ECONOMIC ANALYSIS OF SOLID WASTE MANAGEMENT WITH AN APPLICATION TO SCRAP TIRE DISPOSAL

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CHAPTER I

INTRODUCTION

Modern legislation for solid waste management dates back from 1965 when the Congress enacted the Solid Waste Disposal Act, Title II of Public Law. Important to municipal solid waste (MSW) was the passage of the Resource Conservation and Recovery Act (RCRA) in 1976. RCRA has a set of provisions that apply to nonhazardous waste including MSW, the major provision is Subtitle D which prohibits open dumps and imposes technology-based standards on the construction, operation, and closure of solid waste landfills by the states.

These concerns are aggravated by the continuous rise in the generation of MSW that poses a threat to human health and ecosystems. This has lead to the promotion of several regulatory policies that engage households and firms in efforts to reduce and modify the solid waste stream. These policies are designed to address three main categories of solid waste management namely, source reduction, disposal, and material diversion. In addition, the highly publicized of solid waste and hazardous waste incidents have raised public awareness about the importance of safe waste disposal.

The major challenge is disposing solid waste in the most effective and efficient way while protecting human and environmental health. Recently, great emphasis has been given to diverting solid waste away from landfills through material recovery methods. The economic literature reveals that a variety of policy instruments and regulations are implicit for any system of controlling environmental externalities.

The dominant economic argument implied by a Pigovian tax is to tax pollution sources according to the difference between the marginal social costs and the private marginal costs. However, the implementation of a single policy instrument like tax or subsidy on polluting activities such as solid waste disposal has resulted in illegal disposal problems. As a result, several economic studies have developed with alternative policies that have the desirable features of the standard Pigovian tax without increasing illegal disposal incentives. The most favored is a policy combination of tax and subsidy commonly known as a deposit-refund system. Applications of this combination policy on solid waste disposal have resulted in different taxation and subsidization schemes depending on factors such as type of waste or specific good, disposal options, the stage in which it is applied, and whether it is applied on consumer or producer level.

1.1 Scrap or Waste Tire Management

One of the major challenges of the economy and environment is to manage scrap tires. The recognition of the scrap tire problem began in the early 1980s, but to date there is no specific scrap tire legislation at the federal level and the USEPA has not justified the piles of scrap tires as an environmental hazard. As a result, states must address the regulatory problems of proper disposal and management of scrap tires.

Waste/scrap tire management programs are alternatives to traditional public policies for solid waste management. Their main objective is to manage properly all currently or annually generated scrap tires and to clean up the historical tire dumps or stockpiles by creating incentives to increase recycling, recovery and reuse in order to reduce the externality cost of waste disposal (health and environmental costs). Many states have implemented or experimented with waste tire management programs, with varying degrees of success. Table 1 shows the list of states with waste tire programs. For most waste tire programs, a disposal tax or product charge is instituted on the sale of new tires in order to generate enough revenue to support waste tire recycling programs. The system is similar to deposit-refund; new tire purchasers absorb the charge with no impact on the disposal flow.

Table 1
States with Scrap Tire Management Fees

Arizona
Arkansas
California
Florida
Georgia
Illinois
Indiana
Iowa
Kansas
Kentucky
Louisiana
Maine
Maryland
Michigan
Minnesota
Mississippi
Missouri
Nebraska
Nevada
New Mexico
North Carolina
Ohio
Oklahoma
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Utah
Virginia

Source: EPA, *State Scrap Tire Programs - A Quick Reference Guide: 1999 Update*

1.2 Need for the Study

While waste tire programs have been in operation for more than ten years, there are still concerns and questions about long-term solutions for dealing with waste tires as well as the sustainability of waste tire industries. At the same time the cost of providing waste management services is rising. Some people question the cost-effectiveness of subsidizing these programs while others suggest that emphasis should be on supporting market development. States like Florida have succeeded in developing all four components of the scrap tire industry without using incentives (Farrell, 1999). Some states[1] have allowed tire fees to sunset; others[2] have scheduled sunset dates for their tire fees. As a result, there is a general concern with the sustainability of the markets previously supported by subsidies.

Although waste disposal management and recycling of specific waste streams has attracted many researchers, studies on waste tire management are limited. Previous studies on scrap tires have not investigated tire disposal from the perspective of waste management costs and location. Most studies are based on the surveys of state waste tire programs and scrap tire markets.

1.3 Purpose and Objectives of the Study

This study attempts to evaluate the cost-effectiveness of the waste tire recycling activities by investigating the relationship between the quantities of scrap tires recycled and the cost of the activities involved in the process of waste recycling. The purpose of a cost-effective analysis (CEA) is to find the means (activity, process or intervention) that minimizes resource use to achieve the desired target results; or that maximizes the desired results in the presence of resource constraints. Waste tire recycling is a three-step process; collection and transportation of waste tires to the processing facility, processing which includes shredding and crumbing of scrap tires into small pieces or further

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[1] Connecticut, Idaho, Oregon, Rhode Island, Texas, Washington and Wisconsin (Brown et al, 2001)

[2] Arizona, Arkansas, California, Colorado, Georgia, Maryland, Mississippi, Missouri, North Carolina, Ohio, South Carolina and Utah (Brown et al, 2001)

reduction of tire chips to finer particles, and end-product manufacturing. The 2-inch or 4-inch tire chip is the most common.

The study focuses on the transportation of waste tires from the points of generation to the waste tire facilities; the processing and conversion of these tires to processed or recycled material; and the optimal location of a new waste tire facility. Transportation is important because generation points are distributed widely all over the state while waste tire facilities can be located in finite number of locations. Scrap tire processing which involves separating rubber from other materials contained in tires through mechanical shredding and grinding is the source of revenue for tire facilities since they sell processed product to end users.

Location theory explains spatial organization of economic activities involved in the selection and the determination of optimum location, number and size of plants or facilities. Although plant/facility location models generally assume a single goal of cost minimization or welfare maximization, they do serve as guidelines for the establishment of public policies and incentive systems aimed at encouraging an orderly shift toward the optimum structure. However, these models have not been applied to the waste tire disposal problem, most applications and empirical analysis of plant location model theories are confined to agricultural projects.

By applying spatial and location theory to the waste tire management program, the study provides a more comprehensive alternative approach for scrap tire disposal. A linear programming model is developed in order to examine cost minimization of recycling activities and to identify low cost alternatives to manage waste tires. The model also incorporates social and environmental issues associated with solid waste management. The Oklahoma Waste Tire Program (OKWTP) that began in 1989 is used as a case study. The main purpose of the OKWTP is to facilitate the collection, transportation, processing or the extraction of useful materials for recycling, reuse and energy recovery.

A cost effectiveness study of one state tire program could provide some insight into the understanding of the design and effects of the policy instruments applied to waste tire management programs genarally. The approaches and methods used in the study may be of general interest to research concerned with efficiency in markets and interregional policies. It could also demonstrate alternative ways on how to sustain the existing tire programs.

1.4 Organization of the Study

The study is divided into six chapters. Chapter I covers the introduction, need for the study, purpose and objectives and organization of the study. Chapter II reviews the literature on solid waste management. Chapter III introduces case study data and discusses the general problem of scrap tires, scrap tire disposal process and options, legislation, and scrap tire markets. Chapter IV presents the development of the empirical scrap tire disposal model specific to the objectives of this study. In Chapter V the model is applied, simulations scenarios and results are presented. Chapter VI consists of the conclusions, summary, and the implications of this study.

CHAPTER II

SELECTED LITERATURE REVIEW

Recent studies on solid waste management have shown that waste disposal externalities can be addressed in a variety of ways. If illegal dumping is not a concern, a recommended instrument is a charge for disposal, that is, the standard Pigovian tax. Although this policy instrument has been successful in reducing the amount of solid waste disposed, it also induces improper waste disposal, littering or illegal dumping. Alternatively, when there is a potential for dumping, a tax on output/input combined with a subsidy for proper disposal (recycling), commonly referred to as a deposit-refund systems (DRS) is recommended.

DRS systems have been found to be potentially useful instruments for environmental regulation because they provide economic incentives for compliance without extensive monitoring. The efficiency of deposit and refund depends on various factors such as the responsiveness of the economic agents from legal and illegal markets for waste disposal, estimates of social disposal cost, and the possibility of cross-price effects between legal disposal and dumping. The advantages of the DRS vary across products, most of the time the policy have been implemented for selected items in the waste stream such as beverage containers, batteries, waste lubrication oil, and junked cars.

Scrap tire programs are similar to deposit-refund system. Accordingly, the review begins with an overview of studies on deposit-refund systems followed by discussion of studies related to waste tire disposal, markets for scrap tires, the sustainability of waste tire programs and plant location studies.

2.1 Studies on Deposit-Refund System

Bohm (1981) developed a theory of a deposit-refund system for the case where the use of a good results in an externality that is optimally regulated with deposits and refunds of equal magnitude. He analyzed a market for the product on which there is a deposit, and showed that demand for the product depends on the cost of available disposal alternatives and compliance cost or cost of return.

Bohm's theory has been extended by many studies, some compare efficiency and social welfare effects of deposit-refund with other policy instruments, others consider the application of deposit-refund system on virgin and recycled materials and others apply deposit and refund not only to solid waste but also to any waste of production or consumption. Menell (1990) considers consumers with fixed demand, who vary their willingness to pay for disposal costs and for compliance costs between two types of packages of the same good. He then compares the social welfare effects of a deposit-refund system with the curbside charges, retail charges and status quo and found DRS to be the most efficient policy.

The relationship between compliance and noncompliance is very significant for the efficiency of deposit-refund system. Belzer (1989) examines the gap between compliance and noncompliance costs for used lubricating oil. He uses published risk assessment data to develop estimates for optimal deposit and refund rates in order to estimate the net social benefits from reclaiming the socially optimal quantity of used lubricating oil. He concludes that the optimal incentive consists of a tax on waste disposal based on the residual external damage caused by disposing waste outside the regulatory waste management plus a subsidy for proper or safe disposal. However, he adds that no subsidy could be large enough to capture all noncompliance, the empirical observations that suggest assumptions of full compliance with existing regulations are often not the reality. He modifies his model and applies it to a generic hazardous waste problem that emphasizes illegal dumping. In this case, the existence of positive net social benefits was shown to depend upon differences in risk across disposal options, the ex ante level of regulatory compliance, and the magnitude of unit transactions costs.

