i.e., different networks—for each treatment). If 10 replications are required, for example, then 320 total runs must be implemented in the experiment.

Underlying assumptions of this study based on the empirical analysis of Vergara and Root (2013) are that some factors have no significant effects on the performance of the model or the quality of the solution and can be eliminated, and that higher-order interactions (those between three or more factors) are insignificant. Given these assumptions, a fractional factorial design may be a more appropriate as a time-sensitive design since a half-factorial design (for example) would reduce the number of treatments to 16. However, at less than 5 minutes per replication, using a full-factorial design that provides twice the data of a half-factorial design is still reasonable.

There are important considerations required to minimize confounding variables and to choose how to alias the five experimental factors. Resolution can be used to measure the “strength” of an experimental design, as resolution specifies the extent to which lower order effects are dampened. There is a tradeoff between higher and lower resolution experiments; for example, higher resolution designs can be wasteful and can yield misleading results that have no real implications. On the other hand, lower resolution designs (II or I) may be insufficient to detect lower order effects beyond basic high-level interaction effects (Box et al. 2005). In practice, a resolution four or better experiment would provide sufficient protection from these risks; as such, a resolution IV configuration was selected for this five-factor design.

3.4.2 Factor Levels

Practical low (-) and high (+) levels for the factors considered in our research were chosen empirically based on the computational experiments completed by Vergara and Root (2013). Their analysis of solution quality responses (e.g., solution cost and number of RPs open) is summarized in Figure 8. The levels chosen for our computational experiments based on their previous analysis are summarized in Table 2. Levels were chosen such that they capture the range of change of the main effects considered by Vergara and Root (2013).

Table 2: Summary of Factor Levels

	Factor	-	+
A:	Percentage of imbalance allowed	0	1
B:	Minimum volume required to open an RP (as percent of total volume)	0.02	0.05
C:	Percentage of PtP loads allowed	0.10	0.20
D:	PtP repositioning cost (as a per-mile surcharge)	0.25	0.40
E:	Fixed cost of installing RPs (as a multiplier of $10,000)	1	10

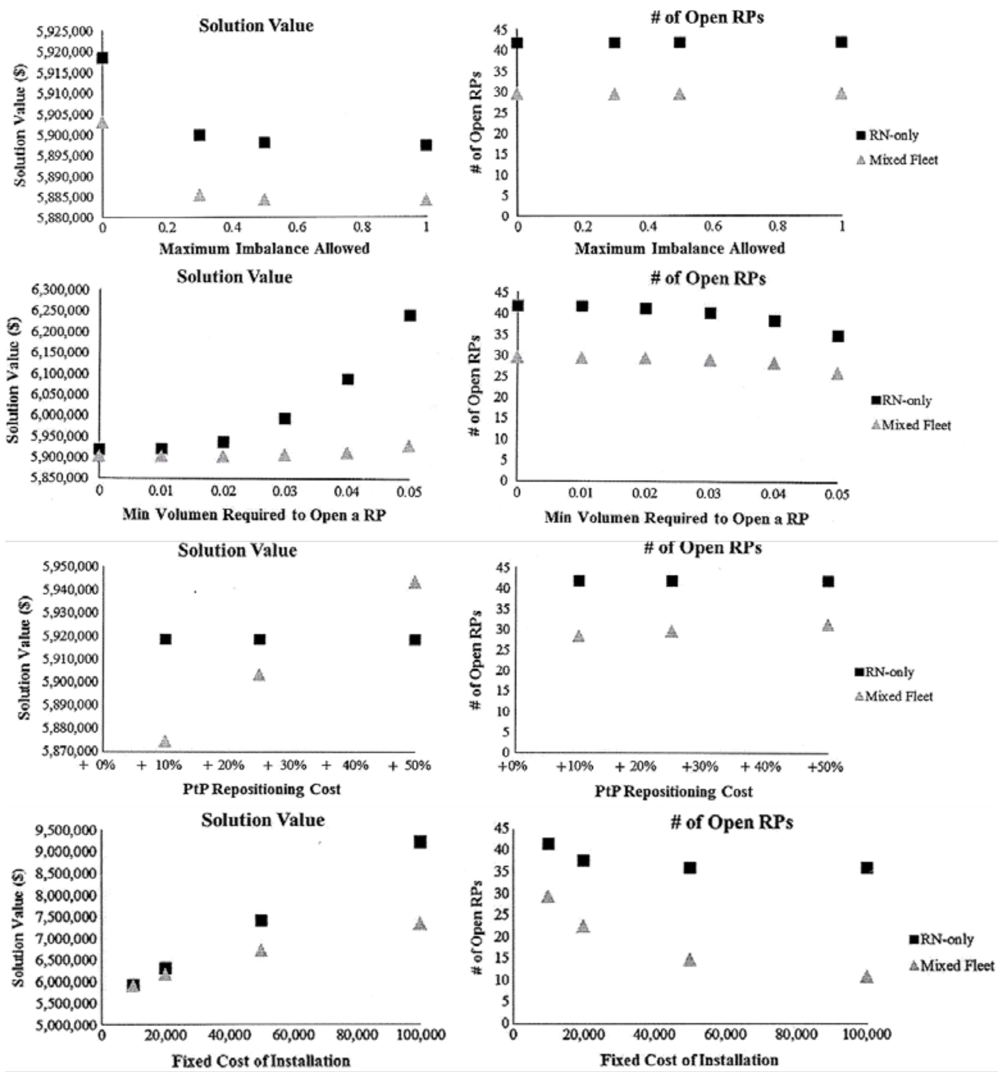


Figure 8: Summary of Solution Quality Results of Vergara and Root (2013)

