A NETWORK DESIGN MODEL FOR MULTI-ZONE TRUCKLOAD SHIPMENTS

A Thesis

by

NIMISH MAHESHWARI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Industrial Engineering

A NETWORK DESIGN MODEL FOR MULTI-ZONE TRUCKLOAD SHIPMENTS

A Thesis

by

NIMISH MAHESHWARI

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Approved as to style and content by:

Halit Uster (Chair of Committee)	Brett A. Peters (Member)
Harold A. Love (Member)	Brett A. Peters (Head of Department)

December 2004

Major Subject: Industrial Engineering

ABSTRACT

A Network Design Model for Multi-Zone

Truckload Shipments. (December 2004)

Nimish Maheshwari, B.E., Punjab Engineering College

Chair of Advisory Committee: Dr. Halit Uster

Truckload shipments constitute a significant portion of the freight transportation industry. In recent years, truckload industry is facing a serious problem of high driver turn over rate. In this research, we present a mathematical model for multi-zone dispatching method to solve this issue. Multi-zone dispatching is a method in which a service area is divided into many zones. Truckload within a zone is carried by local drivers and the truckload between zones is carried by lane drivers. Apart from reducing the driver tour length to a desirable level, the model for multi-zone also contains some unique constraints to address some issues from the perspectives of the company and the customer. The binary integer program is solved by exact methods. As the problem size increases, exact methods fail quickly. Hence, a construction heuristic within tabu search framework is developed to solve the model. Analysis of various parameters concerned is provided to gain better insights of varied aspects of the problem. Computational results for analysis of parameters and comparison of exact and heuristic methods are provided.

To my parents

ACKNOWLEDGMENTS

The author thanks his advisor Dr. Halit Uster, Department of Industrial Engineering, Texas A&M University, for his helpful guidance and educational contributions.

TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Truck is a major mode of freight transportation in United States. Trucking industry accounts for 75% of total freight expenditure in US (Chopra and Meindl 2002). The trucking industry consists of two parts: full truckload (TL) and less-than-truckload (LTL). While the less-than-truckload shipments serve a wide range of customers ranging from individual users to large corporations of any kind, truckload shipping is suited for transportation between manufacturing facilities and warehouses or between suppliers and manufacturers or manufacturers and distributors. For example, GM supplies cars to distribution centers.

Truckload operations have low fixed cost. One can easily enter the market by owning a few trucks. Hence, truckload trucking is a fiercely competitive industry. It consists of hundreds of carriers, each with its own characteristics. They mainly differ in terms of size, Operating and managing policies (Taha and Taylor 1994). One of the largest publicly held company in truckload industry is J.B. Hunt, which operates all over US. Some other truckload companies operating throughout US are Ryder Integrated, Werner, John Fayard / Fastway Systems, Schneider National, etc.

Traditionally, a truckload shipment between two points takes place via direct route using a single driver. This is called point-to-point dispatching of truckloads. However, point-to-point dispatching causes a very long driver tour length. The large driver tour lengths keep the driver away from home for a long time and eventually may cause them to quit their jobs. This results in a very high driver turn over rate, which can be as high as 85% - 110% (Taylor et al. 1999). Contrary to this, the

---

This thesis follows the style and format of *Operations Research*.

driver turn over rate are quite low in less-than-truckload industry. In the less-than-truckload case, hubs are utilized along with two types of drivers, namely the lane and local drivers. The lane drivers are responsible for carrying the load from hub-to-hub and the local drivers are responsible for carrying the load from hub to destination or from source to hub. Therefore, both the local and lane driver tour lengths are much shorter in less-than-truckload industry. In particular, Taylor and Meinert (2000) reported the local driver turnover rate to be 4.5% and lane driver turnover rate to be 10% for Yellow Freight.

Taylor et al. (1999) and Taylor and Meinert (2000) state that the factors affecting the service performance in the truckload industry can be viewed from the points of view of the (1) company, (2) customer and the (3) driver.

1. From the driver point of view, the parameters are:

    - Tour length: For point-to-point dispatching the tour length is defined as the total distance travelled by the driver to deliver a load from its source to destination. Tour length for a local driver is defined as the distance from node-to-hub or hub-to-node. For the lane driver, tour length is defined as the distance between two hubs.
    - Miles per driver per day: Total miles travelled by the driver per day. It is directly proportional to the earnings of the driver.
    - Job quality: Determined by route regularity and get home rates. Route regularity means the consistency of the tour length to which driver is assigned daily.

    The most important of the above criteria is the tour length because it largely determines the job satisfaction of the driver and hence is a major factor in determining driver turnover rate (Taylor and Meinert 2000).

2. From the company's point of view the major factors are cost and service. Service defines the market share of a company. High quality service means on-time pick up and delivery. On the other hand, cost has two major components:

    - Percentage Circuitry: The percentage of additional distance a load travels over and above the point-to-point distance. Excess circuitry causes load to travel more miles than desired and hence results in extra cost.
    - First Dispatch Empty Miles: The amount of miles that the truck runs without carrying any load. This can be when the truck is going to pick-up the load from the source or when it is returning to its place (hub) after delivering the load to its destination.

3. From the customer's point of view, the factors determining the performance metrics are:

    - The total delivery time (the flow time) : The total time since the load was picked up at the source until it was delivered to final destination.
    - Cost associated with the shipment.
    - Reliability : Determines how reliable the service of the truckload carrier is in terms of safety. Issues related to theft and carriage handling (properly delivering the shipment without damage) are considered.

From the above factors we take only some factors which impact the company, customer and driver. For the driver, we only consider the tour length. For the company, we consider circuitry and load imbalance. As will be illustrated in chapter III, low value of load imbalance results in low first dispatch empty miles. From the customer point of view, we do not consider any factors directly, however, since the total delivery time is directly related to dispatching method, we will chose a dispatching method such that the total flow time will be reduced. Cost of the shipments for the customer depends upon the cost incurred by the company. Since we consider the factors affecting the cost to the company, we do not include additional constraint for customer shipments cost. Reliability as defined is difficult to measure quantitatively, and is more on operational side, hence we do not take it into account.

A multi-zone dispatching method can prove to be very effective in reducing driver tour length and hence solve the driver retention problem in truckload industry. Some concepts of this model was developed by Taylor et al. (2001), as described in chapter II. If some additional constraints are added, the model can take care of several factors from the three different perspectives of the driver, company and the customer. The method and the additional constraints will be discussed in detail in chapter III.

A. Motivation

There is no model in our knowledge that addresses the issue of driver tour length in truckload industry. An analytical model especially addressing this issue would be of immense help to the companies like J.B.Hunt who spend significant amount of money in driver training and recruitment every year. Further, we consider the effects of various factors, such as circuitry and load imbalance, that take into account different perspectives of the company and the customer. The analysis of these parameters will help in better understanding of trade offs involved between various competing factors and hence will help company to provide high quality service to the customer at low cost.

B. Objective

The objectives of this research are to (i) formulate a mathematical model for the multi-zone dispatching method, (ii) formulate and analyze various unique constraints in truckload industry from the perspectives of driver, company and the customer, (iii) provide solution methodologies for the model.

C. Organization of the Thesis

The thesis is structured as follows. Chapter II gives the literature review of hubs and spoke as applied to truckload industry, alternative dispatching methods, zoning and multi-zone dispatching method. Chapter III gives the notation, definition and problem formulation. It also discusses various unique constraints applied to multi-zone dispatching method. Following that, chapter IV discusses both the exact and the heuristic solution procedures to solve the mathematical model. Chapter V provides computational results for comparison of exact and heuristics methods and analysis of the parameters. Finally, Chapter VI gives conclusion and recommendations for future research.

CHAPTER II

LITERATURE REVIEW

This thesis focuses on developing a strategic network for multi-zone dispatching. The structure and configuration of multi-zone is similar to that of hub and spoke networks, which are extensively used in airline and less-than-truckload industries. In addition, multi-zone method also includes some concepts of zoning. In section A, we review hub and spoke networks as applied in the truckload industry. Section B reviews the different dispatching methods in truckload industry. Section C gives briefly the planning problems in LTL industry. Section D discusses some of issues relating to zoning. Finally, Section E reviews the previous work in multi-zone dispatching.

A. Hub and Spoke Networks in Truckload Industry

Hub and spoke problem in most general sense (in airline and less-than-truckload industries) consists of locating number of hubs and assigning nodes to each hub. The objective is to reduce the total fixed and transportation cost. The fixed cost results from location of hubs and transportation cost arises out of routing the load from source node to destination node which passes through hubs. The motivation behind the implementation of hub and spoke model is to obtain economies of scale by consolidating the loads at the hubs. The consolidated load is sent through hubs as opposed to sending individual load directly from source node to destination node. Campbell et al. (2002) and Daskin (1995) discusses different variations of hub and spoke model which include cases of single and multiple allocation of demand point to hubs, capacitated and uncapacitated hub location problems, p-hub problems, p-median problems, and hub covering problems.

Taylor et al. (1995) used HUBNET simulator, a simulation software, to generate different hub scenarios comprising of varied number of hubs, driver tour length restriction and model structure (whether its entirely hub network or point-to-point or a combination of the two (hybrid)). They compared performance of these different scenarios based on different measures like lane driver tour length, local driver tour length, average miles driven per driver per day, first dispatch empty miles and average percentage circuitry. They reported that the number of hubs and their location methodology (distance based, flow based or a combination of the two (hybrid)) are important factors in determining performance in circuitry and first dispatch empty miles. Further, they reported that in general, hybrid strategy performs better. This is because the hybrid strategy provides smaller service areas than distance and flow based hub layout. Hence, circuitry, first dispatch empty miles and driver tour length are reduced, although it also reduces average miles per driver per day.

Hub and spoke implementation in truckload industry has some potential advantages. First, since the truckload carriers has full truckload as a shipment, they do not need freight handling at the hubs. Note that there is no consolidation of loads in truckload industry. Secondly, hub and spoke networks can increase truck utilization which is low in truckload industry (Taha and Taylor 1994). Thirdly, hubbing can reduce the total delivery time by making use of multiple drivers at each transshipment hub. Lastly, and most importantly, hub and spoke networks in truckload industry can reduce driver turnover rate by reducing the driver tour length and increasing route regularity. To design the hub and spoke system, Taha and Taylor (1994) examine the location of existing terminals, load and freight volume and physical space between the hubs, to arrive at the location of hubs, assignments of nodes to hubs and the service areas of the hubs. Initial location of hubs is determined by load volume and geographical distance considerations. The assignment of nodes and the service areas of hubs are determined based on proximity. Lastly, the routing between hubs is decided by using shortest path algorithms.