Mrozek (1996) considers the effects of the variations in consumer characteristics, in terms of willingness to pay (W) and compliance costs (CR). He derives two total demand functions - one for those who buy and discard (noncompliance), and one for those who buy and return (compliance), and examines the efficiency and the distribution of changes in social welfare across the agents involved. These changes vary according to the degree of compliance, the size of externality, and the size of deposit and refund. Social welfare is achieved by appropriately setting the deposit and refund magnitude and by maximizing satisfied willingness to pay, less compliance costs, production costs, and externality costs. The model is applied to battery recycling and results showed that a percentage of potential welfare gain achieved is highest where noncompliance has a small externality or where the range of individual compliance cost is low relative to the magnitude of the refund.

Gottinger (1992) adds that uncertainty about the extent of non-compliance is an important factor favoring the use of tax-subsidy instruments over conventional regulatory approaches. He also emphasizes the importance of the transaction costs implicit in the administering of the deposit-refund program. This is supported by Dinan's 1993 study, which considered disposal costs, recycling costs and the cost administering the program to maximize social welfare. In his 1997 study, Gottinger varied the probabilities of initial compliance levels and the levels of transactions costs to explain the different levels of switching from non-compliance to compliance for used oil. He concludes that other factors, which determine the efficiency of tax-subsidy policy might become largely immaterial if transaction costs are not controlled.

Dobbs (1991) discusses deposit-refund as a solution for littering. He argues that imposition of a disposal charge (Pigovian tax) alone is inefficient because it does not differentiate between proper and improper waste disposal. He suggests that the disposal tax should be set at the marginal social cost associated with littering, with a subsidy for proper disposal thereby increasing the price of illegal waste disposal. The advantage of the subsidy is that it makes the would-be "litterer" face a price for littering. He then compares social welfare effects for the optimal disposal charge, optimal subsidy and tax-subsidy combination using consumer surplus, and found the tax-subsidy policy to be more efficient.

Some studies consider the application of deposit-refund system on virgin and recycled materials. Sigman (1995) finds that a tax on virgin lead is equivalent to a deposit-refund system when virgin lead and recycled lead are perfect substitutes in production. Dinan (1993) shows that virgin material taxes used in isolation can either lead to inefficient reductions in the production of valuable consumer products or actual increases in municipal solid waste disposal. He shows that a combined disposal tax on input and reuse subsidy policy could provide signals for an efficient level of waste generation. Palmer and Walls (1994) observe that a recycled subsidy by itself can provide an efficient input mix between virgin and recycled inputs, but could also lead to excess production, consumption and waste. Thus, the recycling subsidy must be combined with a tax on consumption. They add that a deposit-refund system would be easier to implement than a tax on virgin materials with a subsidy to consumption.

Several studies suggest preference over the levels at which deposit-refund system can be imposed. Those in favor of the producer level rather than the consumer level argue that this approach could greatly reduce administrative and transaction costs because the number of the affected producers and products is small compared to the myriad final consumer products. In their study, Palmer, Sigman and Walls (1997) impose an "upstream" tax or advanced disposal fee on the sale of aluminum sheet used by beverage container/can producers and refund collectors of used beverage cans who subsequently sell them for reprocessing. They compare the differences in the cost of waste reduction for recyclable wastes across the use of ADF, recycling subsidies and deposit-refund system and find DRS to be the least-cost policy. This view is supported by Palmer and Walls (1999), who after comparing an "upstream" combined product tax and recycling subsidy (UCTS) with the take-back approach (Extended Product Responsibility), conclude that UCTS is generally more cost-effective and imposes fewer transactions costs than the take-back approach. In addition they suggest that deposit-refund policy should be interpreted to include indirect effects on consumer's incentives for consumption, recycling and disposal.

Most recent studies extend and generalize the application of deposit-refund system. Fullerton and Wolverton (1997) suggest that the deposit and refund need not equal each other, neither do they need to apply to same good or be paid and received on the same side of the market. They introduce a "two-part instrument" (2PI), which is a combination of a presumptive tax and environmental or performance subsidy. A presumptive tax is imposed under the presumption that all production uses a dirty technology or consumption goods become waste, and the environmental subsidy is then provided only to the extent that production uses a cleaner technology or that consumption goods are recycled. The results of the 2PI is analogous to deposit-refund system, the only difference is that tax is applied to resource income while subsidy is on an entirely different commodity.

Advantages of the 2PI include feasibility, lower total social costs of administration, less enforcement problems, and political appeal. Palmer and Walls (1995) add that the implementation of the 2PI requires less information and that the administrative and monitoring costs must be lower for the firm or household than for the government that has less knowledge of the production or disposal process. Another view in the support of the 2PI is that Pigovian tax provides incentives to hide taxable emissions, while the two-part instrument provides incentives to reveal data in order to qualify for the subsidy. Moreover, the Pigovian tax may not be popular if it raises taxes on consumers or firms.

To show that application of a single policy on waste management is not efficient, Fullerton and Mohr (2000) reviewed Sullivan's 1987 study, which used a subsidy as an alternative policy to reduce illegal waste disposal. A consumer demand with assumptions on the determination of prices is added to Sullivan's model. Using data from Sullivan's study, Fullerton and Mohr apply an output tax simultaneously with the subsidy for legal disposal, and show that the tax-subsidy combination results in increased social welfare, subsidy alone is sub-optimal. The reason for the increase in social welfare is based on the fact that the tax on output offsets the increase in production resulting from the reduction in the cost of production caused by the subsidization of legal disposal.

Arnold (1994) compares the effectiveness of the product-charge and the traditional deposit-refund approaches on used oil (automotive DIY). The product-charge system is similar or equivalent to the deposit-refund system applied in scrap tire programs. The traditional deposit-refund system is less effective at increasing the used-oil recycling rate than is the product-charge option. This is also true for social welfare enhancement because the costs of collecting and recycling the additional DIY used-oil under the product-charge system are less than under the deposit-refund system. In addition, traditional deposit-refund system does not generate a significant amount of revenue in the form of unredeemed deposits, which if allocated to recycling programs like with the product charge would improve the system.

2.2 Scrap Tire Disposal Management and Markets

A large part of the literature on the management of waste tire disposal explains and/or evaluates the markets for scrap tire products, applications and uses of the end products. Stedge (1996) developed a cost minimization model for solid waste disposal that also estimates the cost of enforcement and applied it to Virginia scrap tire problem. To compare cost effectiveness of regulation and subsidies, the study provides different definitions for the cost of disposal. Regulation is found to be a more public-cost effective and net-public-cost effective enforcement mechanism than criminalization. If the agency's goal is to minimize the total cost of legal disposal, subsidies seem to be the cost-effective solution. Stedge also emphasizes the importance of knowing fine levels and elasticity of supply since they are the major determinants of the cost of effective legal disposal.

Everett and Douglah (1998) describe proper management of scrap tires as ensuring proper storage, disposal, end-use or a combination of the three. To identify issues involved in waste tire management, they conducted a survey of all 50 state scrap tire programs. They addressed the questions of funding mechanism, exemption of tires from tire fee, financial incentives for scrap tire management activities (processing, recycling, etc), allocation of funds, illegal dump clean up, and marketing issues. In addition to suggestions on how to address management strategies, the survey shows support for incentives to encourage market development and efforts for illegal dump clean up.

The keys to the success of waste tire programs appear to be development of markets for scrap tires, increasing new end-use applications and cleaning up illegal dumps. However, illegal dump clean-ups are expensive, typical clean-up costs are estimated between $1.30 and $1.50 per tire (California Integrated Waste Management Board 1997, and Douglah and Everett 1998). States with tire programs are dealing with stockpiles by providing incentives for clean ups, but very few have completely cleaned up their dumps because more tires are generated and dumped each year.

Unfortunately, the most important and least developed part of the tire industry is the end-use sector. Big players in the end-use sector are tire manufacturers, state transportation agencies, power generators and cement and paper producers that use tire derived fuel (TDF), and manufacturers of rubber products, such as mats, solid wheels, friction brakes and other industrial, agricultural and automotive rubber products.

Over the years, the percentage of the utilization of scrap tires as a percentage of total generation has increased dramatically from 11% (25 million tires) in 1990 to 38% (68 million tires) in 1992, then to 56% (138 million) by 1994 (Scrap Tire Management Council (STMC) Scrap Tire Use/Disposal Study: 1996 Update). By the end of 1995, there were markets for 69% (175 million tires) scrap tires, with the growth rate that is expected to continue rising (STMC, 2001). But, growth in the scrap tire industry slowed down after 1996 from 152.5 million to 140 million tires.

Several reasons are attributable to the scrap tire industry slow down; according to Blumenthal (1997a) of the STMC and Gray (1998) easy markets were picked first. First, Blumenthal argues that the TDF market is the easiest to penetrate while the civil engineering and ground rubber markets take a long time to develop. Secondly, there is a change in the preferences for processed TDF, scrap tire facilities that used to accept 2-3 inch pieces of crumb rubber now prefer smaller and cleaner fuel chips with less steel. Thirdly, changes in the quality and volume of products like cement kilns and the user's concerns with changes in air emissions are contributing to the slow growth. On a positive note, approximately 70 percent of discarded tires are sent to market according to the STMC (2001).

One major problem facing scrap tire industry is the cost of processing. Costs for processing equipment remain quite high. Processing costs vary, but according to Snyder (1998) scrap tires can be processed to appropriate specifications for less than $36/ton. On the other side prices for tire chips are very low, they range between $10 and $45 per ton depending on the quality and size (Brown et al. 2001 and Recyclers World, 2002). This has created revenue problems for tire chips processors whose main revenue sources are tipping fees and the sale of the tire chips. Revenue from tire chips covers only some 15 percent of the processors costs (Barta 1999). In addition, the magnitude of the average tipping fee is greatly influenced by market forces. As many tire chip producers recognize the low value of chips and the fact that their viability in the market is largely dependent upon declining tipping fees, the faster is their shift into the higher value market represented by crumb rubber. Profit margin in the tire chip market is estimated around 15 percent (Brown et al. 2001).