3.4.2.1 Percentage of Imbalance Allowed

Low and high levels of percentage of imbalance allowed at the nodes in the network were selected assuming that balance limitations are enforced (0% imbalance allowed) or not enforced (100% imbalance allowed). This is based on observations by Vergara and Root (2012) and Vergara and Root (2013). In these studies, the authors noted no significant differences in solution approach performance between perfect balance and no balance, but did notice some effect on the number of RPs opened in the network.

3.4.2.2 Minimum Volume Required to Open RPs

Under the baseline scenario in Vergara and Root (2013), no minimum volume requirements were enforced (0% of total volume) in order to allow any node in the network to serve as an RP. However, as demonstrated by Vergara and Root (2013), the minimum volume requirement appeared to have significant effects both on the number of RPs opened in the network and the computation time of the solution method when the minimum volume required takes a positive value. As such, minimum volume requirements mirror theirs, with requirements established at a moderate (2% of the total volume) and high (5% of the total volume) level of traffic through the nodes for the low and high levels of our current experiment, respectively.

3.4.2.3 Percentage of PtP loads allowed

A strict limitation on the percentage of loads dispatched PtP increases the likelihood of reducing driver turnover as more loads are shipped using the RN over more regular routes, but seems to have no significant effect on solution time as compared to a base case where all loads are allowed to be shipped PtP (Vergara and Root, 2013). Thus, moderate (10% of the total number of loads) and high (20% of the total number of loads) restrictions were imposed to set low and high levels for this factor and study how the limitation on PtP loads affects other factors.

3.4.2.4 PtP Repositioning Costs

Levels for PtP repositioning costs are meant to represent the industry average (25% surcharge of travel expenses in a per-mile basis) and an inflated amount of the industry average (40% surcharge of travel expenses in a per-mile basis). Below-average (10% surcharge) and above-average (50% surcharge) repositioning costs were considered in Vergara and Root (2013). For both cases, the effect on solution cost was not significant. As such, this research assumes PtP repositioning costs will most likely inflate in the future and only considers the average (25% per—mile surcharge) and above-average (40% per-mile surcharge) repositioning costs for the low and high levels in our experiment, respectively.

3.4.2.5 Fixed RP Installation Costs

Vergara and Root (2013) considered a baseline scenario with $10,000 for the amortized fixed cost of installation of RPs over the planning horizon and also alternative scenarios with multiples of this amount (2, 5 and 10 times the baseline amount) to study the effects of fixed RP installation costs on model performance and solution quality. In practice, the lower cost may be more realistic for carriers since relatively few resources are required to establish RPs. Therefore, the purpose of setting a higher installation cost is to investigate the effects on the number of RPs opened as observed by Vergara and Root (2013); higher installation costs appeared to reduce the number of RPs opened and subsequently caused the network to behave more like a PtP system. In our research, we consider a low level of $10,000 and a high level of $100,000 for this factor.

3.4.3 Interactions of Interest

There are four cases of particular interest in this research. The first and second cases are directly related to the implementation of the network from an effectiveness and flexibility standpoint. The third and fourth cases consider the costs of implementation.

3.4.3.1 Case I: Maximum Proportion of PtP Loads and Equipment Imbalance Allowed

Controlling the maximum proportion of PtP loads allowed represents the extent to which a carrier implements an RN within their infrastructure. When this factor is decreased (i.e., greater implementation of an RN, letting fewer loads be dispatched PtP), more loads become available for dispatch throughout the RN. In general, increasing the overall number of loads throughout the RN can, if the number of RPs is fixed, increase the ability to obtain balance because each RP on average has a larger "pool" of loads available. Yet, if the number of RPs is not fixed (say, the number of RPs increases faster than the number of loads dispatched through the RN) then the opposite will occur; each RP will have fewer loads on average available in its "pool" and will therefore have greater difficulty attaining balance. These contradicting forces are what drive such interest in the interactions between equipment balance and the maximum proportion of PtP loads available for dispatch.

3.4.3.2 Case II: Minimum Volume to Open an RP and Equipment Imbalance Allowed

Minimum volume to open an RP has the potential to significantly affect the flexibility and effectiveness of the network. By setting higher minimum volumes, for example to justify high operational costs, this will most likely decrease the number of RPs opened in the network. Of course, this assumes the loads are uniformly distributed throughout the network. In areas where demand and supply are greater more RPs will be opened and have the tendency to cluster together (i.e., near an industrial district). Assuming the uniform case, with fewer RPs available to dispatch loads in the network, the RPs will experience higher traffic and the routes may become more circuitous. Likewise in Case I, this may increase the ability to obtain balance with loads concentrated over fewer RPs; each RP will have more loads available in its respective "pool".