B. Dispatching Methods

In Taylor et al. (1999), authors compared different dispatching alternatives on the basis of performance metrics of service provider, driver and customer. Authors discuss the following dispatching methods:

- Baseline model: It describes the method in which loads are dispatched through direct point-to-point method.
- Zone model: The dispatching is done by using six zone perimeter hubs (located at the boundary). Zones were divided in accordance with the business sales unit of J.B Hunt Transport.
- Key lane model: This model moves certain percentage of baseline (point-to-point) loads along a well defined delivery lane which has high freight density.
- Key hub model: In this model a single hub is located in the areas of high freight density instead of multiple hubs.
- Hybrid model: This is a combination of key hub and zone models.

They concluded that the zone model performs well in terms of first dispatch empty miles and percentage late hours (this determines customer service) and almost equivalent miles per driver per day but causes more circuitry.

Taylor and Meinert (2000) conducted simulation studies using SIMNET, a simulation software to measure performance of zone model with baseline point-to-point. They compared total flow time which is important from customer point of view and tour length which on the other hand is important from the perspectives of a driver.

They report that the total flow time is lower (better) in zone model as compared to baseline model. This is because of using multiple drivers for a load. The change of drivers takes place at the transshipment points. They also found that the average driver tour length in zone model is shorter than the baseline model.

C. Motor Carriers in Trucking Industry

Delorme et al. (1987) describes the strategic, tactical and operational aspects in motor carriers industry. The strategic issues are concerned with design of transportation system, i.e., finding the type and mix of transportation services offered, territory coverage and network configuration and service quality decision in terms of speed and reliability. The tactical planning issues are related to equipment acquisition or replacement and capacity adjustment as per the demand forecast. The operational level issues are deciding of assignments of drivers to equipments and transportation scheduling. Braklow et al. (1992) developed SYSNET, a large scale interactive optimization system to optimize the routing of system and design of the network. Magnanti and Wong (1984) gives a good survey of network design models and algorithms.

D. Zoning

Ahituv and Berman (1988) define zoning as the process by which a network is partitioned into smaller networks each of which is delegated with a certain degree of autonomy, in terms of resource allocation and operation. They state following guidelines to set up zones:

- Demand Equity: Division done on the basis of equal demand generated.

- Contiguity: A division is contiguous, if it is possible to travel from every node in the subnetwork to every other node in it, without crossing another subnetwork.
- Compactness: Edges of the zone are not far from each other.
- Avoidance of Enclaves: An enclave is a subset of nodes not formed as zone due to equity criterion and cannot be included with other zones due to non-contiguity.
- Additional criterion: such as natural and administrative boundaries.

For our purposes, instead of demand equity, we consider load imbalance as zoning criterion as would be cleared in next section. Further, our design will ensure contiguity, compactness and avoidance of enclaves.

E. Multi-zone Method

Taylor et al. (2001) compared various configuration of multi-zone dispatching method with the baseline OTR (on the road) method and with baseline multi-zone model. In baseline multi-zone dispatching method, zones were divided in accordance with the sales regions of J.B. Hunt transport. Each zone was configured to have many hubs (transhipment points), which are mostly located at the boundary of the zones. They introduced following alternative configurations for the baseline multi-zone method:

- Reducing the number of hubs: This scenario deletes some of the existing hubs that are underutilized.
- Reducing number of zones
- Allowing low circuitry: In this scenario, an upper limit is set up for the maximum circuitry that a load can undergo. If the load has more circuitous path than allowed it is shipped by point-to-point method.

- Minimum imbalance: In this scenario zones are divided such as to minimize the imbalance (load going out - load coming in) for a zone.

Taylor et al. (2001) compared them in accordance with average driver tour length, flow time and zone boundary imbalance. It was found that the minimum imbalance criterion produced the shortest driver tour length, almost equal flow time as compared to zone baseline scenario, and of course, minimum imbalance.

CHAPTER III

PROBLEM DEFINITION AND FORMULATION

In this chapter, we first define multi-zone dispatching in section A. Next, we give the definition of our problem in section B. Section C discusses various constraints of the model in detail. Section D gives the complete model with the objective function and all the constraints. Finally, section E describes a generalized model for both point-to-point and multi-zone dispatching.

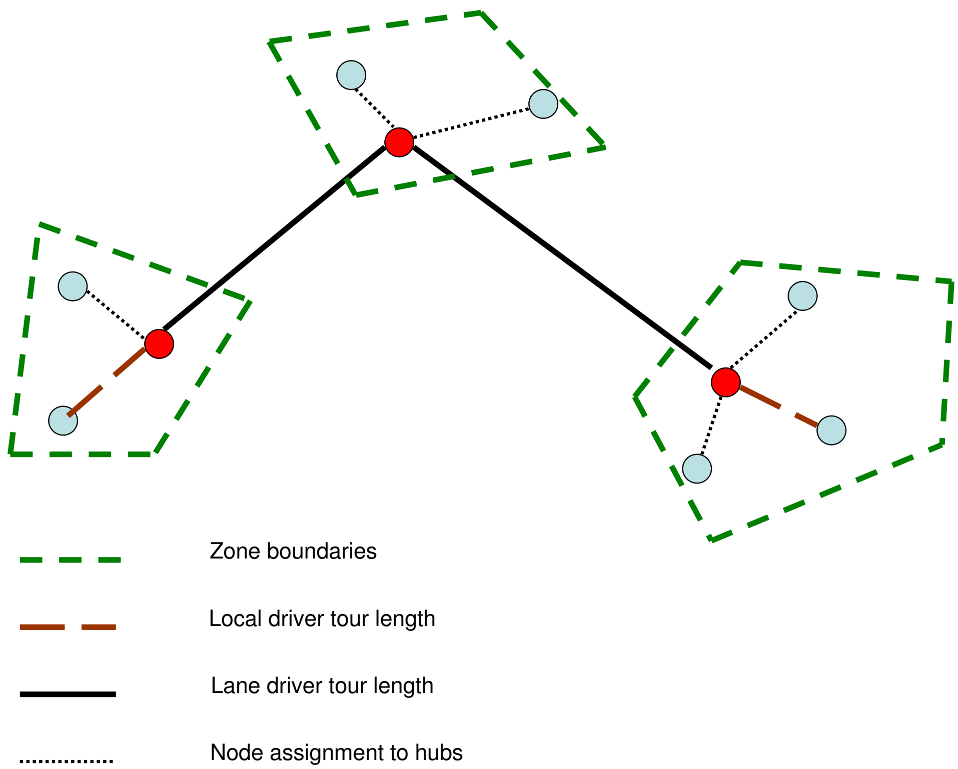
A. Multi-zone Dispatching

Multi-zone dispatching is a method in which a geographical area is divided into several zones. A zone comprises of a single hub and nodes assigned to the hub. Loads originating in a zone has to pass through various hubs (zones) before reaching its destination point, unless the destination is within the zone itself. Loads within the zone are carried to and from the hub by local drivers. Loads between hubs are carried by the lane driver. Figure 1 shows the lane and local driver tour length.

Following are the important points that describe the structure and configuration of multi-zone dispatching.

- Driver tour length is an important factor in determining the retention of the driver in the company. It can be of two types, i.e., lane driver tour length and the local driver tour length. Minimum imbalance results in shorter driver tour length (Taylor et al. 2001). Hence, we try to keep load imbalance to a low level.
- Zone boundaries are defined by the nodes assigned to a hub and each zone has only one hub. Each node is uniquely assigned to a hub. Any load originating at a node has to go to a hub or a series of hubs before reaching to its destination

Figure 1. Multi-zone model defining driver travel



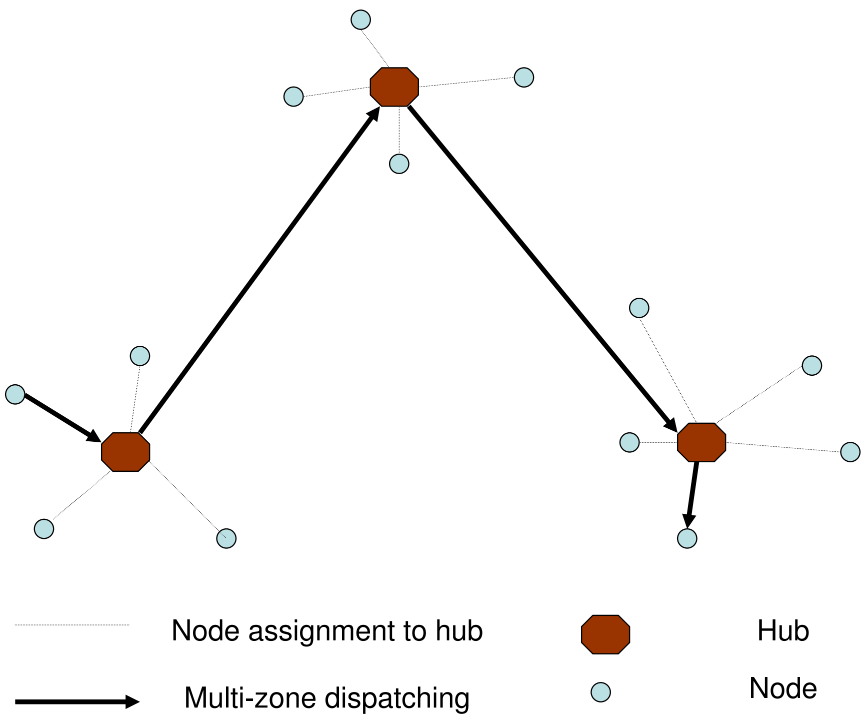
node. Hubs are actually transhipment points where driver carrying the load is changed.

- Location of hubs and the assignment of nodes to the hubs depend upon the driver tour length constraints, load imbalance constraints and the circuitry constraints.

Figure 1 shows, how zones are defined and how local and lane driver travel internally and across the zone, respectively. Figure 2 shows how nodes are assigned to hubs, and a sample truckload dispatch.

In Figures 1 and 2, we can easily see that the multi-zone model with each zone having a single hub, is similar to hub and spoke model with several additional con-

Figure 2. Hub and spoke model



straints.

B. Problem Definition

Given the demands (loads) between pairs of points and candidate location of hubs, we develop a network design model to determine the locations of hubs, assignment of nodes to the hubs (and hence determine the zone boundaries) and actual truckload routes so that the total transportation and fixed hub location costs are minimized. In doing so, the model satisfies local and lane driver tour length constraints along with a desirable load imbalance and percentage circuitry levels.