There are different views about limitations of TDF markets. Brown et al. (2001) argue that cost is not a limitation; technology is the problem. For example, technology limits the expansion of some boiler uses of TDF because they require high quality chips free of wire. Although there is evidence of considerable excess capacity in facilities designed to produce high quality crumb rubber, technological advances for high-grade crumb could result in monopoly in the market for scrap tires (Brown et al). Prices for crumb rubber range between $980-$1,160 per ton compared with $10-$45 per ton received by chip producers.

One reason for the low TDF prices is that they are usually pegged to the cost of coal whose prices are expected to remain low. Another concern is that some people consider TDF as a waste material, thereby undermining its economic value. In addition, the new USEPA regulations on particulate material and the Most Achievable Control Technology (MACT) air emission standards could impact the use of TDF, however, results of air emissions testing programs at nearly 100 facilities have shown that TDF emissions are not a problem (Blumenthal 1997a). On one hand, some facilities like a pulp and paper mill in Lewiston, Idaho had stopped using TDF at the request of the USEPA because of excessive sulfur emissions (Farrell 1999). However, there are counter arguments that emissions are not a problem if the TDF is mixed appropriately with other fuels.

Despite the fact that changes in TDF markets have reduced the number of scrap tires recycled, the SMTC predicts that obtaining a rate of 85 percent of all scrap tires going to the market or being properly managed within the next three to four years should be considered realistic. According to Blumenthal (1997), TDF market segment has the capacity to consume about 250 million scrap tires a year. Brown et al. (2001) conclude that scrap tire processors producing tire chips operate on thin margins given today's technology, and the future prospects of crumb rubber are unclear because production of high-grade crumb rubber is also limited by technology.

2.3 Sustainability of Waste Tire Programs

There is a growing concern about sustainability of scrap tire markets and the tire programs. Some states have scheduled sunset dates for tires fees; others have ended their support for scrap tire programs. The answers to the question of whether subsidies are effective in providing long-term solutions for tire management depend on several issues. Among the states that appear to be successful in establishing sustainable tire recycling programs, some provide support for market development while others emphasize state policies and enforcement. In Farrell (1999), Blumenthal of the STMC comments that subsidies have created false economies that were doomed to failure, "the key is to develop long-term, self-sustaining markets for the recycled tire products." One primary challenge for tire recycling is the difficulty in developing markets other than TDF.

Another area of concern is the cleaning of stockpiles. Although some states have been providing incentives for cleaning stockpiles for more than ten years, they have not completely cleaned up their stockpiles. It is therefore recommended that state programs should set a time horizon with deadlines for stockpile complete clean ups otherwise the problem will never cease to exist. Brown et al. (2001) suggest that the structure of sunset provision should allow for completion of cleanup efforts before eliminating tire fees. Douglah and Everett (1998) suggest that specific illegal dump objectives should be clearly stated in the tire management legislation. The longer the time allowed for dump elimination, the more money required per fiscal period as more tires roll in.

Brown et al. (2001) offer principles that could assist in designing a program that satisfies the individual needs of the state; (1) policy choices must necessarily rely on a detailed assessment of the markets for scrap tire products, and (2) scrap tire policy must be based on a full appreciation of the reasons that underlie the economic vulnerability of a scrap tire processor whose revenues rely on inputs via tipping fees rather than output. In addition, financial incentives should only be discontinued after sufficient markets have been developed. Along with law and code enforcement activities, the identification and simulation of accessible and competitively priced scrap tire markets should prove to be an element of the long-term management solution.

2.4 Optimal Location Studies

Location theory has been extensively researched, some studies propose the least-cost theory, and others propose demand and maximum profit approaches. Although von Thunen's theory is centered primarily on agricultural produce and its transport to a central market, his analysis is used in evaluating the allocation of activities within the urban areas. Instead of concentrating explicitly on transportation costs, the modern and integrated theory of plant location accounts for the distribution of demand, production, distribution of products and pricing policies. Spatial studies focusing on the efficiency of marketing provide clues on how to improve if one could start the activity from the beginning. An important aspect of location decisions is the effect of economies of size.

French (1977) distinguishes between two types of space models that have emerged from location theory. Space economy explains the importance of space (cost of distance) to the development of spatial economics theories. The continuous space approach considers a region with approximately uniform average density of raw product supplied and /or spatial density of demand with a common objective of minimizing long run average costs and average assembly and/or distribution costs. Alternatively, discrete space groups the supply sources and market territories into finite numbers of point locations and considers some pre-determined set of feasible potential plant locations or specifies finite number of markets, locations and raw materials sources. This approach requires knowledge of the transportation cost function and long run processing or handling costs.

One of the first models to determine optimum plant location, size and number with respect to assembly and or distribution was developed by Stollsteimer (1963). The limitations to his model is that it is not applicable to the determination of optimum plant location, size and number with respect to both assembly and distribution systems. A transshipment model has been used as an alternative. King and Logan (1964) were the first to apply a transshipment model of linear programming to agricultural marketing that is utilized to consider simultaneously the costs of shipping raw materials, processing and shipping final product. The problem concerns the location and size of the cattle slaughtering plants given the location and quantity of animals (raw material) and the final product demand. Several studies have extended the application of the location theory.

Dokmeci (1989) recognized the mutual interdependence of price, demand, production cost and transportation cost on optimal location when developing a model that maximizes social welfare. His analysis investigates spatial variations in revenue and costs for each plant. Highfill et al (1994) applied location theory to establish a recycling and waste management program that include location of a recycling center. They observed that the establishment of a recycling program does not require a direct contribution to societal utility from recycling activities, but the cost saving from reduced transportation costs provide an economic justification. The economic optimality of a recycling program is affected by sorting costs per unit of waste; transportation costs per unit of waste and city size, large cities are likely to favor the establishment of a recycling program. This dissertation applies location theory to waste tire-recycling program and also considers possibility of constructing an additional waste tire facility.

CHAPTER III

THE PROBLEM OF WASTE TIRE DISPOSAL

This chapter discusses the general problem of waste tire disposal, the process of tire disposal, the case study data, scrap tire legislation, and scrap tire markets. The case study data are broken down into three subsections; scrap tire program (legislation and procedures), generation of scrap tires and disposal options.

3.1 The General Problem of Scrap Tire Disposal

3.1.1 Introduction

Scrap tires represent a major regulatory problem for the nation and environment. The answer to the big question of whether scrap tires are a waste disposal problem or a recycling opportunity is not easy, but most recyclers are hopeful that there is still an opportunity for the private sector to make profits from the abundant scrap tires produced by an automobile-dependent society. Snyder (1998) describes the problem of the scrap tires as "two separate and distinct problems." One is the present outdoor, aboveground and uncovered accumulation, and the second is the ongoing generation of scrap tires before their aggregation into large collections.

Tires are generated by the ever-growing population that relies on vehicles as the most popular means of transportation. The number of scrap tires generated is based on industry replacement sales and tires on scrapped vehicles. The general view is that the growing accumulation of scrap tires in the United States of America is a consequence of the lack of end-use markets for scrap tires. While the number of scrap tires generated is large, it constitutes only about 1.8 percent of total solid waste generated in the nation. Passenger car tires constitute about 84% of total scrap tires, 15% are from light and heavy trucks, and 1% is from heavy equipment, aircraft and off-road tires (RMA).

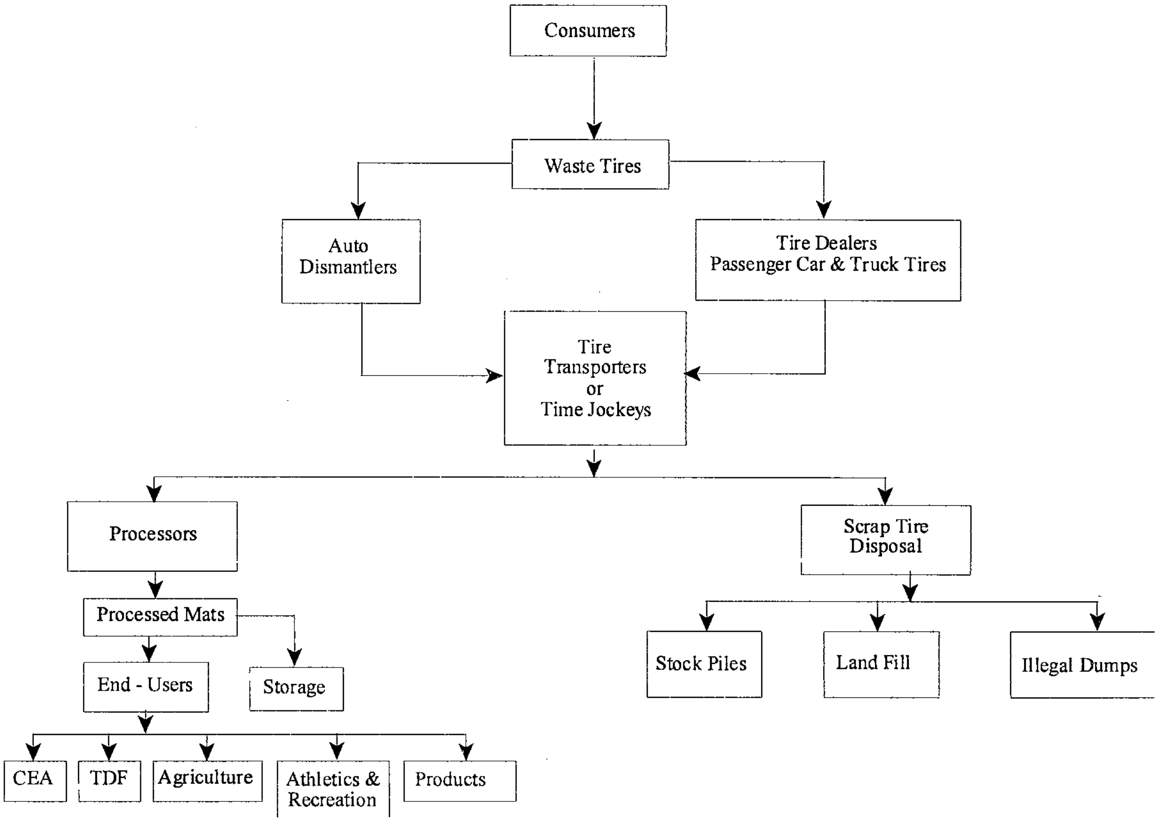
Above the ground, scrap tires are bulky and unsightly, and are potential fire and health hazards. Once started, fires from scrap tries are inextinguishable; they release heavy, unhealthy, black smoke and toxic oils that contaminate air, soil and water. In addition, fire residue represents a substantial cleanup problem. In addition, scrap tires provide an ideal breeding ground disease-carrying mosquitoes and rats. Although a health and safety hazard, scrap tire piles are not believed to pose a threat to the environment; as a result the EPA has not identified scrap tires as a hazardous substance. In fact, the EPA has approved the use of crumb rubber as a playground surface and a soil amendment.