3.4.3.3 Case III: Maximum Proportion of PtP Loads and RP Fixed Installation Costs

When the maximum proportion of PtP loads is allowed to increase, the number of loads dispatched through the RN may decrease and cause fewer RPs to be opened. Increased fixed capital costs may have a similar effect, decreasing the number of RPs opened since the cost of the network is tied to fixed capital costs. However, what would be worth investigating would be which of these factors—the maximum proportion of PtP loads or RP fixed capital costs—has the greatest effect on the number of RPs opened. Understanding this relationship could better help decision-makers decide how to approach the design of the network. For example, if fixed capital costs have greater effect on the number of RPs opened then decision-makers will need to focus efforts on minimizing capital costs in their implementation. If, however, the maximum proportion of PtP loads has greater influence on the number of RPs opened then decision-makers may be able to afford greater flexibility over fixed capital costs.

3.4.3.4 Case IV: Minimum Volume to Open an RP and PtP Repositioning Costs

With greater minimum volume required to justify opening an RP, fewer RPs are likely to be opened. With fewer RPs open, more loads must be dispatched PtP. While minimum volume to open RPs may not imply changes to per-mile PtP repositioning costs, the opposite implication may be true. Increasing PtP repositioning costs, for example, may cause more loads to be dispatched via the RN and as such the minimum volume required to open an RP may become irrelevant at high volumes especially.

3.4.4 Execution of the Experiment

The computational experimentation was carried out on a 64-bit Windows system, with 8.00 GB RAM and an Intel Core i5-2500 CPU at 3.30 GHz. Random replications of the networks under study were generated using Python 2.7.

Since analysis was conducted using ANOVA tables that assume normality, a t-distribution was applied to approximate the minimum number of (network) replications needed (Box et al., 2005). Assuming a 95% confidence interval and a 5% half-width precision, the number of replications was approximated using the following equations (11) – (13).

$$L = t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}} = z_{1-\alpha/2}\frac{s}{\sqrt{n}} \tag{11}$$

Rearranging,

$$n = z_{1-\alpha/2}^{2}\left(\frac{s^2}{L^2}\right) \tag{12}$$

Where,

$$L = 0.05 * \bar{x} \tag{13}$$

To determine the actual required number of replications for our experimentation, ten replications of a “base” network (as discussed in Vergara and Root (2013)) were run for a 100 node network at 20% O-D pair density. Table 3 summarizes the results of these experiments when using the low levels for all of our design parameters.

With an average of 2.17 minutes and a sample standard deviation of 0.0989 minutes, the number of replications evaluated to 3.17 (rounding up to 4 replications). Five replications were chosen for the final experiment for a higher confidence level.

Table 3: Summary of Base Network Parameters and Results

Replication	**Solution time (min)**
1	2.20
2	2.26
3	2.19
4	2.05
5	2.20
6	2.04
7	2.23
8	2.33
9	2.03
10	2.25
Average	**2.17**
Sample Standard Deviation	**0.0989**

3.4.5 Analysis of the Experimental Results

Multiple analytical tools are available to analyze the results obtained from a factorial design experiment. Statgraphics Centurion XVI was the primary tool used to conduct this analysis.

Since analysis tools such as ANOVA assume normally-distributed response variables, these variables were first tested for normality and independence. Several graphing tools are available to measure the normality via visual inspection, such as normal probability plots and the plots of residuals versus predicted values (Box et al., 2005). These graphs also include quantifiable measures such as skewness and kurtosis. When these tools indicated non-normality; transformations were applied to achieve sufficient normality. Measures of independence were measured with serialized correlation plots.

Factors were screened via ANOVA according to the “Pool Rule”. As described in Lorenzen et al. (1993), the “Pool Rule” eliminates factors according to two rule-of-thumb criteria: (1) factors that have p-values greater than 0.25, and (2) factors that do not have significant higher-order interactions. For instance, if ABCD has a p-value of 0.67 it would be eliminated provided that ABC and BCD also have p-values greater than 0.25. If ABC has a p-value of 0.15, ABCD would need to be retained in the experiment. However, common-sense is always relevant in the analysis. Using p-values mechanically bears the risk of removing potentially valuable or influential factors, while failing to dismiss factors that would never have real-world significance.

Lastly, investigation of interactions was accomplished with normal probability plots of the residuals and interaction plots. These graphs combine normal probability plots with bar charts of the levels of significance of the factors. These visuals can be especially helpful weighing the relative significance of the factors. Interaction of factors was ascertained by visual inspection of interaction plots, looking for crossed lines or parallel lines. However, like all other visuals, the scale of the axes must be taken into consideration—depending on how the graph is scaled, effects can appear more or less noticeable to the eye (Box et al., 2005).

4 ANALYSIS OF COMPUTATIONAL EXPERIMENT RESULTS

In this section, the results of the computational experiment are analyzed in terms of the response variables: solution time (Section 4.1), number of RPs opened (Section 4.2), and solution cost (Section 4.3). Additionally, the interactions of interest discussed and hypothesized in Section 3.4.3 are revisited and evaluated (Section 4.4). Throughout these sections, the factors are coded alphanumerically, and for convenience they are summarized again in Table 4.