C. Model Formulation

In this section, we provide details of the model formulation. The model is a binary integer program that builds on hub and spoke model for network design (Campbell et al. 2002). Important differences include additional constraints for load imbalance, percentage circuitry and driver tour length and routing of the load through several hubs instead of two hubs. Some structural constraints similar to some structural constraints in hub location problems are also included.

1. Parameters and Decision Variables

Let $\mathcal{N}$ denote the set of nodes, $\mathcal{N} = \{1....n\}$. D_{ij} denotes the demand associated with a node pair (i,j) and d_{ij} represents the distance between them. Let γ_1 be the maximum permissable distance between a hub and a node assigned to it, i.e., γ_1 relates to the local driver tour length. Let γ_2 be the maximum permissable distance between any two hubs, i.e., γ_2 relates to the lane driver tour length. Further, let β be the maximum acceptable percentage circuitry and δ be the maximum acceptable percentage load imbalance associated with a zone. Lastly, let F_k denote the fixed cost of locating a hub at a candidate node $k \in \mathcal{N}$.

In order to represent the hub locations and the assignment of the nodes to hubs, we define a binary decision variable X_{ik}, which takes the value of 1 if the node i is assigned to a hub at node k and 0 otherwise. In addition, to determine the route followed by an individual load, we define another binary decision variable Y_{kl}^{ij}, which takes the value of 1 if the load originating from a source node i destined to a node j is transferred through a hub-to-hub link (k, l) and 0 otherwise. Note that a load originating at node i can be transferred through several hub-to-hub links before it reaches to its destination node j.

2. Objective Function

The following represents the objective function:

$$\sum_i \sum_k \psi \, d_{ik} X_{ik} \sum_j \left(D_{ij} + D_{ji}\right) + \sum_i \sum_j \sum_k \sum_l \phi \, Y_{kl}^{ij} \, D_{ij} \, d_{kl} \; + \sum_k F_k X_{kk} \quad (3.1)$$

The first component represents the cost of total transportation from source nodes to hubs and from hubs to destination nodes for all truckloads. The second component represents the total transportation cost on hub-to-hub links, and the third component represents the total fixed cost associated with locating hubs.

Note that we take the cost coefficients ϕ and ψ to be 1 in all the future calculations.

3. Constraints

Next, we present each of the particular constraints that define our problem as well as the required structural constraints in the model.

a. Percentage Circuitry

Percentage circuitry is defined as the percentage of additional distance a load travels between the node pair (i,j) when shipped via multi-zone dispatching instead of direct point-to-point dispatching.

$$D_{ij}\,\big(\sum_k d_{ik}X_{ik}+\sum_k\sum_l d_{kl}\,Y^{ij}_{kl}+\sum_l d_{jl}\,X_{jl}\big)-d_{ij}\,D_{ij}\leq\beta\,d_{ij}\,D_{ij}\quad\forall\,i,j\in\mathcal{N}\quad(3.2)$$

The constraint (3.2) calculates the maximum amount of percentage circuitry that a load between the node pair (i,j) can experience. This is restricted to a maximum value of β. Note that if a load does not exist for a pair of nodes (i,j) then this constraint is automatically nullified for that pair. This is ensured by the inclusion of D_{ij} on both sides of the constraint.

b. Tour Length

Traditionally, tour length is defined as the distance that a driver travels while delivering the load from its source to its destination. However, in multi-zone dispatching the tour length is defined in terms of segments of travel. As defined before, local driver tour length refers to a distance that driver travels for carrying the load on node-to-hub or hub-to-node links, and lane driver tour length refers to the distance that a driver travels for carrying the load on hub-to-hub link.

Constraints (3.3) restrict the local driver tour length to a maximum acceptable value of γ_1 miles. Note that these constraints restrict the maximum distance on node-to-hub link.

$$d_{ik}\, X_{ik} \le \gamma_1 \quad \forall\, i, k \in \mathcal{N}, \tag{3.3}$$

Constraints (3.4) restricts the lane driver tour length to a maximum value of γ_2 miles. Note that these constraints restrict the maximum distance on a hub-to-hub link.

$$d_{kl}\, Y_{kl}^{ij} \le \gamma_2 \quad \forall\, i, j, k, l \in \mathcal{N}, \tag{3.4}$$

c. Load Imbalance

Load imbalance for a zone is defined as the difference between the total incoming and total outgoing load. As mentioned earlier, load imbalance constraints helps in shorter driver tour length for multi-zone dispatching as compared the other dispatching methods. As will be illustrated later, a high load imbalance will cause higher first dispatch empty miles, which are undesirable to both the company and the customer. To the company, it is just an extra deadhead miles with no gain in terms of load movement, and for the customer, large first dispatch empty miles simply means lack of prompt service and a possible increase in delivery time. In addition, the load imbalance has two meanings for a zone. It affects the zone both internally and externally as will be illustrated later in the section.

The following expression gives total outgoing load from a zone represented by a hub $k \in \mathcal{N}$.

$$O_k = \left(\sum_i X_{ik} \left(\sum_j D_{ij} - \sum_j D_{ij} X_{jk} \right) \right) \tag{3.5}$$

and the expression total incoming load to a zone $k \in \mathcal{N}$ is

$$I_k = \left(\sum_i X_{ik} \left(\sum_j D_{ji} - \sum_j D_{ji} X_{jk} \right) \right) \tag{3.6}$$

Traditionally, the load imbalance is calculated as.

$$|O_k - I_k| \tag{3.7}$$

Load imbalance as mentioned by (3.7) has very different meaning for different companies depending upon their market size. A certain value of load imbalance can be acceptable for one company but cannot be acceptable for another company. Hence, instead of controlling the load imbalance in terms of value, we control it by means of percentage deviation, thus we have the following constraint (3.8).

$$|O_k - I_k| \leq \delta_1 \; Max\{O_k, I_k\} \tag{3.8}$$

In (3.8), δ_1 represents the maximum acceptable percentage load imbalance.

We observe that both (3.5) and (3.6) are non-linear expressions. Further, their difference (3.7) is also non-linear. We can utilize following equalities:

$$\sum_i \sum_j D_{ij} \, X_{jk} = \sum_i \sum_j X_{ik} \, D_{ji} \tag{3.9}$$

$$\sum_i \sum_j X_{ik} \, X_{jk} \, D_{ij} = \sum_i \sum_j X_{ik} \, X_{jk} \, D_{ji} \tag{3.10}$$

and rewrite (3.7) as follows:

$$|\sum_i \sum_j X_{ik} \, D_{ij} - \sum_i \sum_j X_{jk} D_{ij}| \tag{3.11}$$

The expression (3.11) needs to be explored in meaning and definition. To understand the meaning of the expression (3.11), we define the following:

- C_1 is the total load originated inside zone k and reaching to hub k. C_1 has two components:
  - C_{12} is the total load having origin and destination within zone k.
  - C_{13} is total load originated in zone k and destined to another zone.
- C_4 is the total incoming load to hub k which originated outside zone k. C_4 has two components:
  - C_{42} be the total load coming from outside of zone k but having the destination within zone k.
  - C_{43} be the load coming to hub k from other zones whose destination is not in zone k.

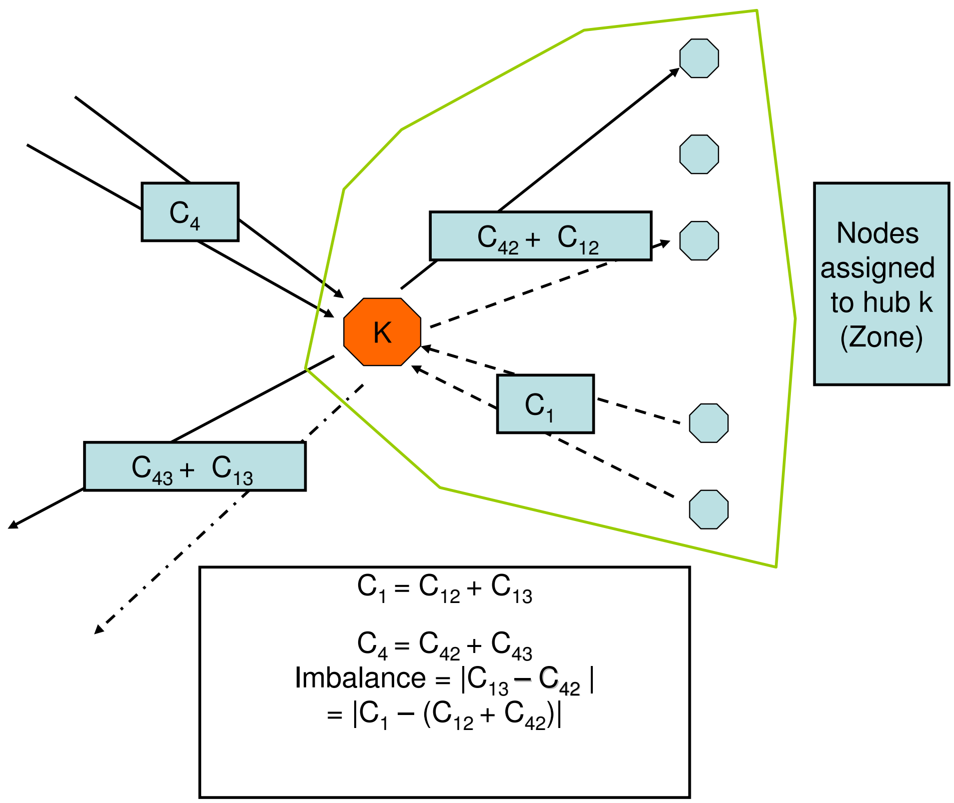
We illustrate the notation in figure 3. Thus, we have

$$C_1 = C_{12} + C_{13} \tag{3.12}$$

$$C_4 = C_{42} + C_{43} \tag{3.13}$$

and the expressions for the components of flow through hub k can be written as follows:

Figure 3. Load imbalance



$$C_1 = \sum_i \sum_j X_{ik} D_{ij} \tag{3.14}$$

$$C_{12} = \sum_i X_{ik} (\sum_j D_{ij} X_{jk}) \tag{3.15}$$

$$C_{13} = \sum_i X_{ik} \big(\sum_j D_{ij}(1 - X_{jk}) \big) \tag{3.16}$$

$$C_{42} = \sum_i X_{ik} \big(\sum_j D_{ji}(1 - X_{jk}) \big) \tag{3.17}$$

$$C_4 = \sum_i \sum_j \sum_m Y^{ij}_{mk} D_{ij} \tag{3.18}$$

$$C_{43} = C_4 - C_{42} \tag{3.19}$$

$$C_{43} = \sum_i \sum_j \sum_m Y^{ij}_{mk} - \sum_i X_{ik} \sum_j D_{ji}(1 - X_{jk}) \tag{3.20}$$