To compound the problem, scrap tires are undesirable landfill components. First, they do not biodegrade. Second, because of their low bulky density and tendency to float up to the surface of the landfill they can harm landfill covers. Third, they occupy more space than other waste materials; for example, it takes 13 passenger-car tires to occupy a cubic yard of landfill space. To minimize this problem, some states require chipping or grinding tires prior to disposal in landfill, other states monofill them and others ban them from the landfills. This leads to higher tipping fees resulting in illegal dumping which, exacerbate the problem of scrap tires already contained in numerous stockpiles.

On the other hand, tire recycling is difficult and expensive. A tire is a composition of fiber and steel reinforcements, all cured within the confines of several different types of rubber compounds and other unique materials. Breaking down a tire involves heavy-duty shredders, granulators and cracker mills, as well as the use of cryogenics and separation equipment that usually has high capital costs. However, grants and subsidies have been provided to fund tire disposal, recycling and re-use projects, and retrieving and transporting scrap tires from stockpiles.

In these days, tires are built to last; some are now guaranteed up to 100,000 miles. The best way to reduce the number of scrap tires generated is to purchase longer-tread life tires, rotate tires every 6,000 miles, maintain proper tire pressure once a month or before every long trip, correct wheel balance and alignment, and avoid excessive acceleration and braking (*STMC and EREN*). Manufacturing also strives to design tires with increased durability, thereby prolonging the useful life of tires. Figure 1 shows the scrap tire disposal process.

Figure 1
Scrap Tire Disposal



3.1.2 Tire Disposal Process

The players in the disposition and recycling of scrap tires are generators, state, local governments, collectors, processors, and end users. Because most people buy new tires from dealers, scrap tires generally become the dealers' responsibility. About 80 percent of all scrap tires are handled by retail tire vendors, auto dismantlers handle the remaining 20 percent. The process of scrap tire disposal is illustrated in figure 1. State and local governments regulate the flow of scrap tires and state regulations differ for each state.

Under normal conditions (no tire program regulations) tire generators pay processing facilities a tipping fee for accepting scrap tires. Tire collectors separate usable casing for retreading and deliver the remainder to storage yards, processors and disposal site (landfills, monofills, tire stockpiles, or illegal dumps). Landfills usually accept scrap tires, but charge a tipping fee to cover collection cost. Tipping fees vary from state to state depending on various factors. Processors recycle scrap tires through the production of tire chips or crumb rubber and the product is sold to the TDF users and manufactures.

3.1.3 Scrap Tire Disposal Options

The growing accumulation of scrap tires in the United States of America is attributable to the lack of markets for scrap tires. As a result many states offer grants, loans, tax credits, and reimbursements to promote sound tire recycling markets and other feasible end uses to scrap tires. Efforts and policies to address the problem of scrap tires vary from state to state. Initially, a deposit-refund system similar to the bottle bills was suggested but was renounced as unworkable by tire manufacturers and tire dealers. Tire manufacturers are currently using up to 5% recycled rubber in the production of new tires and are also striving to design tires with increased durability in order to prolong the useful life of tires. The RMA and Scrap Tire Management Council (STMC) expect the percentage of recycled rubber used in the manufacturing of new tires to grow to up to 15%.

This section briefly discusses the three main disposal options for scrap tires, landfilling, recycling and reuse, and illegal dumping, including tire stockpiles. Retreading, which extends the life of scrap tires is not a disposal option. Retreaded tires are treated as a diversion out of the waste stream and are assumed to re-enter the waste stream after two years of use (*Franklin Associates,* 1999). However, retreading plays a very important role in scrap tire management and is briefly discussed below.

3.1.3.1 Tire Retread

The Tire Retread Information Bureau (2000) estimates that about 30 million scrap tires are retread and sold each year, leaving about 250 million scrap tires to be managed annually. More truck tires are retreaded than passenger car tires however, medium truck tires are more difficult to chop and command a higher tipping fee. Retread tires have been safely used on school buses, trucks, cars, airlines, fire engines and other emergency vehicles. The market for retread tires is growing, in year 2000 alone approximately 26.2 million retread tires were sold in North America and about 575 million pounds of tread rubber was used by the North American retread industry in approximately 1200 plants.

Benefits from tire retread include saving millions of gallons of crude oil (it takes only 7 gallons of oil to retread a used truck tire compared to 22 gallons to produce a new tire), landfill space, money (a retread tire costs between 30 and 70 percent less than a new tire), and post consumer material (a retread tire contains 75 percent post consumer material). According to Tire Retread Information Bureau, retread truck tires represent a savings of over $2 billion dollars annually for truckers and trucking companies in North America.

3.1.3.2 Landfill Disposal

EPA (1999) estimates that about one quarter of scrap tires generated end up in landfills each year despite all the reuse and recycling efforts. STMC estimates that at least 32 million tires or 12% of the total scrap tires generated were legally disposed (landfilled or monofilled) at the end of 1998. Scrap tires are either landfilled or monofilled when there are no viable markets for scrap tires within an economically accessible distance and /or when scrap tires are not acceptable to municipal solid waste landfills.

Landfilling and monofilling are the least-cost legal disposal options available to the market place but their existence can restrict the development of other markets for scrap tires. Thus, it is always recommended that states with scrap tire management programs should assist in the development of end-user markets so that land disposal does not become a preferred disposal option. However, using monofills for scrap tires is preferable to above ground storage in stockpiles, especially if a stockpile is not well managed.

3.1.3.3 Processing, Recycling and Reuse

The second alternative disposal option for scrap tires is processing, recycling and reuse. A typical scrapped automobile tire weighs 20lbs, about 12-13lb of that is recoverable rubber composed of 35 percent natural rubber and 65 percent synthetic rubber. The average weight of a truck tire is 100lb and contains between 60 to 70 percent recoverable rubber. According to Serumgard in STMC 2001, the rate of tire recycling is higher than the rate of paper (62.5%), glass (50%), and aluminum cans (35%) recycling.

The increase in the generation of rubber tires between 1960 and 1998 has been accompanied by a gradual increase of rubber recovery. Approximately 22.3 % of the total weight of scrap tires generated in 1997 was recovered for recycling and reuse; this excludes tires for Tire Derived Fuel (TDFs). Since the lack of end-use markets for scrap tires is blamed for the accumulation of waste tires, efforts to develop these markets is always recommended. It is generally believed that as long as there is ongoing supply of waste tires, recycling/reuse and processing of scrap tires should be subsidized, and development of end-use markets for scrap tires is also recommended.

3.1.3.4 Stockpiles and Illegal Dumping

Besides the need to manage scrap tires generated, million of tires are contained in numerous stockpiles. Stockpiles are the residue of the past and some current illegal methods of handling scrap tires. Scrap tires are dumped for several reasons, for example poor enforcement of anti-littering and anti-dumping laws; limited availability of alternative uses, and the less than noble motivation of profit-seeking tire jockeys trying to make more money by illegally dumping tires rather than paying tipping fees.

In 1994, the STMC estimated that between 700 and 800 million scrap tires existed nationally, this number is lower than the EPA estimate. Due to aggressive programs to clean up stockpiles, improvements in stockpile estimates, and the loss of tires in tire fires, the number of scrap tires in stockpiles has declined. According to the *Scrap Tire Use/Disposal Studies*: *1998-99 Update* estimates, approximately 500 million scrap tires were in stockpiles in 1998. Because retrieving and transporting scrap tires from stockpiles is expensive, some states subsidize processing of scrap tires from stockpiles.

3.2 Oklahoma Scrap Tire Program

The Oklahoma Waste Tire Recycling Act (OWTRA) was established in July of 1989. The purpose of OWTRA is to facilitate the collection, transportation, processing or the extraction of useful materials from scrap tires for recycling, reuse and energy recovery. The Act provides for a \$3.50/tire surcharge on new truck tires ($\geq$ 17.5 inches rim diameter); a \$1/tire surcharge on new passenger car tire ($\leq$ 17.5 inches rim diameter) sales; \$4.00 fee assessed the first time a vehicle is registered in Oklahoma; and \$1.00 per tire to be used on motorcycles, minibikes, motor-driven cycles, or motorized bicycles in order to pay for their ultimate disposal. These funds are collected by Tire Dealers and then deposited in the Waste Tire Indemnity Fund (WTIF) managed by the Oklahoma Tax Commission (OTC), to provide incentives for the elimination stockpiles, tire collection, transportation, processing and end-use.

In exceptional cases for which payment did not occur, voluntary payments in the Fund by people who wish to have waste tires collected for processing is allowed. Examples include automotive dismantlers and parts recyclers who have tires from automobiles purchased prior January 1, 1995, and tire dealers in possession of tires for which no fees have been paid. The Act has been amended 10 times. Table33 shows how the tire fee is allocated.