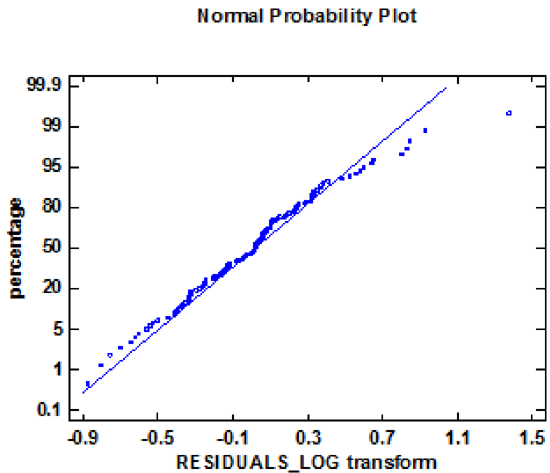
Table 4: Factor Codes and Levels

Factor Code	Factor
A	Percentage of imbalance allowed
B	Minimum volume required to open an RP (as a percentage of total volume)
C	Percentage of PtP loads allowed
D	PtP repositioning costs (as a per-mile surcharge)
E	Fixed cost to install RPs (as a multiplier of $10,000)

4.1 Effects on Solution Time

Initial inspection of assumptions for normality with normal probability plots of residuals indicated departure from normality in the response *solution time* (in minutes). To correct for non-normality, the data was transformed using the natural logarithm function. The normal probability plot of residuals of the transformed data and the summary statistics are presented in Figure 9.

Using the ANOVA table to sort factors by significance of their p-values (p-value less than 0.05) revealed that percentage of imbalance allowed, minimum volume required to open RPs, maximum proportion of PtP loads allowed, and fixed costs to install RPs had a significant effect on solution time; only PtP repositioning costs had no significant effect on solution time. This analysis also uncovered significant two-way interactions between the factors, and these interactions are summarized in Table 5. Interaction plots of these two-way interactions are displayed in Appendix A, Figure A.1.



Summary Statistics for RESIDUALS_LOG transform	
Count	125
Average	1.15E-08
Median	0.019448
Standard deviation	0.370143
Coeff. of variation	3.23E+07
Minimum	-0.87124
Maximum	1.37484
Range	2.24608
Stnd. skewness	2.15854
Stnd. kurtosis	2.63984

Figure 9: Normal Probability Plot of Residuals for Transformed Computational Time

Table 5: Significant Effects on Solution Time

Main Effects	Two-Way Interactions
A: Imbalance Allowed	AE
B: Min. Vol. to Open RPs	BC
C: Max PtP Loads Allowed	BE
E: Fixed Cost of RPs	

4.2 Effects on Number of RPs Opened

Inspecting the response *number of RPs opened* using normal probability plots of the residuals revealed departures from normality. The data was transformed using the natural logarithm function, as illustrated in Figure 10. With this transform, both the skewness and kurtosis were within the range expected for a normal distribution.

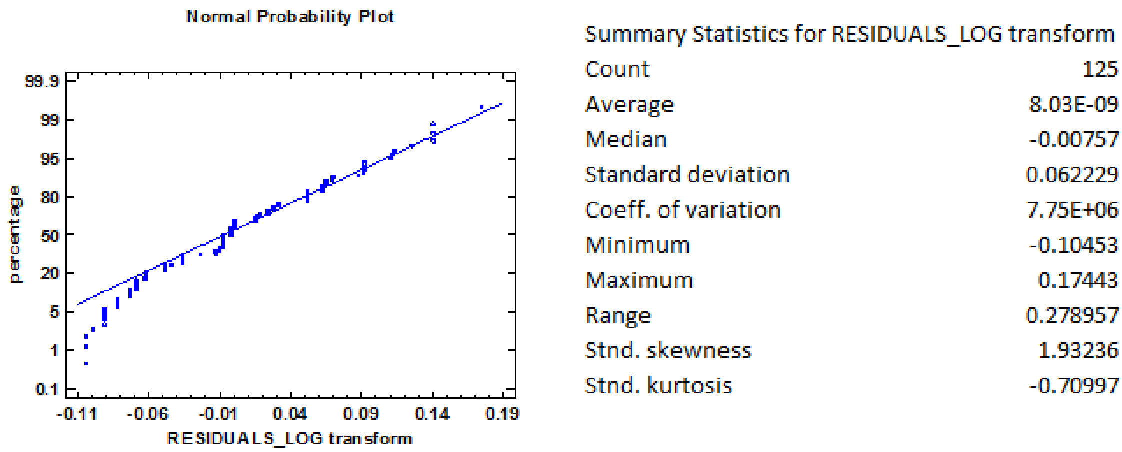


Figure 10: Normal Probability Plot of Residuals for Transformed Number of RPs Opened

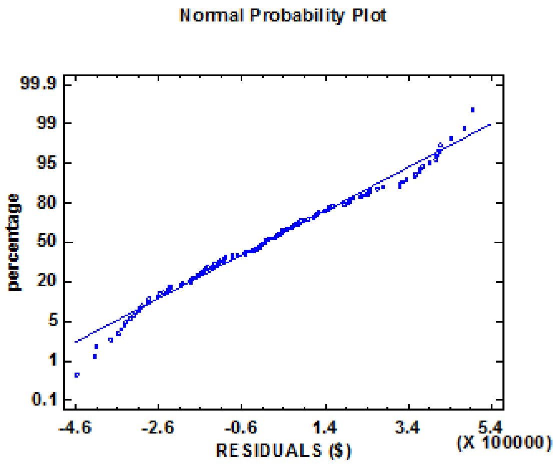
Using ANOVA tables to eliminate factors with p-values less than 0.05 revealed that the minimum volume required to open an RP, maximum proportion of PtP loads allowed, and fixed cost to install RPs had significant effects on the number of RPs opened. Significant two-way interactions were also uncovered in this analysis, and these are summarized in Table 6. Interaction plots of two-way interactions are displayed in Appendix A, Figure A.2.