From the above expressions and (3.5, 3.6), we observe that

$$O_k = C_{13} \tag{3.21}$$

$$I_k = C_{42} \tag{3.22}$$

Hence, we have

$$|O_k - I_k| = |C_{13} - C_{42}| \tag{3.23}$$

and adding and subtracting C_{12}, we obtain:

$$|O_k - I_k| = |C_1 - (C_{12} + C_{42})| \tag{3.24}$$

Since we constrain the load imbalance in terms of percentage rather than absolute value, we define the following constraints for load imbalance:

$$|C_1 - (C_{12} + C_{42})| \leq \delta_2 \; Max\{C_1, C_{12} + C_{42}\} \tag{3.25}$$

Using (3.9) and (3.10), we reduce the above constraints to:

$$|\sum_i \sum_j X_{ik}\, D_{ij} - \sum_i \sum_j D_{ij}\, X_{jk}| \leq \delta_2 \;\; Max\{\sum_i \sum_j X_{ik}\, D_{ij}, \sum_i \sum_j D_{ij}\, X_{jk}\} \tag{3.26}$$

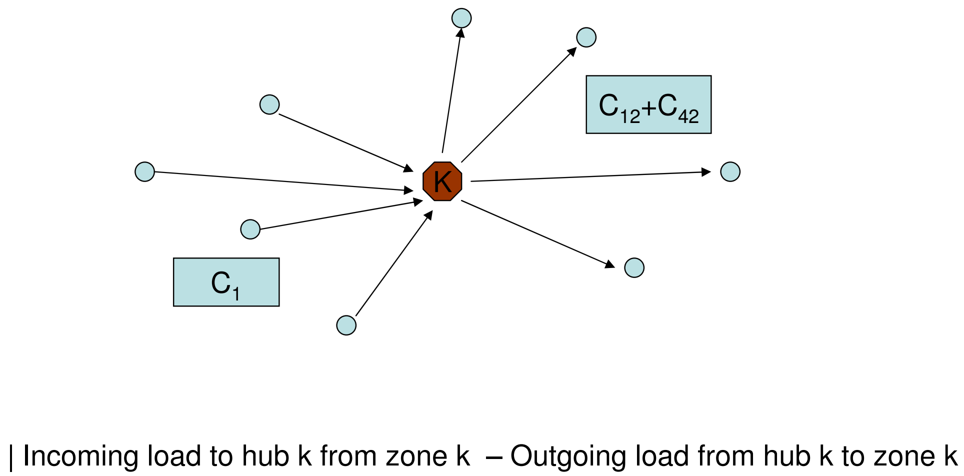
The constraints (3.26) can be written as two linear constraints for the load imbalance as follows:

$$\sum_i \sum_j X_{ik}\, D_{ij} - \sum_i \sum_j D_{ij}\, X_{jk} \leq \delta_2 \;\; \sum_i \sum_j X_{ik}\, D_{ij} \quad \forall\, k \in \mathcal{N} \tag{3.27}$$

$$\sum_i \sum_j D_{ij}\, X_{jk} - \sum_i \sum_j X_{ik}\, D_{ij} \leq \delta_2 \;\; \sum_i \sum_j D_{ij}\, X_{jk} \quad \forall\, k \in \mathcal{N} \tag{3.28}$$

The left hand side of the constraints (3.27, 3.28) represents the difference between total incoming load to the hub k from zone k and total outgoing load from hub k to the nodes within zone k. The quantity on the right hand side constraints the left hand side to a δ_2 percentage amount of the maximum of the two quantities on the left hand side. This shows how the load imbalance affects the zone internally. See figure 4. Note that large load imbalance would cause large value of first dispatch empty miles. In an ideal case for every incoming load on the hub k from zone k, there is an equivalent load from hub k to within zone k. In this case, the local driver delivering the load from hub k to destination node within zone k will pick up the load from any source node within zone k to hub k. This will reduce the first dispatch empty miles unless, the destination node (from hub k) and the source node (having load towards

Figure 4. Internal effects of load imbalance

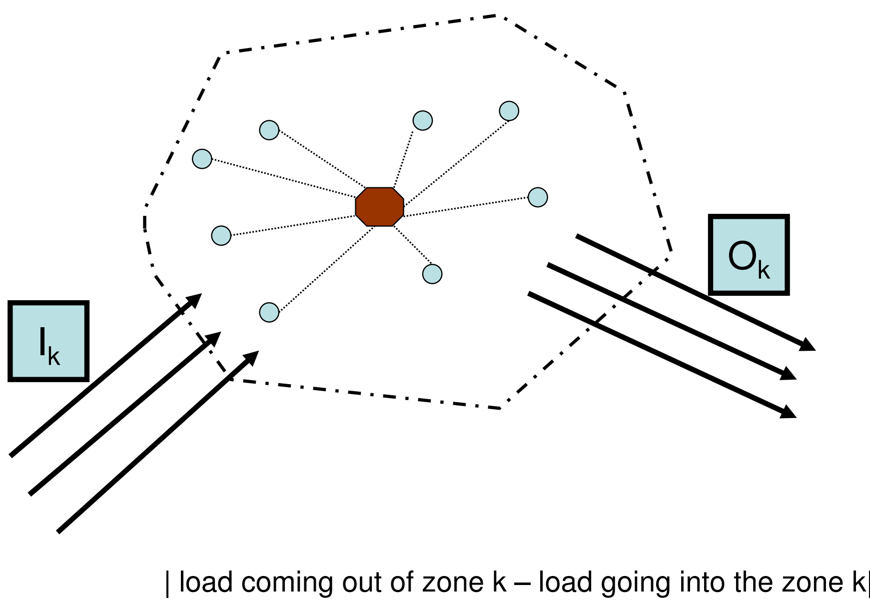


hub k) lies in opposite directions.

On the other hand, the left hand side of constraint (3.8) represents the difference between the total incoming load and total outgoing load for a zone k. The right hand side constraints the left hand side to a percentage amount of maximum of the two quantities on the left hand side. This shows how the load imbalance affects the zone externally. See figure 5.

Note that the left hand side of set of constraints (3.27, 3.28) and the set of constraints (3.8) are the same. This left hand side represents the traditional definition of load imbalance. However, as discussed earlier, we want to control load imbalance in terms of percentage deviation rather than absolute deviation. Hence, we introduced

Figure 5. External effects of load imbalance



δ_1 and δ_2. As the right hand side the of constraint set (3.27, 3.28) is greater than constraint set (3.8), and the left hand side is the same, therefore δ_2 will be smaller than δ_1. Either set of constraints can be used for load imbalance calculations, as per ones criterion of defining percentages. We use the constraints set (3.27, 3.28) because of its linearity on the right hand side. From now onwards, we will denote δ_2 by δ.

d. Hub Conservation

The load at the hub should be conserved.

$$\sum_i \sum_j \sum_m D_{ij} Y_{mk}^{ij} + C_1 = \sum_i \sum_j \sum_l D_{ij}\, Y_{kl}^{ij} + (C_{12} + C_{42}) \quad \forall\, k \in \mathcal{N} \tag{3.29}$$

$$\sum_i \sum_j \sum_m D_{ij} Y_{mk}^{ij} + \sum_i \sum_j X_{ik}\, D_{ij} = \sum_i \sum_j \sum_l D_{ij}\, Y_{kl}^{ij} + \sum_i \sum_j D_{ij}\, X_{jk} \quad \forall\, k \in \mathcal{N} \tag{3.30}$$

Above constraints, (3.29,3.30) give the conservation at the hub only when all the demands are assumed uniform, i.e., the commodities are assumed uniform. However, in our case we assume that for each demand node pair (i,j) there is a different type of commodity that exists and hence conservation of each of these must hold true at each hub. Therefore our disaggregated hub conservation constraints become

$$\sum_m D_{ij} Y_{mk}^{ij} + X_{ik}\, D_{ij} = \sum_l D_{ij}\, Y_{kl}^{ij} + D_{ij}\, X_{jk} \quad \forall\, i, j, k \in \mathcal{N} \tag{3.31}$$

Alternate load imbalance constraints

From the constraints, (3.29, 3.30), we can write alternative constraints for load imbalance as follows:

$$\sum_i \sum_j \sum_l D_{ij}\, Y_{kl}^{ij} - \sum_i \sum_j \sum_m D_{ij} Y_{mk}^{ij} \leq \delta \sum_i \sum_j \sum_l D_{ij}\, Y_{kl}^{ij} \quad \forall\, k \in \mathcal{N}, \quad (3.32)$$

$$\sum_i \sum_j \sum_m D_{ij} Y_{mk}^{ij} - \sum_i \sum_j \sum_l D_{ij}\, Y_{kl}^{ij} \leq \delta \sum_i \sum_j \sum_m D_{ij} Y_{mk}^{ij} \quad \forall\, k \in \mathcal{N}, \quad (3.33)$$

Since the alternative constraints (3.32, 3.33) involve four index variables we prefer using the original constraints (3.27, 3.28) to the alternative load imbalance constraints (3.32, 3.33).

e. Other Constraints

Following constraints ensure correct allocation of hubs and assignment of nodes to hubs.