Table 2
Allocation/Use of Oklahoma the Tire Fee

Monetary Amount	Recipient
2.25 % of collected fees	Tire Dealer (administration)
4 % of remittance	Tax Commission (administration)
4 % of remittance	Oklahoma DEQ (administration)
Remainder of remittance	Tire processing and end-use reimbursement

Source: *Everett and Douglah, 1998*

In addition, ten percent of monies accumulated in the Fund is set aside for the reimbursements to the end users who manufacture new products or derive energy benefits from processed waste tires (The Oklahoma Department of Environmental Quality or OKDEQ Report 2002). End users are also allowed reimbursement for one hundred percent of their capital equipment costs.

Only Waste Tire Processors/Facilities (WTFs) that are permitted by the Oklahoma Department of Environmental Quality (DEQ) under the Solid waste Management Act can receive money from the fund. Presently, there are three permitted WTFs in Oklahoma. Tire haulers and transporters are not regulated, however DEQ must permit collection of more than 50 tires except for tire manufacturers, retailers, wholesalers, or retreaders who store 2,500 or fewer used tires. To be eligible for tire processing reimbursement permitted WTFs must document that at least 10 percent of the tires processed came from illegal tire dumps identified by DEQ to participate in the State's reimbursement programs and/or from DEQ approved community wide clean-up events (CWCs). In addition to a number of documents required before reimbursement is paid, Oklahoma has a sound manifest tracking system and conducts tire dealer inspections and tire dump surveys. WTFs are not allowed to collect less than 1000 tires from anyone location.

For each dollar collected from a sale of a new tire, WTFs receive a total of $0.85, that is, $0.35/18.7 lb for collection/transportation and $0.50/18.7 lb for processing. They are allowed to obtain reimbursement at the rate of $37.43/ton for tires collected and transported statewide and $53.48/ton of tires processed. End-users receive $20/ton of processed tire materials used as fuel or manufacturing of new products. Riverbank stabilization projects are eligible for $1.50/tire ($\geq$ 17.5 inches rim diameter) coming from dumpsites on the priority enforcement list. SB 1218 authorities DEQ to recover costs for waste tire cleanup from people who illegally disposed of such tires. The reimbursement for tires cleaned up from illegal Tire Dumps has been increased to $2.25 for truck tires and $0.45 for passenger car tires.

3.2.1 Scrap Tire Generation

On average, Oklahomans generate around 3.5 million waste tires per year. For every new tire sold, a scrap tire that must be disposed is created. The main generators are tire dealers. According to the OKDEQ 2002 Report, approximately 2,000 tire dealers are responsible for collecting waste tire recycling fees and about 154 tire dealers were exempted from collecting fees beginning 2001. The DEQ maintains a list of illegal dumps statewide, (Priority Cleanup List or PCL). At the end of the reporting period, there were 121 PCL ranging in size from fewer than 100 to as many as 80,000 tires, with the total estimate of 562,500 tires. Although many illegal dumps contain less than 1000 tires, a significant number of dumps contain between 1,000 and 5,000. However, great progress has been made to reduce tire dumps, 3.42 million scrap tires have been clean up from large historical dumps and only 22 historical tire dumps remain on the PCL. Currently, 99 percent of tire dumps on the PCL contain fewer than 5,000 tires, and it appears that large tire dumps are no longer being created. Community-wide cleanups mandated by the Act, are organized by county commissioners and community leaders to collect tires that would have ended up in illegal dumps. Tables 3, 4, and 5 below summarize waste tire generation or availability and consumption.

Table 3
Scrap Tire Availability - Oklahoma (Millions)

SOURCE	FY 1998-1999	FY 1999-2000	FY 2000-2001
Annual Generation	3,069,108	3,103,953	3,144,607
Exempted Tires*	86,187	100,730	313,578
Stockpiles (PCL)	79,071	157,236**	44,107
Community Wide Clean Ups (CWCs)	42,582	66,694	51,634
TOTAL AVAILABILITY	**3,104,574**	**3,114,630**	**2,926,770**

* Tires exempted from paying disposal charge, these are subtracted from the total generation

** Includes 105, 523 tires collected from PCL for river bank stabilization

*** Formula for converting number of tons is based on WTMC 1994 formula and OK per tire weight
Tons = (Total number of scrap tires) x [(0.90 x 18.7 + (0.10) x (100)] /2000

Table 4
Scrap Tire Availability - Oklahoma (Tons)

SOURCE	FY 1998-1999	FY 1999-2000	FY 2000-2001
Annual Generation	41,172	41,640	42185
Exempted Tires*	1,156	1,351	4,207
Stockpiles (PCL)**	1,061	2,110	592
Community Wide Clean Ups (CWCs)	571	895	693
TOTAL AVAILABILITY	**41,648**	**43,294**	**39,262**

Table 5
Scrap Tire Distribution/Consumption (Tons)

Fiscal Year	Total Availability	Total Generated	Collected, Transported, And Processed	Landfill/ Illegal Disposal	River Stabilization	Other
98-99	41,648	41,172	33,187	6,829	-	1,632
99-00	43,294	41,640	33,138	7,139	1,416	1,465
00-01	39,263	42,185	30,545.	7,433	-	1,284

3.2.2 Scrap Tire Disposal

The existing program although very successful, cannot keep up with the volume of tires generated each year, very few tires still end up in landfills while others are dumped illegally and are susceptible to fire. With advances in technology Oklahoma may soon become a leader in scrap tire recycling. Two cement kilns; Holnam and Blue

Circle have installed equipment that allows them to use whole tires (The OKDEQ *2000 Annual Report*). The State of Oklahoma has recently approved the construction of the first gasification facility in Safe Tires Recycling Corporation. In addition, Safe Tires Recycling Corp. is negotiating for the construction and installation of new machines expected to use 100 percent old tires or recycle up to 3 million tires each year from the stockpiles, according to Scott Holden (*Daily Oklahoman, January 11, 2002).* Scrap tire disposal is broken down into three disposal options.

3.2.2.1 Legal Disposal Market

In Oklahoma landfilling of waste tires is not legally banned, it is discouraged. As a result, the very few scrap tires disposed of in landfills come from private individuals (telephone survey of Oklahoma landfill managers or operators). Some landfills accept tires and store them until picked up by the processors, they charge tipping fees ranging from $1 to $5 per passenger car tire and $5 to $10 per truck tire. Very few tires have been landfilled over the past years as a result no records are kept according to the telephone interview. Out of the total number of scrap tires generated, exempted and processed, a small number is unaccounted for (entered as landfilling/illegal disposal in Table 5). Nationwide, the estimate for scrap tires landfilled each year is approximately 12 percent (STMC, 2001).

3.1.2.2 Waste Tire Recycling Market

Approximately 80 percent of tires generated are recycled each year. Because of the way in which the Oklahoma waste tire program is designed, the three waste tire processors do not charge tipping fees. This eliminates the incentive to dump old tires in roadside ditches. During processing, scrap tires are reduced to various sizes of tire chips and crumb rubber that are sold to end users for a variety of applications like septic tank system installers, solid waste landfill drainage layers, Tire Derived Fuel (TDF) at cement kilns, playground safety material, horse arena floors, manufacturing of rubber mats and other molded products.

Four-D Tire Recycling destroyed by fire in September 2000 is expected to be back in operation in three to six months (*Shawnee Online,* February 05, 2002). Four-D produces different sizes of steel free crumb rubber and playground material. Frontier Recycling is a tire chips producer. Safe Tire Disposal Corp., the largest and fastest growing waste tire facility in the state has collected more than 4 million tires and expects to consume about 2.8 million tires every year in future. Of the total scrap tires shredded at Safe tire Disposal Corp., approximately 40 percent become fuel at the Holnam plant, about 30 percent goes to contractors for uses as filtering material in septic tank lines, landfills uses, about 25 percent in filter systems, and the rest goes to a gasification system (*Shawnee Online*, February 05, 2002). Table 6 illustrates the distribution of processed materials in Oklahoma.

Table 6
Processed Material Distribution/Consumption

FY	**Collected, Transported & Processed (mill.)**	**Collected, Transported & Processed (tons)**	**Marketed (tons & %)**	**Stored (tons& %)**
98-99	2,473,866	34,387	31,577 (91.8)	2,810 (8.2)
99-00	2,470,235	34,473	31,806 (92.3)	2,667 (7.7)
00-01	2,276,960	32,996	29,297 (88.8)	3,699 (11.2)

Source: The Oklahoma DEQ Report, *Management of Oklahoma's Annual Waste Tire Stream, and Market Outlook for Processed Scrap Tires,* 2002

Besides tire processing, waste tires are used for soil erosion control, bank stabilization, or other approved conservation projects permitted by the U.S. Army Corps of Engineers or local conservation di*strict. Tree planting is required for all erosion control projects. Noble Rubber Products Inc. has cleaned up 3 PCL sites containing 102,523 tires during 1999-2000 FY, it was reimbursed for installing three bank stabilization projects (OKDEQ, *2002 Report*).

3.2.2.3 Illegal Disposal

As mentioned above a fraction on waste tires generated is illegally disposed. Except for data for scrap tires remaining in tire dumps in the PCL and scrap tires collected by community clean up events (that would have been illegally dumped), there are no available data for scrap tires illegally disposed of every year. According to the OKDEQ 2002 Report, "it appears that lager tire dumps are no longer being created." However, about 20 percent of waste tires generated are unaccounted for. Since a very insignificant amount of scrap tires is landfilled, it is reasonable to assume that about 15 percent of this amount is illegally disposed.

3.3 Scrap Tire Legislation in the United States

The recognition of the tire disposal problem began in the early 1980s, but to date there is no specific scrap tire legislation at the Federal level. Although environmental laws of Clean Air, Solid Waste and Superfund affect scrap tire management, USEPA has not justified the piles of scrap tires as an environmental hazard. As a result almost every state in the U.S. faces the challenging regulatory problem of proper disposal of scarp tires either through specific scrap tire laws and regulations or through state solid waste or transportation legislation. As mentioned above, each state establishes its own scrap tire program with laws and regulations specific to is problem.