Table 6: Significant Effects on Number of RPs Opened

Main Effects	Two-Way Interactions
B: Min. Vol. to Open RPs	BE
C: Max. PtP Loads Allowed	CE
E: Fixed Cost to Install RPs	

4.3 Effects on Solution Cost

Normal probability plots of the residuals of the response *solution cost* (in dollars) revealed normally-distributed data, as illustrated in Figure 11. No transformations were applied to the data.



Summary Statistics for RESIDUALS_untransformed	
Count	125
Average	-0.00936
Median	-4731.4
Standard deviation	229505
Coeff. of variation	-2.45E+07
Minimum	-457543
Maximum	494992
Range	952535
Stnd. skewness	0.896443
Stnd. kurtosis	-1.69874

Figure 11: Normal Probability Plot of Residuals for Solution Cost

Using ANOVA tables to eliminate factors with p-values less than 0.05 revealed that the maximum proportion of PtP loads allowed and the fixed cost to install RPs had significant main effects. Only one two-way interaction—between the maximum proportion of PtP loads allowed and the fixed cost to install RPs—had a significant effect on solution cost. These results are summarized in Table 7 below, and the interactions plot is displayed in Appendix A, Figure A.3.

Table 7: Significant Effects on Solution Cost

Main Effects	Two-Way Interactions
C: Max. PtP Loads Allowed E: Fixed Cost to Install RPs	CE

4.4 Discussion of Cases of Interest

In Section 3.4.3, four cases of interest were presented for this research. The results of these experiments are now weighed for each of these cases.

4.4.1 Case I: Maximum Proportion of PtP Loads and Equipment Imbalance Allowed

Previously, it was hypothesized that the maximum proportion of PtP loads allowed and the percentage of equipment imbalance allowed would significantly affect the number of RPs opened in the network. This was based on the assumption that allowing fewer PtP movements would result in opening more RPs, which would in turn decrease the number of loads available for each RP and therefore restrict the ability of the network to obtain equipment balance. The results from our experiments show no significant interactions between these factors for the number of RPs opened, solution time, or solution cost. Individually, these factors do significantly increase solution time; however, unlike previously believed, their interaction does not affect the number of RPs opened in the network significantly.

4.4.2 Case II: Minimum Volume to Open an RP and Equipment Imbalance Allowed

There was interest in understanding if minimum volume required to open an RP and percentage of equipment imbalance allowed together had significant effects on the number of RPs opened. For similar reasons to Case I, enforcing high minimum volume requirements to open RPs was hypothesized to decrease the number of RPs opened, which would increase the number of loads available for each RP and therefore facilitate balancing equipment at the nodes in the network. However, our analysis reveals no significant interaction between these factors. Minimum volume requirements alone do affect the number of RPs opened, but equipment balance requirements have no such effect.

4.4.3 Case III: Maximum Proportion of PtP Loads and RP Fixed Installation Costs

The interaction between maximum proportion of PtP loads allowed and installation costs was believed to have significant effect on the number of RPs opened under the presumption that increasing installation costs and increasing the maximum proportion of PtP loads allowed would discourage opening RPs. Our analysis supports this hypothesis, as the interaction of these factors has significant effects on the number of RPs opened, and there is also a significant effect on solution cost. Understandably, interactions that increase the number of RPs opened will also increase the overall network cost.

4.4.4 Case IV: Minimum Volume to Open an RP and PtP Repositioning Costs

The interaction between minimum volume required to open RPs and PtP repositioning costs was predicted to have a significant effect on the number of RPs opened, under the assumption that decreasing the minimum volume requirement and that increasing PtP repositioning costs would open more RPs. However, analysis reveals no significant interaction effects of these factors on solution time, solution cost, or the number of RPs opened. Individually, minimum volume required to open RPs had significant effects on all measures and supports this initial reasoning. However, PtP repositioning costs only had a significant effect on solution cost in the high RP fixed installation cost case and had no effect on the number of RPs opened.

4.4.5 Other Significant Interactions

Three interactions between design factors that were determined to be significant in our analysis were not considered in the cases above. These are the interaction between percentage of equipment imbalance allowed and fixed cost of installation of RPs, the interaction between the minimum volume to open and RP and maximum proportion of PtP loads allowed, and the interaction between minimum volume to open an RP and the fixed cost of installation of RPs.

Equipment imbalance allowed and fixed costs of installation of RPs have a significant interaction effect on solution time, possibly because as fixed installation costs increase, the number of RPs opened decreases and the difficulty to attain balance in the network increases.