Constraints (3.34) allows a load between the node pair (i,j) to go on several hub-to-hub links. Constraint (3.35) ensures that a node is not assigned to another node until a hub is located on it. Constraint (3.36, 3.37) ensures that a load is not routed through a node unless it is a hub. Constraint (3.38, 3.39) ensures that if a load has origin and destination belonging to the same hub then it is not transferred to other zones. Constraint (3.40) are the integrality constraints for the variables.

$$\sum_k \sum_l Y_{kl}^{ij}\, D_{ij} \geq \; D_{ij}, \quad \forall\, i, j \in \mathcal{N} \qquad (3.34)$$

$$X_{ik} \leq X_{kk}, \quad \forall\, i, k \in \mathcal{N} \qquad (3.35)$$

$$Y_{kl}^{ij} \leq X_{kk}, \quad \forall\, i, j, k, l \in \mathcal{N} \qquad (3.36)$$

$$Y_{kl}^{ij} \leq X_{ll}, \quad \forall\, i,j,k,l \in \mathcal{N} \tag{3.37}$$

$$Y_{kk}^{ij} \leq X_{ik}, \quad \forall\, i,j,k \in \mathcal{N} \tag{3.38}$$

$$Y_{kk}^{ij} \leq X_{jk}, \quad \forall\, i,j,k \in \mathcal{N} \tag{3.39}$$

$$X_{ik},\;\; Y_{kl}^{ij} \in \{0,1\}, \quad \forall\, i,k \in \mathcal{N} \tag{3.40}$$

D. Final Model

Minimize

$$\sum_i \sum_k d_{ik} X_{ik} \sum_j \big(D_{ij} + D_{ji}\big) + \sum_i \sum_j \sum_k \sum_l Y_{kl}^{ij}\, D_{ij}\, d_{kl}\; + \sum_k F_k X_{kk} \tag{3.41}$$

Constraints

$$D_{ij}\,\Big(\sum_k d_{ik} X_{ik} + \sum_k \sum_l d_{kl}\, Y_{kl}^{ij} + \sum_l d_{jl}\, X_{jl}\Big) - d_{ij}\, D_{ij} \leq \beta\, d_{ij}\, D_{ij}, \quad \forall\, i,j \tag{3.42}$$

$$d_{ik}\, X_{ik} \leq \gamma_1, \quad \forall\, i,k \tag{3.43}$$

$$d_{kl}\, Y_{kl}^{ij} \leq \gamma_2, \quad \forall\, i,j,k,l \tag{3.44}$$

$$\sum_i \sum_j X_{ik}\, D_{ij} - \sum_i \sum_j D_{ij}\, X_{jk} \leq \delta\;\; \sum_i \sum_j X_{ik}\, D_{ij}, \quad \forall\, k \tag{3.45}$$

$$\sum_i \sum_j D_{ij}\, X_{jk} - \sum_i \sum_j X_{ik}\, D_{ij} \leq \delta\;\; \sum_i \sum_j D_{ij}\, X_{jk}, \quad \forall\, k \tag{3.46}$$

$$\sum_m D_{ij} Y_{mk}^{ij} + X_{ik}\, D_{ij} = \sum_l D_{ij}\, Y_{kl}^{ij} + D_{ij}\, X_{jk}, \quad \forall\, i,j,k \tag{3.47}$$

$$\sum_k \sum_l Y_{kl}^{ij}\, D_{ij} \geq D_{ij}, \quad \forall\, i,j \tag{3.48}$$

$$X_{ik} \leq X_{kk}, \quad \forall\, i, k \tag{3.49}$$

$$Y_{kl}^{ij} \leq X_{kk}, \quad \forall\, i, j, k, l \tag{3.50}$$

$$Y_{kl}^{ij} \leq X_{ll}, \quad \forall\, i, j, k, l \tag{3.51}$$

$$Y_{kk}^{ij} \leq X_{ik}, \quad \forall\, i, j, k \tag{3.52}$$

$$Y_{kk}^{ij} \leq X_{jk}, \quad \forall\, i, j, k \tag{3.53}$$

$$X_{ik} \in \{0, 1\}, \quad \forall\, i, k \tag{3.54}$$

$$Y_{kl}^{ij} \in \{0, 1\}, \quad \forall\, i, j, k, l \tag{3.55}$$

Note that i, j, k, l, m, all $\in \mathcal{N}$.

E. A Generalized Model

Model presented above for the multi-zone dispatching can be generalized to incorporate point-to-point dispatching. For this purpose, we need to introduce additional parameters. Recall that the main drawback of point-to-point dispatching method is that the driver turn over rate is very high. To represent the cost associated by the possible high turnover rate due to point-to-point dispatching, we introduce a new parameter θ. Hence, every time a driver is assigned to point-to-point dispatching there is a penalty cost factor of θ associated with it.

There exists a trade off between the point-to-point dispatching and multi-zone dispatching. The trade off involved is that if a load is assigned to multi-zone, then the costs increases due to circuitry and location of hubs. If however, the load is assigned to point-to-point dispatching then the costs increases due to the penalty factor θ which is due to higher costs of turnover. To incorporate this tradeoff we introduce a binary decision variable T_{ij}, which takes the value of 1, if the load from i to j uses point-to-point dispatching and a value of zero otherwise.

Hence, the following term needs to be added to objective function:

$$\theta \ \big(\sum_i \sum_j d_{ij}\, D_{ij}\, T_{ij}\big) \tag{3.56}$$

In addition, the constraint (3.34) is modified to ensure that a load can be assigned to only one dispatching method, i.e., either point-to-point or multi-zone dispatching, as follows:

$$\sum_k \sum_l \ Y_{kl}^{ij}\ D_{ij} + T_{ij}\ D_{ij} \geq D_{ij}, \quad \forall\, i, j \in \mathcal{N} \tag{3.57}$$

Also, the decision variable is binary, hence

$$T_{ij} \in \{0, 1\}, \quad \forall\, i, j \in \mathcal{N} \tag{3.58}$$

Therefore our final model incorporating point-to-point dispatching is as follows:

Minimize

$$\sum_i \sum_k d_{ik} X_{ik} \sum_j \big(D_{ij} + D_{ji}\big) + \big(\sum_i \sum_j \sum_k \sum_l \ Y_{kl}^{ij}\ D_{ij}\ \ d_{kl} + \sum_k F_k X_{kk}\big)$$

$$+\, \theta \ \big(\sum_i \sum_j d_{ij}\, D_{ij}\, T_{ij}\big) \tag{3.59}$$

Constraints

3.42, 3.43, 3.44, 3.45, 3.46, 3.47, 3.57, 3.49, 3.50, 3.51, 3.52, 3.53, 3.54, 3.55, 3.58

As evident, this model is much more difficult to solve than the multi-zone model. Further, analytical studies needs to be conducted with some real data to correctly estimate the value of θ. Since we do not have any analytical data, we do not consider estimating value of θ.

CHAPTER IV

SOLUTION METHOD

Following sections describe the different techniques to solve the problem.

A. Exact Method

As mentioned before, the multi-zone model is of binary integer programming type. CPLEX 7.1 with default settings was applied to solve the problem optimally, whenever the problem size permitted. Concert technology was used with CPLEX to implement the problem. Concert technology is a tool provided by ILOG to write constraints in C++ for input to CPLEX. As will be illustrated in the next chapter, CPLEX fails very quickly upon increase in problem size. Hence, we resort to heuristic methods which are described in the next section.

B. Heuristic Method

We select tabu search methodology as it has proved to be a powerful technique in solving combinatorial optimization problems. Tabu search effectively guides a heuristic to obtain good solutions to combinatorial optimization problems. An initial feasible solution is obtained with the help of a construction heuristic. A neighborhood function helps to obtain a subset of the neighborhood of the initial solution by applying moves. The subset of neighborhood is searched for local optima. The best solution (local optima) move is made if it is not in tabu list. A tabu list of certain length is maintained to store the attributes of some recent moves to prevent cycling. If a move is in tabu list but satisfies an aspiration criteria then the move is still made. Tabu search methodology and advance applications can be found in Glover (1989) and Glover (1990). A good source for tabu search methodology can also be found in Glover (1997) and Sait and Youssef (1999).

1. Initial Solution

First step in a tabu search algorithm is to find an initial feasible solution. Our problem is highly constrained because of the numerous criteria that it has to satisfy, i.e., the constraints on lane driver tour length, local driver tour length, percentage circuitry and load imbalance. Hence, finding an initial solution itself is very difficult in this case. Also, there is no easy way to determine whether the problem with given set of data is feasible or not. As mentioned before, our main purpose is to reduce driver turn over rate, which can be effectively controlled by reducing both lane and local driver tour length. Hence, we form an initial solution such that it satisfies both the tour length constraints without taking into consideration the constraints of percentage circuitry and load imbalance. One approach can be to add the circuitry and load imbalance violations as a penalty to the objective function. However, in the absence of real data it is difficult to determine the weight that each term, i.e., transportation cost, fixed cost, imbalance violation and circuitry violation, should receive in objective function. As stated, our main objective is to reduce tour length, hence we form an initial feasible solution taking tour length constraints into consideration and measure circuitry and imbalance for the solution obtained, together with objective function. This will give a better idea of the quality of the solution. More details on this are provided in chapter V.

Definition of some terms used in the heuristics:

- **Node-cover**: Set of nodes that lie within γ_1 distance of a node.
- **Hub-cover**: Set of nodes that lie between γ_1 and γ_2.

- **All-nodes**: Set of all nodes.
- **Traffic**: Measure of all loads originating out of the node and going into the node.

Refer to chapter III for the definition of γ_1 and γ_2.

a. A Construction Heuristic

The construction heuristic finds the solution such that the local and lane driver tour length constraints are always satisfied.

1. Generate hub-cover and node-cover matrix individually for all nodes. Also generate a vector containing all nodes.
2. Determine traffic of each node from the demand matrix.
3. Arrange the traffic list in descending order and make the node with the highest traffic a hub.
4. Delete the nodes covered by this hub, select another hub from the hub-cover candidate list such that it has maximum traffic among all the candidates.
5. Repeat step 4 until all the nodes are covered. Hence obtain the hub-list.
6. Assign nodes to the hubs based on proximity.
7. Obtain routes for each demand pair (i, j) by employing shortest path method (we use Dijkstra's algorithm for this purpose), and hence obtain route for each demand pair (i,j). We call this route-ij. Note that the shortest path are formed such that they satisfy node-hub (local driver tour length) and hub-hub (lane driver tour length) constraints.

8. Obtain the objective function, which includes the hub location cost and routing cost.

Figure 6 illustrates how initial solution is obtained. Following is the description of the example shown in the figure.