According to Rubber Manufacturers Association's (RMA) 2000 report, forty-eight states have legislation on scrap tire collection and disposal with varying programs across the country; thirty three states ban whole tires from landfills; twelve ban all scrap tires from landfills; five have no landfill restrictions; seven allow monofills; and thirty charge a fee (27 charge a fee on the sale of new tires, and 3 impose a fee at the time the title for a motor vehicle is transferred or at the time a motor vehicle is registered). The fee ranges from 25 cents - $2 per passenger tire. Because all scrap tires must be stored somewhere until they can be used, most states have specified adequate storage methods and prescribed the necessary record keeping on the origins of the tires accepted and license provisions for storage site, including fees. Some states license tire haulers and others require them to keep manifests of their deliveries. Some states have enacted rules and regulations for use of Rubber Modified Asphalt (RMA) in highway construction; others are in the process of establishing similar rules.

3.4 Scrap Tire Markets

The largest volume markets today are in chip markets, with TDF, crumb or ground rubber, and civil engineering uses dominating. The four main markets of scrap tire products are discussed below.

3.4.1 Combustion and Tire-Derived Fuel (TDF) Markets

The most common way to recycle or dispose of tires is by burning them for fuel. Approximately 63.8% (125 million) of the current end-use of recycled scrap tires is Tire Derived Fuel, used in approximately 72 facilities (SMTC, 2001). Although pioneered in Germany in the 1970s, the use of TDF as fuel for cement kilns has been widely adopted by various countries. In the U.S. the largest consumers of TDF are utilities, cement kilns, and paper and pulp mills. Tires can be an excellent fuel, they have a higher BTU/lb level (heat combustion level) compared to other fuels; they produce the same amount of energy as oil and 25 percent more energy than coal; and are low in sulfur, nitrogen and moisture. The cement industry discovered that tire chips actually increase coal's BTU value and steel beading could serve as a replacement for iron oxide. As Snyder (1998) points out, "when we consign tires to a landfill, we are paradoxically burying better fuel than we are mining."

3.4.2 Ground Rubber Markets or Crumb Rubber Applications

Ground or crumb rubber, the second most popular method of recycling tires is the highest value-added sector of tire recovery and markets. Crumb rubber producers who take shredded tire scraps and reduce their size further, removing all non-rubber components (dire, steel fiber, etc.), consume about 13 million scrap tires annually. American Tire Recyclers (ATR) in Florida is one of the largest crumb producers. The EPA documents, USEPA, Part V, 40CFR Part 247 and Part VI (1995) essentially endorse crumb rubber use as play turf and soil amendment affected ground rubber market.

The overall market demand for crumb rubber was approximately 460 million pounds at the end of 1998, compared to 160 million pounds in 1992; 240 million pounds in 1994, and 400 million pounds in 1996. According to the International Rubber and Tire Association (ITRA) and Rubber Advisory Council, crumb rubber production capacity rose by 200 to 300 percent after the passage of the federal highway act, which called for the increased use of crumb rubber in highway projects. The increased demand is met through the processing of more scrap tires; a 15 - 20 percent annual growth is expected in the future although the market remains dominated by 8-10 companies that generate and sell 80-85 percent of the supply.

The prognosis of crumb rubber producers looks positive; however, more research and development is necessary in order to allow the use of crumb rubber products. Factors that could assist in the development of this market include technological improvement, standardization, specifications and testing criteria for ground rubber. The American Society for Testing Materials (ASTM) has developed standards for crumb rubber applications. According to Riggle (1995), this will increase the supply of finely grounded rubber because customers are interested in getting the end product cleaner and smaller, and as the ground rubber particles become smaller, markets for materials will expand. Another factor development that could have an impact on the development of ground rubber market is listing scrap tire-derived materials on the Chicago Board of Trade cash exchange market for recyclables.

There are six categories of markets for ground rubber. The fastest growing new markets are playground cover, soil amendments, and rubber products where a large amount of crumb rubber is combined with a small amount of virgin rubber to produce high-quality rubber mats and other products. According to 1997 *Scrap Tire and Rubbers Users and Directory*, 33 firms are producing rubber products. Finely rubber ground particles can be used to make shoe soles, sealants, nonpneumatic tires and carpet padding.

(a) Bound Rubber Product Market

This market consumes about 113 million pounds of recycled rubber, and has a potential for significant growth. Bound rubber products include carpet underlay, dock bumpers, roof walkway pads, rubber in railroad crossing and equestrian areas, and sewage sludge composting (where rubber replaces wood chips).

(b) New Tire Manufacturing

Beyond recycling, there is work underway by some tire manufacturers to increase the recycled content of new tires they manufacture and to provide a significant end market for scrap tires at the same time. Michelin North America is the only major tire manufacturer that is producing tires with the 5% recycled crumbs. Recently, Continental General in North Carolina received a grant to use up to 25% recycled crumb rubber. This market consumes about 32 million pounds of recycled crumb rubber. According to Blumenthal (1997b), if the new technology to build a test wire with a recycled content by Michelin North America proves safe and cost effective, a market for an additional 30 million scrap tires a year it could be created.

(c) Crumb Rubber Modified Asphalt (CRMA/RMA)

Asphalt products consume about 44 percent of the total ground rubber produced in the United States. In the transportation sector, CRMA is used as crack sealant to patch or repair damaged and cracked highway surface areas. The market was greatly influenced by the passage of the1991 Intermodal Surface Transportation Efficiency Act (ISTEA) whose section 1038(d) mandated the use of asphalt rubber in federally funded highways beginning with 5% in 1994 and increasing to 20% by 1997. Because CRMA is more expensive than unmodified asphalt, the Act resulted in states' protest, and due to a number of unresolved questions associated with product availability and the ability to recycle, the Act was repealed. In 1995, the Federal Highway Administration funded a study of CRMA's technology and application, engineering soundness and cost effectiveness.

Crumb rubber is expensive; it costs approximately $0.13/lb (Snyder, 1998). Nonetheless, there has been a steady adoption of CRMA especially in Texas, Florida, California and Arizona where its use has reached approximately 20 percent of highway construction. Rubberized asphalt also faces competition from a number of other recyclable commodities that are finding their way into paving mixtures. Any large-scale increase in the use of RMA depends on the state's Department of Transportation's acceptance of national test results, and its willingness to implement them in their own state and local programs (gradual increase is expected over the next five years). Barriers to the use of CRMA include high initial costs, inconsistent long-term performance data, and lack of standards and long-term testing projects.

On the other hand, potential growth for ground rubber markets is affected by the fact that 75 percent of the estimated 240 million pounds sold annually originate from buffing dust produced by the tire retreading industry; only 25 percent is derived from processing whole scrap tires. Thus, ground rubber markets do not significantly reduce the volume of whole scrap tire, and stockpile tires cannot be processed into ground rubber. Secondly, all rubber products gain their toughness and stability through the process of vulcanization (bonding of the carbon atoms of rubber with sulfur). The major limiting factor is that the development of a commercially viable technology to break these bonds has not been developed; thus, vulcanized rubber cannot be returned to its virgin state (Blumenthal and Serumgard, March 1996).

(d) Athletic and Recreational Applications

This is a growing market that includes running track and playground cover. Crumb rubber sprinkled on top of grass has been enjoying a higher price twice the market price of crumb used for other applications. According to Snyder whose company is the sole marketer for Crown III in the United States and abroad, they sell a ton of crumb for about $480 compared to $200. The main market is the golf course industry, which is willing to pay the price of crumb rubber treatment. Grass turf applications are the potential savers of crumb rubber industry.

(e) Molded/Extruded Products

Ground rubber can be added to other polymers to extend or modify their properties in molded/extruded products. This market has a potential to grow.

(f) Friction Brake Material Uses and Automotive Parts

This is a mature industry with little or no growth expected in future.

3.4.3 Civil Engineering Applications

The most dynamic market for scrap tires is in civil engineering applications such as septic drain system and road construction. In most cases, civil engineering applications of the scrap tire materials replace some of the materials currently used in construction. For civil engineering application scrap tires are a cost competitive alternative to stone, they weigh less and are easier to handle. This is a growing market that uses whole or shredded scrap tires, and is the one of the best uses for stockpile tires. Civil engineering applications for whole tires include construction of artificial reefs, slope stabilizers to prevent soil erosion, bumpers for boats along docks, crash barriers at racetracks, and construction of dams in steep-carved channels to prevent land erosion. Typical applications include road embankment fill, lightweight backfill for walls and bridge abutments, daily landfill cover material, leachate collection systems in new landfill cells, subgrade insulation for roads, and septic field aggregates. Limits include low value-added applications that consume only a small portion of the scrap tires.

In 1996 civil engineering projects used about 10 million scrap tires to create artificial reefs, boat bumpers, crash barriers at race tracks, playground equipment, slope stabilizers and erosion control, compared to the 30 million used in 2000. This temporary reduction in the use of scrap tires for civil engineering applications is attributable to the well-publicized heating incidents (2 in Washington State and 1 in Colorado), and the misunderstanding and misinterpretation of the facts and circumstances from these events.

However, the STMC in conjunction with Dr. Humphrey of the University of Maine has prepared a document, which lists the characteristics, properties and examples of scrap tires in civil engineering applications (Blumenthal, 1997b).

3.4.4 Cut, Stamped, and Punched Rubber Products

This is one of the oldest markets and there has been no change for years. It only uses bias ply tires or fabric bodied radial tires and consumes approximately eight million tires annually. Products include muffler hangers and snow blower blades.

3.5 Conclusions and Implications

Although the slow pace of market development for scrap tire applications and products has not caught up with the industry supply, there is a continuous improvement in the efficiency of scrap tire recovery and processing; and remediation of stockpiles with the total stockpiles dropping to an estimated 500 million tires (nearly 100 million tires were permanently removed in the past two years). As the market capacity is gradually catching up with processing volumes, recyclers must continue to focus on value-added finished products and seeding the markets, which, in the long run, will be more profitable.

The key factors for long-term economic success in this field are sound marketing for recycled products, appropriate recycling technology, innovative product development and a local and national government that are supportive of recycling efforts. This will ultimately result in sufficient demand for all annually generated scrap tires. The industry is not without risk and uncertainty, and the distribution of markets relative to the tire supply across the U.S. is at times uneven, but as the end-use markets become more widely accepted, future market development should become less difficult.