Minimum volume to open an RP and the maximum proportion of PtP loads allowed have a significant interaction effect on solution time. This is likely due to these factors being correlated negatively. If the minimum volume to open an RP increases but the maximum proportion of PtP loads allowed decreases, then it would be more difficult to even find feasible solutions and therefore computational time would increase.

Minimum volume to open an RP and fixed cost of installation of RPs have a significant interaction effect on both solution time and the number of RPs that are opened. An increase in the minimum volume required to open an RP, similar to an increase in the fixed costs of installing RPs, results in fewer RPs to be opened and this affects finding feasible solutions such that the solution time of the problem is increased.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The objective of the current research was to investigate the interaction effects of design factors used in the mathematical and solution approach for the TLRND-MD problem presented by Vergara and Root (2013). The responses of interest were model performance (solution time) and solution quality (number of RPs opened and solution cost). The design factors under study included maximum imbalance allowed, minimum volume required to open RPs, percentage of PtP loads allowed, PtP repositioning costs, and fixed installation costs for RPs.

As mentioned above, solution time is a measure of model performance. All design factors, except for PtP repositioning costs, significantly affected solution time. Further, minimum volume required to open an RP and percentage of PtP loads allowed are negatively correlated. Increasing the minimum volume required to open RPs results in network designs where an increasing number of loads are dispatched PtP. Finding feasible solutions that satisfy this constraint will be computationally more difficult if stricter restrictions are placed on the number of PtP loads that can exist in the RN. Note, however, as described below that this interaction between the minimum volume required to open an RP and percentage of PtP loads allowed does not significantly affect the number of RPs opened.

In addition to model performance, we also considered responses related to solution quality (characteristics of the resulting network designs). The number of RPs opened in the network was one of these responses. Our analysis determined that the interaction between the minimum volume required to open an RP and percentage of PtP loads allowed was not significant for the number of RPs opened because the fixed costs of installing RPs had a greater effect. Ultimately, while initial network topology (i.e. the location of potential nodes and the arcs connecting nodes) affects the feasibility of opening an RP the most, the fixed cost of installing RPs has a very significant effect on whether a RP is opened and subsequently how many RPs are opened in the network. With larger fixed costs of installation of RPs, the number of RPs opened in the network reduces regardless of the interaction between minimum volume required to open an RP and the percentage of PtP loads allowed throughout the network. As such, it is the interaction of these factors with fixed RP installation costs—and not with each other—that affects the number of RPs opened.

Finally, another measure of solution quality considered in our study is the solution cost (i.e. the total transportation and installation cost associated with a resulting network design). One interaction—that between the maximum proportion of PtP loads allowed and the fixed cost of installation of RPs—had a significant effect on solution cost. When fewer PtP loads are allowed in the network, then more traffic must travel through the RN; subsequently, more RPs need to be opened which results in an increase in the cost of the network.

Four cases of interest were investigated in this research. Only one of these four cases—that of the interaction between the maximum proportion of PtP loads allowed and the fixed installation costs of RPs—has significant interaction effects on any of the response variables. In this case, the interaction of these factors was significant on the number of RPs opened and solution cost.

Other interactions were found to have significant effects on solution time and the number of RPs opened, that were not considered in the cases investigated. Solution time was affected by the interactions between equipment imbalance allowed and fixed cost of installation of RPs, and between minimum volume to open and RP and maximum proportion of PtP loads allowed. Both solution time and the number of RPs opened were affected by the interaction between the minimum volume to open an RP and the fixed cost of installation of RPs.

5.2 Future Work

Many limitations of the current research present opportunities that merit future investigation.

In this paper, all nodes (i.e. locations of origins, destinations and potential locations for RPs) were uniformly distributed over a rectangular area. Researching how changes in topology affect the significance of design factors may provide valuable insights into real cases where cities tend to be clustered.

There are also opportunities to investigate the interaction effects of network size with other design factors on solution time, number of RPs opened, and solution cost. Additionally, the limitations on the distances defining local and lane movements that were fixed in this research may affect how the network is constructed and the performance of the modeling and solution approach proposed by Vergara and Root (2013). A more strict limitation results in fewer feasible routes through the RN which reduces the size of the model, but might affect the ability to find a solution depending on the limitations for other design factors such as minimum volume to open RPs and maximum proportion of PtP loads allowed. On the other hand, a more relaxed limitation increases the size of the model significantly which directly affects solution time and might affect the network configuration as well as fewer RPs would be required.

Finally, this research also assumed fixed per-mile transportation costs; worth investigating may be the effect of variable per-mile costs; for example, how costs vary near cities with high traffic density versus areas with lower traffic density and what is their effect on model performance, network configuration, and solution cost.

The ultimate hope of this research is to help carriers prioritize how to allocate their resources implementing RNs that will ultimately decrease driver turnover.