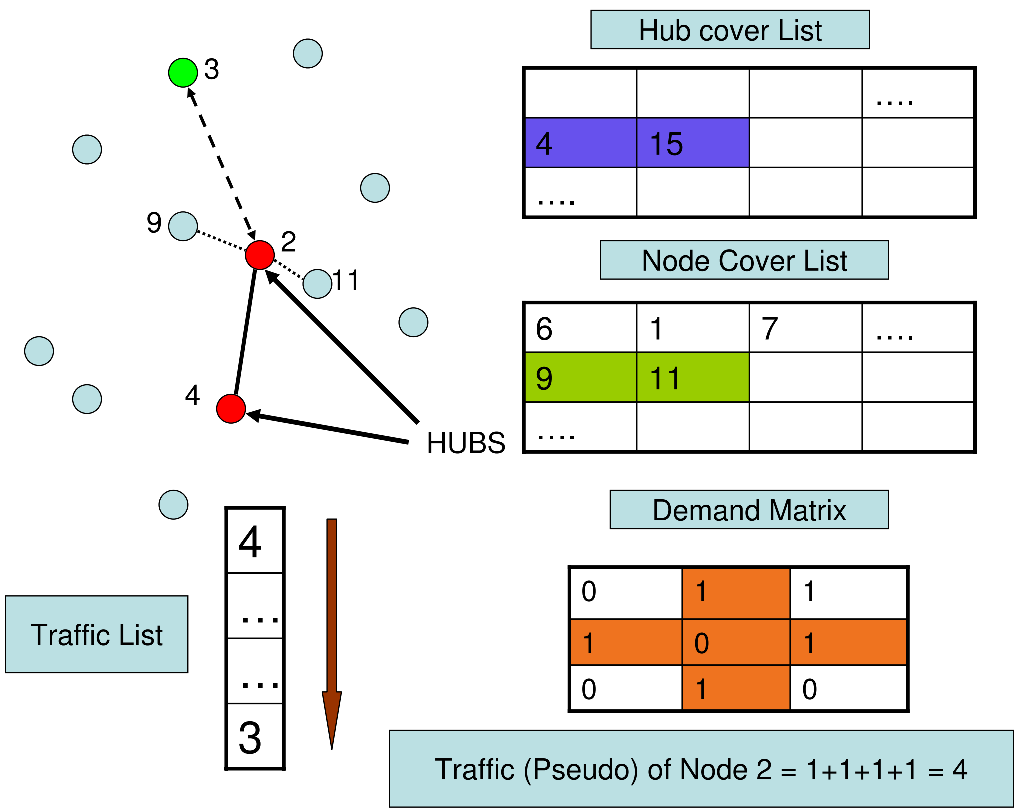
Since node 2 has the highest traffic we make it a hub. Next, we look at the nodes which lie within permissable hub-node distance from node 2, which can be seen from the node cover list. These nodes are 9 and 11. After assigning these nodes to hub 2, we go one step down the traffic list and see if the second highest traffic node lies within permissible hub-hub distance from hub 2. The nodes satisfying this criteria can be found in hub cover list. If it does not lie in the hub cover list of hub 2 we go further down in the traffic list and so on until we find a node which lies in the hub cover list of hub 2. In the present case, we find node 4 having the traffic 3 lies in the hub cover list of hub 2, hence it is made a hub. This process goes on until every node is covered by a hub or itself made a hub.

Note that, we call this traffic, pseudo because it does not indicate the real traffic at the node (which is made hub). This is because of the the tour length constraint that the load has to pass through many zones (hubs) and traffic on a zone (hub) can actually be much higher than just the sum of loads originating from it and loads going into it.

2. Improvement Heuristics

We use tabu search framework for improvement heuristics. We implement basic tabu search, i.e., we use short term memory and a fixed length of tabu list. More advanced techniques like approaches for handling dynamic tabu list or diversification and intensification strategies are considered outside the scope of this thesis. The

Figure 6. Initial solution



following defines the terminology and the algorithm used for short term memory tabu search (Sait and Youssef 1999).

Notation

Ω	Set of feasible solutions.
S	Current solution.
S^*	Best admissible solution.
$Cost$	Objective function.
N(S)	Neighborhood of S $\in \Omega$.
$\mathbf{V}^*$	Sample of neighborhood solution.
T	Tabu list.
AL	Aspiration Level.

Tabu Search Algorithm

Begin

Start with an initial feasible solution S;

Initialize tabu list and aspiration level;

For fixed number of iterations **Do;**

Generate neighbor solutions $\mathbf{V}^* \subset N(\mathrm{S})$;

Find best $S^* \in \mathbf{V}^*$;

If move S to S^* is not in **T Then**

Accept move and update best solution;

Update tabu list and aspiration level;

Increment iteration number;

Else

If Cost(S^*) $<$ **AL Then**

Accept move and update best solution;

Update tabu list and aspiration level;

Increment iteration number;

EndIf

EndIf

EndFor

End

In accordance with the above algorithm and our problem structure, we define the following terms:

- Move: A move is generated by replacing an existing hub with a non-hub in the current solution. Hence our neighborhood is generated by exchanges.
- Feasible Move: For a move to be called feasible, two conditions must be satisfied:
  a. Each hub can be reached from at least one hub, without violating the lane driver tour length constraints.
  b. All nodes are covered with the given set of hub list, i.e., there exists at least one hub satisfying local driver tour length constraint for each node.
- Attributes stored in the tabu list is the exchange pair (outgoing hub and incoming hub)
- Aspiration criterion: If the objective function (Cost) of any candidate move is lower than the current solution, then the move is made even if it is in tabu list.

- Candidate Moves: Set of moves that are feasible.

Following steps gives the steps of implemented algorithm.

Tabu Search Algorithm

Step 1. Obtain initial current solution using the construction heuristic. Initialize best solution = current solution.

Step 2. Generate candidate moves.

a. Generate current hub list and non-hub (nodes that are not hubs) list from the current or the initial solution.

b. Obtain a neighborhood solution by making move from current solution.

c. Check for the feasibility of move.

d. If the move is feasible, select it as a candidate move.

Step 3. Repeat step 2 until "P" number of candidate moves are obtained. Value of P is varied as per the problem size.

Step 4. Obtain objective function of each candidate move.

a. Given the hub list, generate the assignment of nodes by assigning node to the nearest hub. Hence, we obtain X_{ik}.

b. Generate routes for each demand pair by using shortest path algorithm (we use Dijkstra's algorithm), this gives us routes-ij. Note that the shortest path are formed such that they satisfy node-hub (local driver tour length) and hub-hub (lane driver tour length) constraints.

c. Obtain Y_{kl}^{ij} from routes-ij.

e. Obtain objective function for the candidate move which includes fixed cost of hubs and transportation cost of loads.

Step 5. Repeat step 4 until all objective functions for all the "P" candidate moves are obtained.

Step 6. Select the best candidate move

a. Sort the objective functions of candidate moves in increasing order.

b. Select the candidate move with the minimum objective function as the current solution, if it is not in the tabu list.

c. If the move is in the tabu list then check the aspiration criterion. If the move satisfies the aspiration criterion, then make the move and select it as current solution, otherwise proceed to the next lowest objective function value move.

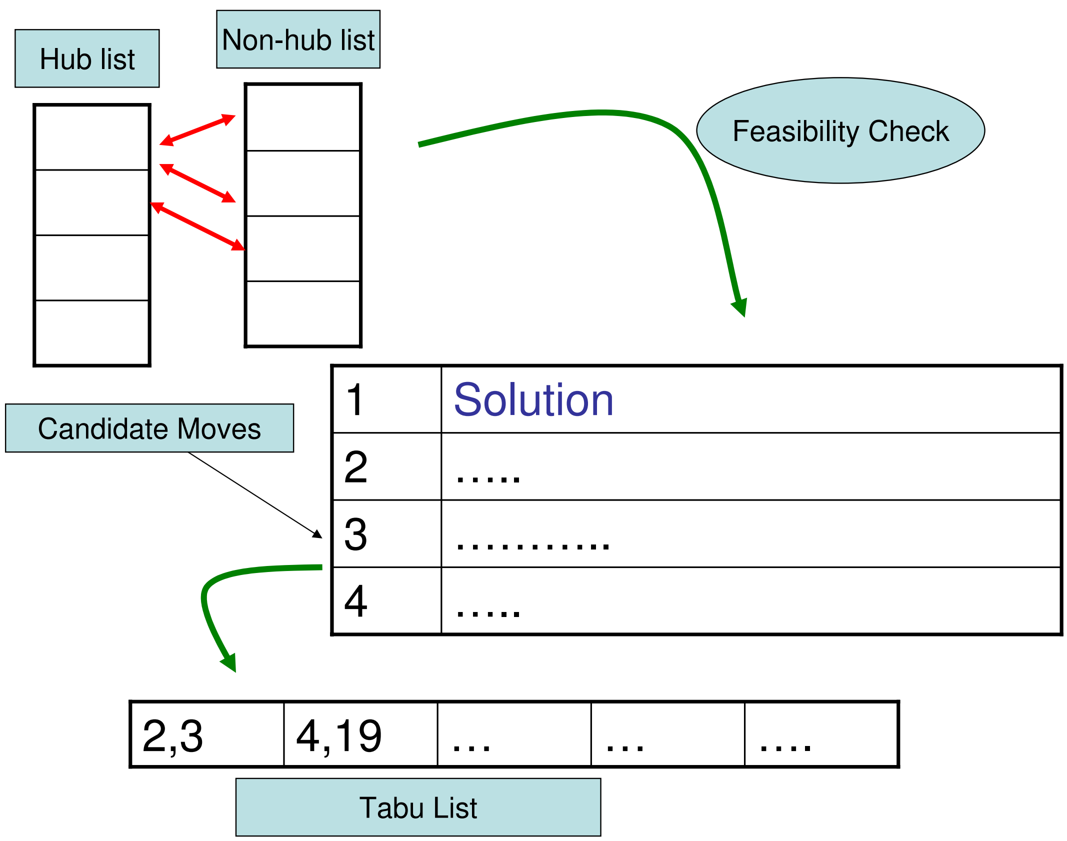
d. After selecting a move and making it as a current solution, add it to the tabu list.

e. If best solution > current solution, then make best solution = current solution.

Step 7. If maximum number of iterations for tabu search is done then stop, otherwise go to step 2.

Figure 7 illustrates moves, candidate moves and tabu list. The candidate moves are obtained by exchanging an element of hub list with an element of non-hub list. Once exchange is done, feasibility is checked for that particular configuration of hubs. If it is feasible then complete solution is obtained including the objective function. Solution obtained are sorted with respect to their objective function. Before selecting

Figure 7. Neighborhood and tabu search



a solution, it is checked with tabu list. Figure 7 shows that both the leaving and incoming nodes are stored as the attributes of the move in the tabu list.

The next chapter gives the computational results for comparison of heuristics and exact methods.

CHAPTER V

COMPUTATIONAL RESULTS

Section A provides the details of experimental set up. Section B discusses the experimental results when multi-zone dispatching model is solved by CPLEX. Section C describes the analysis of various parameters and explores their relationship with each other. Finally, section D provides computational comparisons of results from CPLEX and tabu search.

A. Experimental Set Up

The coordinates of the location of the nodes are generated from uniform distribution between (0, upper limit). The upper limit is varied from 50 onwards, as the number of nodes are increased in subsequent runs. Hence, all the nodes for a problem are contained in a square plot area of (upper limit * upper limit). In the tables the plot area is denoted by upper limit. The distance between any pair of nodes is taken to be euclidian. Demand between any pair of nodes is uniformly distributed between (0, 20). Hence, there can be a maximum of 2000% variation in demand for any given pair (i,j). There is a 20% probability of assignment of demand to any node pair (i, j). The unit of demand is truckload. The fixed cost of locating a hub on the node is derived from uniform distribution (1000, 2500).

For all the computational results that follow in the coming sections, the runs were made on Pentium IV, 3.06 Ghz, 512 MB RAM.