The response to subsidies (grants and loans) offered to processors and users of chopped tires has been excellent. Because of the rising use of scrap tiles, existing piles may soon be depleted; Snyder (1998) estimates that they cannot last three years. The whole scene could change, and tipping fees would begin to erode as the intrinsic material value of scrap tires improves.

CHAPTER IV

A MODEL OF WASTE TIRE DISPOSAL

The development of an analytical framework for investigating cost efficiency of waste tire recycling requires modeling cost components for the activities involved and examination of how these costs could be minimized to achieve the desired target results. A linear programming model and a mixed integer model is developed in order to examine transportation cost, the profit maximization, and location of a new tire facility. The model consists of a set of constraints that define the scrap tire flow mass, the capacity limitations of the facilities and the binary solutions for the allocation of the waste tire facility.

The modeling task is broken down to address three tasks necessary for scrap tire management. The first task is to determine a transportation plan that minimizes the cost of transporting scrap tires from each point of generation to the permitted waste tire facilities. The second task is to examine maximization of net profits from processing tires received by the facilities. The third task is to determine of the optimal location for additional tire facilities.

4.1 Transportation of Scrap Tires

The model formulation assumes that the location of waste tire facilities is fixed and the capacity of each facility is also fixed and given. The focus of the model is the transportation of tires from the points of collection to the permitted waste tire facilities.

The least-cost transportation model takes the form of the following linear programming model:

(3.1) $\text{Minimize TC} = \sum_{i} \sum_{j} D_{ij} \times M \times X_{ij}$

subject to

(3.2) $\sum_{j} X_{ij} = T_i$ (quantity limit at i)

$j = 1, \ldots, N$

(3.3) $\sum_{i} X_{ij} \leq K_j$ (capacity constraint at j)

$i = 1, \ldots, N$

(3.4) $X_{ij} \geq 0$

where:

TC = transportation costs to be minimized

D_{ij} = the distances between points of origin (i) and facilities (j)

M = cost/ton/mile

X_{ij} = the amount of waste tires transported from (i) to (j).

K_i = capacity at tire facility (j)

The indices (i) and (j) represent the counties from which the scrap tires are transported and waste tire facilities that receive the tires for processing.

Equation (3.1) is the objective function and is defined as the cost of transporting the tires from points of origin (i) to the processing facilities (j). Constraint (3.2) shows that the amount of tires transported from site (i) to the various tire-processing facilities (j) is equal to the amount of tires available, T_i assumed to be exogenous. Constraint (3.3) simply shows that the tires received at facility (j) cannot exceed the capacity of the facility. Constraint (3.4) ensures the nonnegativity of the amount of tires transported.

4.2 Profit Maximization from Recycled Product

This model focuses on the conversion of the tires into a "recycled" product. The model formulation assumes that the location of waste tire facilities is fixed and the capacity of each facility is also fixed and given. A linear programming model that maximizes net profits from the tire processing plant operations is formulated as follows;

$$(3.5) \quad \text{Maximize } Z = \sum_{j=1}^{J} b_j Y_j - \sum_{i=1}^{I} \sum_{j=1}^{J} M_{ij} X_{ij}$$

subject to

$$(3.6) \quad \sum_{j=1}^{J} X_{ij} = T_i \qquad \text{(quantity limit at i)}$$

$$i = 1, \ldots, N$$

$$(3.7) \quad Y_j - a_j \sum_{i=1}^{I} X_{ij} = 0 \qquad \text{(tire balance constraint at j)}$$

$$j = 1, \ldots, J$$

(3.8) $\sum_{i=1}^{I} X_{ij} \leq K_j$ (capacity constraint at j)

$j = 1,\ldots, J$

(3.9) $Y_j \leq G_j$ (processing capacity at j)

$j = 1,\ldots, J$

(3.10) $X_{ij} \geq 0$

where:

Z = net profits from the tire processing plant operations

M_{ij} = transportation cost per unit

X_{ij} = the amount of waste tires transported from (i) to (j).

T_i = total scrap tires generated and available in (i)

K_i = maximum capacity of waste tire facility (j)

b_j = profit margin per unit of processed materials at waste tire facility (j)

Y_j = total amount of processed material at processing facility (j)

a_j = amount of processed material per unit of tires received at processing facility (j)

G_j = processing facility (j) capacity limit

The indices (i) and (j) represent the counties from which the scrap tires are transported and the existing waste tire facilities that receive the tires.

Equation (3.5) is the objective function and is defined as net profits from the tire processing plant operations. The first term shows the revenue as the "profit" from processed materials derived from the use of old tires and the second term shows the cost of transporting the tires to the processing facilities. Constraint (3.6) shows that the amount of tires transported from site (i) to the various tire-processing facilities (j) is equal to the amount of tires available, T_i assumed to be exogenous. Constraint (3.7) shows that the total amount of processed material produced at facility (j) is proportional to the total quantity of tires transported and received at facility (j) from the respective counties. Constraint (3.8) simply shows that the tires received at facility (j) cannot exceed the capacity of the facility. Constraint (3.9) shows that the tire processing or the quantities of processed material cannot exceed the facility's processing capacity. Constraint (3.10) ensures the nonnegativity of the amount of tires transported.

4.3 Waste Tire Facility Location

To achieve the third objective of the study, the model assumes that there is a potential to build two additional waste tire facilities in the region. The three existing facility are assumed to maintain their processing capacities. A mixed integer model that determines which of the "two potential plants" should be constructed to minimize annualized ownership and transportation costs to fulfill anticipated demand of scrap tires is developed.

$$(3.11) \quad \text{Minimize TA} = \sum_{i=1}^{I} \sum_{j=1}^{J} M_{ij} X_{ij} + \sum_{j} V_j \beta_j$$

subject to

$$(3.12) \quad \sum_{j=1}^{J} X_{ij} = T_i \qquad \text{(quantity supply limit at i)}$$

$$i = 1, \ldots, N$$

$$(3.13) \quad \sum_{i=1}^{I} X_{ij} \le \beta_j K_j \qquad \text{(capacity limit at j if constructed)}$$

$$j = 1, \ldots, J$$

(3.14) $\sum_{j=1}^{J} \beta_j K_j \geq T_i$ (supply limit at i if j is constructed)

$j = 1,\ldots, J$

(3.15) $\sum_{i=1}^{I} X_{ij} \leq K_j$ (capacity constraint at j)

$j = 1,\ldots, J$

(3.16) $\beta_j = 0, 1$

$j = 1,\ldots, J$

(3.17) $X_{ij} \geq 0$

where:

TA = annualized ownership and transportation costs

M_{ij} = transportation cost per unit

X_{ij} = the amount of waste tires transported from (i) to (j).

V_j = annualized cost of building and operating plant (j)

β_j = a zero-one binary choice variable equal to one if economical to construct the plant and equal to zero if not economical to construct

T_i = total scrap tires generated and available in (i)

K_i = quantity demanded or capacity at tire facility (j)

Equation (3.11) is the objective function and is defined as the transportation and annualized ownership cost. The first term shows the cost of transporting the tires to the processing facilities, and the second term illustrates annualized ownership cost per facility to fulfill anticipated demand for scrap tires at the five tire facilities destinations while determining which of the potential plants should be constructed. Constraint (3.12) shows that the amount of tires transported from site (i) to the various tire-processing facilities (j) is equal to the amount of tires available, T_i assumed to be exogenous. Constraint (3.13) imposes a condition that the total amount of tires transported and received from (i) cannot exceed total waste tire capacity of the facilities (j) if constructed. Constraint (3.14) shows that the capacity of all the facilities (if constructed) can exceed the amount of total tires available. Constraint (3.15) simply shows that the tires received at facility (j) cannot exceed the capacity of the facility. Constraint (3.16) shows the zero-one facility binary variable. Constraint (3.17) ensures the nonnegativity of the amount of tires transported.

4.4 Data Sources and Assumptions

We assume a single planning period in which the waste tire program is conducted, that is year 2000. Total waste tire generation was 3,450,563 (46290 tons) estimated using the standard EPA estimate that each person generates one scrap tire. Thus, the number of tires generated is equivalent to the number of people living in each of the seventy-seven counties in Oklahoma. Population data is obtained from the 2000 Census.

The cost of transporting waste tires is estimated by considering the total quantity generated and transported, the distance in miles between each county seat and each facility, and the cost/ton/mile. For the cost/ton/mile, we use an estimate of $0.45 per ton/mile[3] from the literature (Barta, 1999 and Stedge, 1996). City to city

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[3] This includes drivers wages and a return on the capital investment.

mileage distances reported in the official Oklahoma road maps were used to estimate the distance between county seats and the waste tires facilities.

Although a county could have more than one tire dealer from which scrap tires could be collected, we assume that county seats are the points of collection for tires generated in each county. Table 7 indicates counties, county seats/cities, distance between counties and facilities, population and the amount of tires generated by each county. Scrap tire facilities are Four-D Corporation (4-D or Plant #1), Safe Tire Disposal Corporation (Safe or Plant #2) and Frontier Recycling (Front or Plant #3).