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7 APPENDIX A: INTERACTION EFFECTS PLOTS

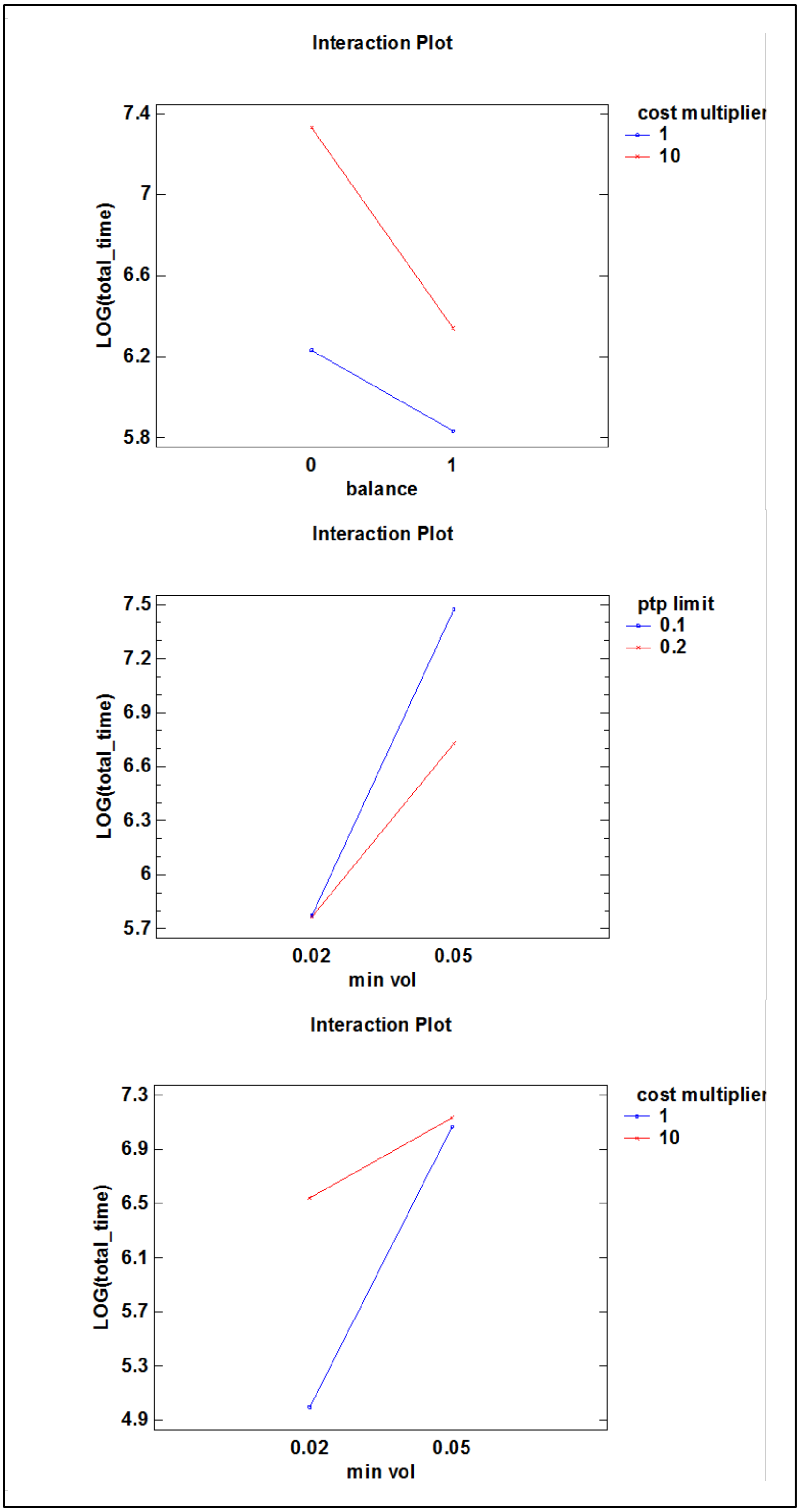

Figure A.1: Interaction Effects on Solution Time