B. Experimental Results from CPLEX

CPLEX was used to solve the multi-zone model formed in chapter III. Note that the constraints of local driver tour length, lane driver tour length, percentage circuitry and load imbalance are all imposed on the model.

Table I gives the computational results for few representative cases having varied problem size. The second and the third column of the table gives the number of nodes and the plot areas respectively, which are increased subsequently to increase the problem size. The forth and fifth columns lists the maximum percentage circuitry and imbalance obtained for the problem size. The sixth and the seventh column gives the average values of percentage circuitry and load imbalance obtained for each instance. The eighth and ninth column gives the CPU time in seconds and objective function. Finally, the last three columns gives the lane driver tour length, local driver tour length and tour length obtained in point-to-point dispatching of the test case, respectively. The * indicates that the problem could not be solved by CPLEX due to insufficient memory.

For test1, test2, test3 and test4, the maximum imbalance constraint was set at 100%. For these small size problems there is a possibility of forming isolated hub with only demand origination or destination, with the given tour length constraint, hence, maximum imbalance is allowed to a value of 100% to keep problem feasible. For the cases, test 5 onwards the maximum imbalance constraint was restricted to a value of 75 %. This is because with the given size there is a rare possibility of forming isolated hubs with only origin or destination. Hence, we can afford to restrict maximum imbalance to a lower value and still obtain feasible solution. For all the test cases the maximum circuitry constraints was kept at 250 %.

The results show that even though the driver tour length in point-to-point dis-

Table I. Results from CPLEX

Test Case	No. of Nodes	Plot Area	Max % circ	Max % imbl	Avg % circ	Avg % imbl	Time	Objective function	Lane TL	Local TL	Pt-to-Pt TL
test1	5	50	80.89	37.5	33.09	28.75	0.41	4243.81	40	20	54.58
test2	7	70	41.43	100	7.89	65.4	0.74	12578.1	50	20	75.66
test3	10	90	151.95	100	41.11	59.58	3.1	29601.6	40	20	104.35
test4	15	100	213.64	87.09	35.06	54.26	7.08	52288.4	40	20	115.60
test5	17	110	130.08	65.6	20.66	48.1	194.2	52452	50	30	127.02
test6	20	120	137.56	68.1	22.39	36.88	1800	65488.1	50	30	139.05
test7	27	130	198.89	61.2	21.39	33.04	5830.78	116797	50	30	139.05
test8	30	140	202.02	59.3	24.35	38.76	806	151037	50	30	150.62
test9	35	150	******	******	******	******	******	******	******	******	******
test10	37	160	******	******	******	******	******	******	******	******	******
test11	40	170	******	******	******	******	******	******	******	******	******

patching goes on increasing with increase in problem size, the local and lane driver tour length are constrained to be within desirable limits in multi-zone dispatching. Hence, multi-zone method proves to be very effective in controlling the local and lane driver tour length. Note that for test2 the lane driver length is 50. This is because, with the given configuration of test2 and values of parameters, a feasible solution could not be obtained. Hence the lane driver tour length was increased from 40 to 50. This results in fall of average circuitry.

As the problem size increases, the longest distance between any demand pair increases, which causes more circuitry. Hence, the maximum percentage circuitry increases with increase in problem size, for a particular constrained value of local and lane driver tour length. Further, if with increase in the problem size we increase the maximum local and lane driver tour length then the maximum circuitry can drop down. This is because with increase in permissible local and lane driver tour length, the demand pair having the farthest distance can have more direct route than before.

Given a particular value of maximum permissible lane and local driver tour length, the maximum imbalance is expected to decrease with increase in number of nodes. The increase in number of nodes assigned to a hub can lead to increase in size of the zone and ultimately leads to increase in aggregation of demand. This reduces the variation between incoming load and outgoing load in a zone and hence reduces load imbalance. However, several exceptions can be seen in the table for this general rule. The reason can be attributed to the reduction in number of nodes assigned to the hub due to increase in plot area. Maximum circuitry constraint can also cause changes in assignments of nodes to hub and therefore can affect load imbalance. Hence, there are several competing factors for load imbalance for the same value of lane and local driver tour length namely, the number of nodes and their assignment to hubs, maximum circuitry allowed and plot area. The relationship among these is explored further in the next section. Some test cases have the maximum value of load imbalance as high as 100%. This happens when only either outgoing or incoming load is present for a zone. This case frequently arises when isolated hubs are formed as a zone with no nodes assigned to them and serving only as either origin or destination.

In general, solution time increases very sharply with increase in problem size. Test 8 is an exception to this trend. This can be attributed to the particular structure of the problem or good value of parameters which gave tighter bounds.

Computer runs out of memory for problem sizes having greater than or equal to 35 nodes.

C. Analysis of Parameters

This section explores how the important parameters, i.e., lane driver tour length and local driver tour length, relate to other parameters like percentage circuitry and load imbalance, for a given problem. To evaluate the impact of the local and lane driver tour length over other parameters we relax the constraints of circuitry and load imbalance and measure their maximum and average values. Further, since all the local and lane driver tour length constraints would not be tight, we measure the average values of local and lane driver tour length as well. Better understanding of the relationship involved between different parameters can help in developing a better insight into the problem and can help transportation manager to make better and more practical decision.

Table II gives the test cases for a 25 node problem with same experimental design as discussed in section A. Second and third column gives the maximum permissible values of local and lane driver permissible and forth and fifth column gives their average values, respectively. Sixth and seventh column gives the maximum and average

Table II. Analysis of Parameters

Test Case	Max TL local	Max TL lane	Avg. TL local	Avg. TL lane	Max TL Pt-to-Pt	Avg. TL Pt-to-Pt	Max % Circ	Avg. % Circ	Max % Imbl	Avg. % Imbl	No. of Hubs
25test1	10	50	2.73	35.1	150.62	76.12	85.29	8.1	100	43.4	23
25test2	10	60	6.95	39.5	150.62	76.12	44.68	4.9	100	43.4	23
25test3	10	70	6.59	45.68	150.62	76.12	44.68	3.1	100	43.43	23
25test4	10	80	6.59	49.94	150.62	76.12	38.49	2.47	100	43.43	23
25test5	20	50	13.25	37.43	150.62	76.12	117.22	13.81	100	36.35	16
25test6	20	60	7.99	41.25	150.62	76.12	117.23	12.47	100	36.35	15
25test7	20	70	9.07	46.05	150.62	76.12	117.23	10.73	100	36.35	15
25test8	20	80	12.25	50.79	150.62	76.12	85.29	9.77	100	36.35	15
25test9	30	50	15.46	36.85	150.62	76.12	221.55	15.59	81.15	35.44	15
25test10	30	60	15.5	40.2	150.62	76.12	221.55	17.06	69.38	34.06	13
25test11	30	70	16.34	46.32	150.62	76.12	221.55	17.69	79.72	31.6	13
25test12	30	80	18.93	51.91	150.62	76.12	221.55	19.99	84.26	35.97	12
25test13	40	50	17.36	36.73	150.62	76.12	221.55	20.55	54.34	33.06	13
25test14	40	60	23.5	40.78	150.62	76.12	221.55	20.25	43.62	31.66	12
25test15	40	70	20.01	46.48	150.62	76.12	221.55	18.52	43.62	31.66	12
25test16	40	80	23.23	53.68	150.62	76.12	221.55	19.5	47.47	30.96	11

values of tour length when point-to-point dispatching method is used. This remains same for all the test cases as it is same problem. Last five columns give maximum and average values of percentage circuitry and load imbalance obtained and the number of hubs located in the test case.

From the table, we observe that the values of average local and lane driver tour length are much less than the maximum permissible local and lane driver tour lengths. This indicates that only a few local and lane driver tour length constraints are tight. Keeping the local driver tour length constant, if the lane driver tour length is increased then the average tour length of the lane driver increases and vice versa.

The maximum circuitry and average circuitry have very high difference between them. This is due to the fact that a certain load which is carried over to long distance has a very high circuitry compared to the average circuitry faced. Similarly, the average imbalance is low in comparison to the maximum imbalance. The 100% imbalance in several cases for small local driver tour length is because of the reason explained in section B.

The number of hubs, average circuitry and average imbalance share a very complex relationship with each other in addition to their relationship with tour length. Average imbalance is expected to decrease when lane driver tour length is increased for decrease in hubs, for a particular value of local driver tour length . This is because with less number of hubs more aggregation of demand would be possible which would results in lower variation. However, with change in lane driver tour length, assignment of nodes to a hub can vary and hence, can affect load imbalance. Therefore, no general trend can be set. Average circuitry is expected to decreases with decrease in number of hubs, increase in lane driver tour length and same value of local driver tour length. This can be attributed to the decrease in number of hubs which causes the load to follow a less circuitous route. The exceptions to this may result due to different assignments of node which changes with change in lane driver tour length. Hence, it is difficult to set up general trends.

For a particular value of lane driver length, if local driver tour length is varied then there is much larger reduction in number of hubs. Due to this, average load imbalance decreases. This is because of increase in size of zone which causes demand aggregation.

From the above discussion, we conclude that there are several factors competing against each other. These factors are local driver tour length, lane driver tour length, circuitry, imbalance, number of nodes, assignment of nodes and plot area. All of them affect each other. It is difficult to set up general trends. However, some conclusions can be drawn which can prove very useful to a manager. The following subsection describes these inferences.

1. Inferences for a Manager

Based on the earlier discussion following inferences can be drawn to help the manager in decision making.

1. Average values for local and lane driver tour length are much lower than the maximum values. Hence, while designing the network a manager can set a high, even though undesirable value of permissible tour length. Only very few drivers would travel such a distance. Majority of the drivers would travel a much lower average distance. Setting up a higher value of permissible tour length would aid in obtaining a feasible solution with less number of hubs, which will help in lowering the total fixed cost incurred due to setting up of hubs.

2. Average values of circuitry and imbalance are much lower than the maximum values. Hence, it is advisable that certain loads which are on highly circuitous

routes can be assigned to point-to-point dispatching rather than multi-zone dispatching. Similarly, the loads that are causing isolated hubs which in-turn causes high load imbalance, can be moved to point-to-point dispatching.

3. Fixed cost of the hubs should be kept low, as much as possible, due to creation of large number of hubs in multi-zone dispatching method. Recall that the hubs are actually the transhipment points in our case which requires no consolidation of loads. Hence, cost of hubs can be kept low.

4. More careful attention is needed while setting up the local driver tour length than setting up lane driver tour length. A small change in local driver tour length may result in a significant change in average circuitry and average load imbalance.

D. Heuristic Results

As stated in section B, computer runs out of memory while solving the multi-zone model with CPLEX, when number of nodes in the problem becomes equal to greater than 35 nodes. Hence, we apply heuristic methods to solve larger problems. This section provides a comparison of solutions obtained from tabu search and CPLEX in terms of solution quality and computational time for some test cases.

In solving the model from CPLEX and TS, we consider only the constraints of local and lane driver tour length. As discussed in the chapter IV, the constraints of circuitry and load imbalance are relaxed. Further, no violations of circuitry and imbalance are added as part of objective function. Table III gives the description of the parameter values used for the test cases. The demand data, fixed cost for hubs are set in accordance with the experimental design described in section A.

Table IV gives the comparison of local and lane driver tour length between

Table III. Problem Structure

Test Case	No. of Nodes	Plot Area	Max. TL local	Max. TL lane
TStest1	5	50	20	40
TStest2	10	100	35	60
TStest3	15	100	35	60
TStest4	20	110	35	60
TStest5	25	120	35	60
TStest6	30	120	35	60
TStest7	35	140	40	80
TStest8	40	150	45	80
TStest9	45	160	50	75
TStest10	50	170	50	80

CPLEX and tabu search. Recall that the values of local and lane driver tour length plays a key role in determining the driver turn over rate. We observe form the table IV that the average values of local and lane driver tour length are close for CPLEX and tabu search, except for test case TStest2, where the average local driver tour length formed in tabu search is quite high. This happened because there was large number of hubs formed by tabu search in this case. This causes majority of drivers to travel along the lane and very few to travel as local drivers. Further, the ones which are travelling locally have high local tour length values. Test case TStest3 has higher local and lane driver tour length for both tabu search and CPLEX. This is because there are less number of hubs formed in this test case relative to its problem size, as compared to other test cases. The * indicates that the problem could not be solved by CPLEX due to insufficient computer memory. The average lane and local driver tour length obtained are much shorter than the average point-to-point driver tour length. This further reinforces effectiveness of multi-zone dispatching method to obtain small values for driver tour lengths.

Table IV. Solution Quality Comparison between CPLEX and TS

	CPLEX	TS	CPLEX	TS	
Test Case	Avg. TL local	Avg. TL local	Avg. TL lane	Avg. TL lane	Avg. TL Pt-to-Pt.
TStest1	16.92	15.39	26.42	22.82	33.65
TStest2	16.93	30.08	43.84	41.47	59.16
TStest3	24.21	23.96	45.9	49.5	60.64
TStest4	17.76	19.1	42.87	44.22	57.8
TStest5	16.64	21.53	41.49	41.16	70.26
TStest6	15.26	14.9	40.69	41.17	72.07
TStest7	******	11.56	******	47.07	76.74
TStest8	******	16.28	******	49.92	81.99
TStest9	******	20.59	******	49.95	80.28
TStest10	******	15.54	******	52.34	88.51

Table V gives the comparison for average percentage circuitry and average percentage load imbalance between CPLEX and tabu search. The * indicates that the problem could not be solved by CPLEX due to insufficient computer memory. Competitive values of average circuitry and load imbalance are obtained for tabu search in relation to CPLEX. We observe that the hubs formed by tabu search are always greater than the hubs formed by CPLEX. This is because the number of hubs remains fixed in the tabu search after it is obtained from the initial feasible solution. This can be improved by using an add and drop neighborhood function together with the exchange neighborhood function.

Table V. Solution Quality Comparison between CPLEX and TS

	CPLEX	TS	CPLEX	TS	CPLEX	TS
Test Case	Avg. % Circ	Avg. % Circ	Avg. % Imbl	Avg. % Imbl	No. of hubs	No. of hubs
TStest1	33.09	33.09	28.75	19.16	2	3
TStest2	20.65	7.29	47.64	54.82	6	9
TStest3	40.12	35.51	7.88	16.75	4	5
TStest4	37.63	30.45	29.62	24.5	6	8
TStest5	22.14	30.93	32.74	28.72	11	12
TStest6	32.55	18.59	36.43	37.24	13	20
TStest7	*****	7.47	*****	33.78	*****	26
TStest8	*****	9.33	*****	30.34	*****	29
TStest9	*****	37.38	*****	24.64	*****	17
TStest10	*****	17.94	*****	24.83	*****	26

Table VI gives the comparison of computational time and objective function between CPLEX and tabu search. The CPU time is measured in seconds. The tabu search was stopped after 50 iterations. As can be observed in table VI, the gap % obtained for tabu search suggests that it reaches within reasonably good solution within reasonable time for the test cases presented. Further, the solution time are very low for tabu search as compared to CPLEX. Lastly, CPLEX runs out of memory for the problems of size greater than or equal to 35. Tabu search is able to solve larger size problems than CPLEX in less time and has low memory requirement.

Table VI. Objective Function and Solution Time Comparison between CPLEX and TS

		CPLEX	TS		CPLEX	TS
Test Case	No. of Nodes	Objective function	Objective function	Gap %	Time seconds	Time seconds
TStest1	5	4243.81	4530.8	6.76	0.62	14.2
TStest2	10	26212.2	31589.9	20.52	3.85	8.2
TStest3	15	37013.1	38197.9	3.2	90	35.8
TStest4	20	56086.8	59316.7	5.76	2583.2	88.38
TStest5	25	99806.6	108308	8.51	11096	189.56
TStest6	30	142939	154475	8.07	565995	162.17

CHAPTER VI

CONCLUDING REMARKS

A. Conclusions

This research involves mathematical formulation of multi-zone dispatching method for truckload industry with the aim of reducing driver tour length. The model includes several unique constraints like lane driver tour length, local driver tour length, percentage circuitry and load imbalance. These constraints inculcate several factors from the three perspectives, namely, the driver, the company and the customer. The binary integer program is attempted to solve using CPLEX solver with concert technology. Test runs confirmed that the solution time rises very quickly with increase in number of nodes which defines the problem size. Further, computer runs out of memory very quickly and therefore a solution cannot be obtained for large size problems. Hence, a construction heuristic is proposed and implemented within a tabu search framework. Significant reductions in solution time and memory requirements was obtained for several test cases presented. The unique constraints were analyzed to develop insights into the problem structure and relationship of the parameters involved. Test cases results indicated that there is a significant difference between the maximum and average values for circuitry and load imbalance. The advantage of this can be taken by shifting unfavorable load from multi-zone to point-to-point dispatching. Hence, a generalized model was proposed that includes both multi-zone and point-to-point dispatching. Finally, test results confirm that significant reduction in driver tour length can be obtained using multi-zone dispatching as compared to using point-to-point dispatching method.

B. Recommendations for Future Work

The mathematical model for multi-zone dispatching can be expanded in terms of scope and structure. To increase the scope of the model, some additional factors can be taken into consideration which can come from any perspective, i.e., driver, company or the customer. Some factors that can be taken into consideration are first dispatch empty miles, miles per driver per day, driver route regularity, total flow time, etc. For changing the structure, multiple hubs can be used instead of single hub for a zone. Further, the nodes can be assigned to several hubs rather than uniquely to a single hub, which will help in reducing load imbalance. Advance tabu search techniques such as maintaining dynamic tabu list, intensification and diversification strategies can be applied to improve the quality of solution obtained. Further, an add and drop neighborhood function combined with exchange neighborhood function could be implemented for tabu search to improve quality of solution obtained. A good idea might be to consider it as a multi-objective problem with appropriate weights assigned to different criteria like transportation cost, fixed cost of hubs, load imbalance and circuitry. Lastly, more extensive and rigorous experimentation can be done with real life data to get better insights into the relationship between various parameters involved.

REFERENCES

Ahituv, N., O. Berman. 1988. *Operations Management of Distribution Services - A Practical Quantitative Approach.* Plenum Press, New York.

Braklow, J. W., W. Graham, S. Hassler, K. Peck, W. Powell. 1992. Interactive optimization improves service and performance for yellow freight system. *Interfaces.* **22**(2) 147–172.

Campbell, J. F., A. T. Ernst, M. Krishnamoorthy. 2002. Hub location problems. *Facility Location: Applications and Theory.* Springer-Verlag, New York. 373–403

Chopra, S., P. Meindl. 2002. *Supply Chain Management.* Prentice Hall, New York.

Daskin, M. S. 1995. *Network and Discrete Location: Models, Applications and Algorithms.* John Wiley and Sons, Inc., New York.

Delorme, L., J. Roy, J-M. Rousseau. 1987. Motor Carriers Operations Planning Models : A State of the Art. L. Bianco, A. La. Bella, eds. *Freight Transport Planning and Logistics.* Springer-Verlag, Berlin, 510–545.

Glover, F.. 1989. Tabu Search - Part I, *Journal on Computing.* **1**(3) 190–206.

Glover, F.. 1990. Tabu Search - Part II, *Journal on Computing.* **2**(1) 4–32.

Glover, F.. 1997. *Tabu Search.* Kluwer Academic Publishers, Norwell, MA.

Magnanti, T., R. Wong. 1984. Network design and transportation planning. *Transportation Science.* **18** 1–55.

Sait, S. M., H. Youssef. 1999. *Iterative Computer Algorithms with Applications in Engineering*. IEEE Computer Society Publishers, Los Alamitos, CA.

Taha, T. T., G. D. Taylor. 1994. An integrated modeling framework for evaluating hub-and-spoke networks in truckload trucking. *Logistics and Transportation Review*. **30**(2) 141–166.

Taylor, G. D., T. Meinert. 2000. Improving the quality of operations in truckload trucking. *IIE Transactions*. **32** 551–562.

Taylor, G. D., T. Meinert, R. Kilian, G. Whicker. 1999. Development and analysis of alternative dispatching methods in truckload trucking. *Transportation Research Part E*. **35** 191–205.

Taylor, G. D., H. Santhanam, J. English, G. Whicker. 1995. Hub and spoke networks in truckload trucking: configuration, testing and operational concerns. *Logistics and Transportation Review*. **31**(3) 209–234.

Taylor, G. D., G. Whicker, J. S. Usher. 2001. Multi-zone dispatching in truckload trucking. *Transportation Research Part E*. **37** 375–390.

VITA

The author of this thesis, Nimish Maheshwari, was born in Chittorgarh, Rajasthan, India. He graduated from Punjab Engineering College, Chandigarh, India, in June 2002 with a Bachelor of mechanical engineering. He entered Texas A&M University in the Master of Science program in industrial engineering in the fall of 2002, and graduated in December 2004.

His permanent address is 13/142, Malviya Nagar, Jaipur, Rajasthan, 302017, India.

The typist for this thesis was Nimish Maheshwari.