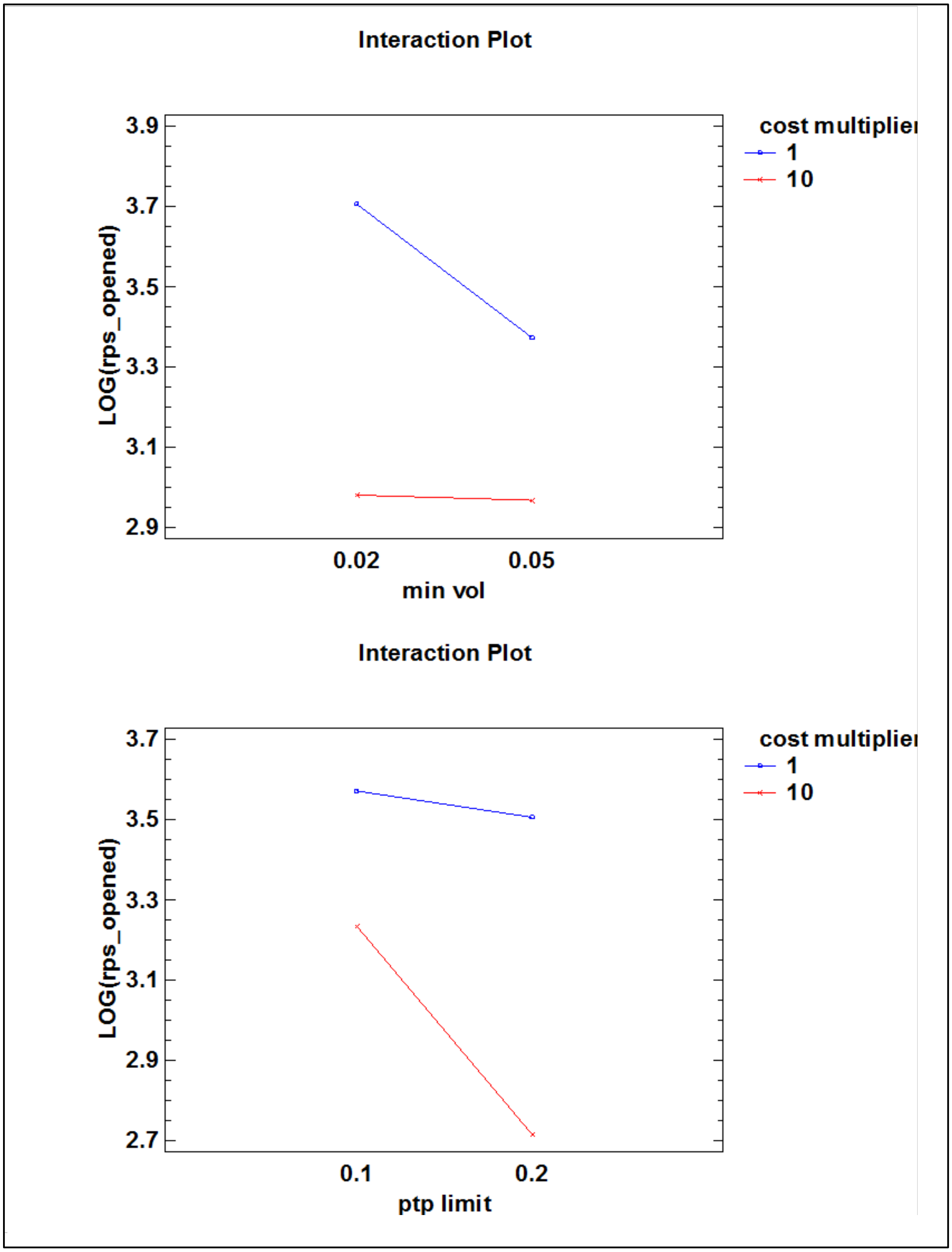

Figure A.2: Interaction Effects on Number of RPs Opened

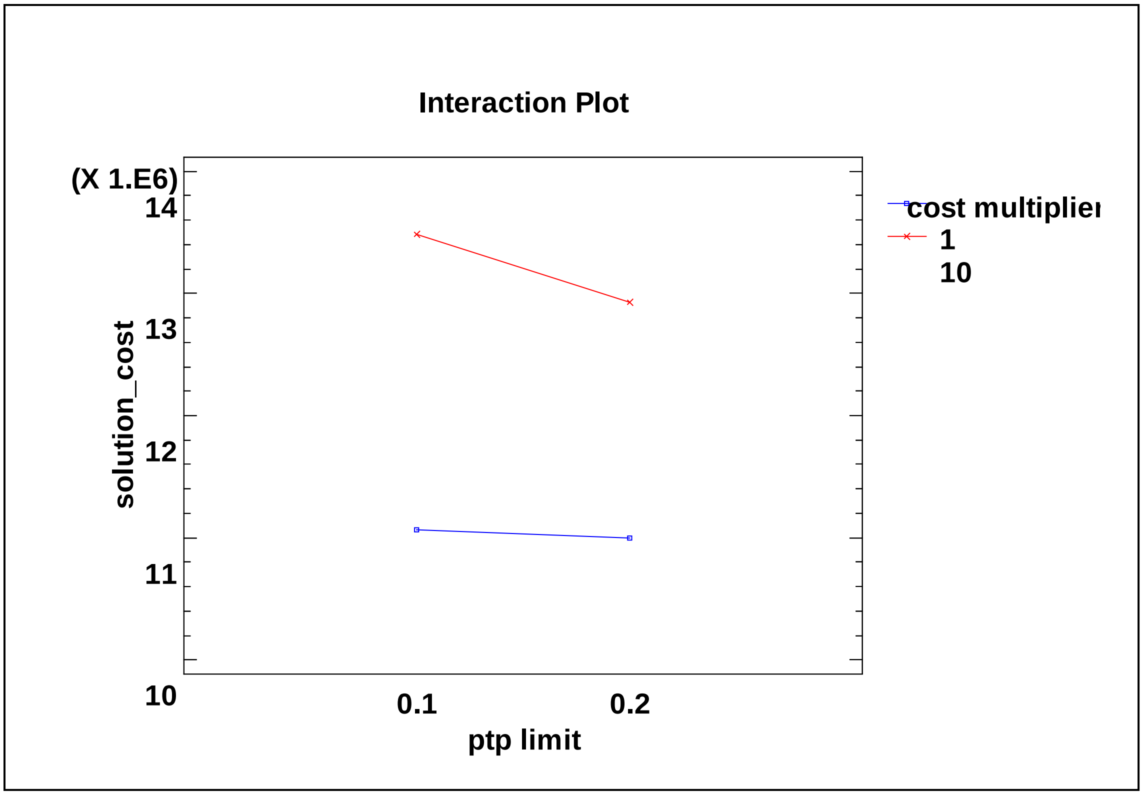

Figure A.3: Interaction Effects on Solution Time