Table 7
Counties, County Seats/Cities, Distance between Counties and Facilities, Population, and Amount of Tires Generated by each County

COUNTY	COUNTY SEAT	CTY - 4-D (miles)	CTY - SAFE (miles)	CTY – FRONT (miles)	POP. (2000)	TIRES (tons)
ADAIR	STILWELL	275.6	277.2	99.1	21,038	282.2
ALFALFA	CHEROKEE	224.8	250.1	169.3	6,105	81.9
ATOKA	ATOKA	146.2	79.4	133.7	13,879	186.2
BEAVER	BEAVER	290.6	323.5	280.7	5,857	78.6
BECKHAM	SAYRE	151.0	226.3	237.1	19,799	265.6
BLAINE	WATONGA	121.5	168.0	180.8	11,976	160.7
BRYAN	DURANT	116.1	51.2	163.0	36,534	490.1
CADDO	ANADARKO	61.1	130.2	164.6	30,150	404.5
CANADIAN	EL RENO	105.4	124.7	133.6	87,697	1176.5
CARTER	ARDMORE	64.5	-	164.6	45,621	612
CHEROKEE	TAHLEQUAH	245.6	257.1	75.0	42,521	570.4
CHOCTAW	HUGO	167.2	103.3	158.9	15,342	205.8
CIMARRON	BOISE CITY	391.1	475.7	388.1	3,148	42.2
CLEVELAND	NORMAN	86.6	80.7	122.7	208,016	2,790.5
COAL	COALGATE	161.0	96.2	129.1	6,031	81
COMANCHE	LAWTON	34.0	103.7	193.5	114,996	1,542.7
COTTON	WALTERS	35.5	84.3	212.7	6,614	88.7
CRAIG	VINITA	251.4	276.9	64.0	14,950	200.6
CREEK	SAPULPA	233.0	244.2	43.2	67,367	903.7
CUSTER	ARAPAHO	143.2	188.6	197.5	26,142	350.7
DELAWARE	JAY	281.3	310.1	91.1	37,077	497.4
DEWEY	TALOGA	169.5	216.0	205.4	4,743	63.6
ELLIS	ARNETT	206.7	254.4	236.7	4,075	54.6
GARFIELD	ENID	173.2	194.7	115.3	57,813	775.6
GARVIN	P. VALLEY	56.3	42.1	161.3	27,210	365
GRADY	CHICKASHA	43.6	112.7	147.4	45,516	610.6

COUNTY	COUNTY SEAT	CTY - 4-D (miles)	CTY - SAFE (miles)	CTY – FRONT (miles)	POP. (2000)	TIRES (tons)
GRANT	MEDFORD	213.7	216.3	134.2	5,144	69
GREER	MANGUM	117.7	186.8	314.8	6,061	81.3
HARMON	HOLLIS	129.8	198.9	334.8	3,283	44
HARPER	BUFFALO	225.2	271.3	242.1	3,562	47.8
HASKELL	STIGLER	261.2	254.1	106.4	11,792	158.2
HUGHES	HOLDENVILL	123.2	119.2	95.5	14,154	189.9
JACKSON	ALTUS	90.8	159.9	246.5	28,439	381.5
JEFFERSON	WAURIKA	29.0	52.0	210.8	6,818	91.5
JOHNSTON	TISHOMINGO	89.0	34.8	155.6	10,513	141
KAY	NEWKIRK	205.2	215.7	107.6	48,080	645
KINGFISHER	KINGFISHER	108.9	152.9	150.9	13,926	186.8
KIOWA	HORBAT	97.5	166.5	271.6	10,227	137.2
LATIMER	WILBURTON	259.8	153.8	120.5	10,692	143.4
LEFLORE	POTEAU	273.6	199.3	128.8	48,109	645.4
LINCOLN	CHANDLER	129.8	140.5	63.9	32,080	430.4
LOGAN	GUTHRIE	114.2	124.6	110.9	33,924	455.1
LOVE	MARIETTA	81.3	19.4	232.9	8,831	118.5
MCCLAIN	PURCELL	62.6	65.3	145.5	27,740	372.1
MCCURTAIN	IDABEL	216.4	152.5	206.6	34,402	461.5
MCINTOSH	EUFAULA	219.7	207.7	88.1	19,456	261
MAJOR	FAIRVIEW	187.3	204.6	159.2	7,454	100
MARSHALL	MADILL	91.1	26.9	175.5	13,184	176.9
MAYES	PRYOR	230.8	266.3	43.5	38,369	514.7
MURRAY	SULPHUR	56.7	33.4	146.8	12,623	169.3
MUSKOGEE	MUSKOGEE	221.5	233.0	57.5	69,451	931.7
NOBLE	PERRY	147.1	157.5	78.9	11,411	153.1
NOWATA	NOWATA	239.2	250.8	50.3	10,569	141.8
OKFUSKEE	OKEMAH	151.5	163.0	70.3	11,814	158.5
OKLAHOMA	OK. CITY	84.7	96.9	106.7	660,448	8,860
OKMULGEE	OKMULGEE	183.9	195.4	38.9	39,685	523.4
OSAGE	PAWHUSKA	240.3	267.5	66.8	44,437	596.1
OTTAWA	MIAMI	276.7	301.6	90.0	33,194	445.3
PAWNEE	PAWNEE	175.9	198.1	55.5	16,612	222.8
PAYNE	STILLWATER	151.8	162.5	70.2	68,190	914.8
PITTSBURG	McALESTER	231.0	127.7	94.5	43,953	576.2
PONTOTOC	ADA	85.9	91.7	120.4	35,143	471.4
POTTAWATOMIE	SHAWNEE	115.5	89.9	94.1	65,521	879
PUSHMATAHA	ANTLERS	146.9	115.6	146.0	11,667	156.5
ROGER MILLS	CHEYENNE	174.5	242.6	247.6	3,436	46.1
ROGERS	CLAREMORE	216.0	227.4	28.1	70,641	947.6
SEMINOLE	WEWOKA	127.6	118.2	83.7	24,894	334.0
SEQUOYAH	SALLISAW	263.1	251.1	98.3	38,972	522.8
STEPHENS	DUNCAN	-	64.4	189.6	43,182	579.3
TEXAS	GUYMON	335.3	368.3	325.7	20,107	269.7
TILLMAN	FREDERICK	84.1	121.7	241.6	9,287	124.6
TULSA	TULSA	193.0	201.1	-	563,299	7,556.7
WAGONER	WAGONER	231.4	242.9	44.2	57,491	771.2
WASHINGTON	BARTLESVILLE	238.0	249.2	48.3	48,996	657.3
WASHITA	CORDELL	109.7	204.4	250.1	11,508	154.4
WOODS	ALVA	216.9	273.2	193.9	9.089	121.9
WOODWARD	WOODWARD	192.2	248.3	203.1	18,486	248

The estimates for the processing costs are based on the amount of the processed material and the price at which a unit of processed material is sold. According to the estimates provided by Safe Tires and Frontier (telephone interviews), it costs approximately \$0.32 to process one PTE (per tire equivalent). This is approximately \$32/per ton[4] and is very close to the \$36/ton processing cost estimated by Snyder (1998).

Prices for tire chips are determined by the quality and the size, they range between \$10 and \$45 per ton (Brown et al, 2001 and Recyclers World, 2002). The estimate for the price of tire chips in Oklahoma is approximately \$20/ton (telephone interviews). According to Roger Falk, a scrap-tire consultant, processors make between 25 and 30 cents profit per tire (Barta, 1999). Brown et al (2001) estimated profit margin to be approximately 15 percent for processors charging \$0.65 tipping fee and selling tire chips at \$10/ton. Based on the price of tire chips and the fact that processors in Oklahoma charge no tipping fees, it is assumed that profit margin is between 25 and 30 percent.

Out of the total scrap tires collected/processed during FY 99-00 in Oklahoma, Safe Tires Corp. collected/processed 72 percent; Four-D Corp.17 percent and Frontier 11 percent. This information is used to estimate the number of tires transported and collected by the waste tire facilities and plant capacity of each facility. According to the information provided by Frontier Recycling, (telephone) it takes about 150 tires (1.5 tons) to produce a ton of tire chips. The problem is set such that there are 77 points of origin for scrap tires and 3 facilities.

The notion of constructing a new facility is based on the fact that the two larger existing facilities are located in the southern part of the state and the only facility in the

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[4] 100 tires equals 1 ton (RMA, 2001)

northern part is the smallest in the state. Since the study considers transportation costs, it may be economical to construct a new plant in the northern part of the state. In addition, approximately 7.7 percent of total scrap tires generated are not transported to the existing tire facility. It is likely that this amount is illegally dumped.

Location of the new waste tire facility is determined by the tradeoff between the investment outlays or cost and transportation cost, and the market for the processed material. The proposed facility will be located in either Enid (Garfield county) or Vinita (Craig County). In order to determine optimal location of the new plant, we need estimates for the annual cost of operating the plant and the useful life expectancy of the facility.

The decision to locate a plant or facility and the choice of plant size at any potential location are discrete variables and the processing capacity of potential facilities is constrained by a zero-one integer. The total fixed cost (TFC) are charged to the objective function only if the corresponding binary variables attain the value of one. Annualized ownership costs (AOC) are defined as

$$AOC = AFC + AOMC \tag{3.11}$$

where AFC is the annual amortized fixed charge over the life of the facility and AOMC is the annual operating and maintenance cost. According to the EPA Study HM 10103, annual AOMC is 2.5 percent of the AFC. The study assumes a ten-year facility life, a 10 percent interest rate and a $1.50/tire fixed cost based on the Business Plan for Tire Operation by Brunswick Research Inc.

4.5 Sensitivity Analysis

Experiments corresponding to a departure from the base models are performed. These experiments are performed to observe the outcomes for different combinations of the magnitudes of transportation cost per unit and profit margins per ton. While these experiments use parameters suggestive of an application to scrap tires, the goal is not to draw policy conclusions. Instead, the results from the experiments are used to suggest alternative approaches and methods that could be considered when establishing a waste management program. The models determine an optimum combination of scrap tire recycling activities from the transportation to profit maximization from processing, and plant location.

The first scenario assumes reductions of the cost/ton/mile, and the experiment is performed on the transportation model. These reductions may result from a transportation subsidy introduced by the agency to enhance waste tire recycling. In the second scenario, the magnitude of the profit margin is varied together with the levels of cost/ton/mile. The third scenarios considered the optimal location of a new waste tire facility.

CHAPTER V

RESULTS

A linear programming model and a mixed integer programming model that allow us to analyze the specific objectives of this study are developed. The results are found by implementing the Generalized Algebraic Modeling System (GAMS). A base case scenario from which several experiments are conducted is established. In this study, waste tire recycling (processing) is assumed to be the only effective disposal option. Scrap tires generated from each county are transported to three waste tire-processing facilities in the state. In 2000 approximately 82.3 percent of the total tires generated (44,900 tons) was transported and processed, and about 3 percent was exempted from the tire program. Data used for the base model scenario is estimated according to OKDEQ tire allocation and the discussions in Chapter III.

Table 8
The Base Scenario Estimates

ACTIVITY (tons/dollars)	FOUR D	SAFE TIRES	FRONTIER	MODEL
Tires Trans. & Processed	6,282	26,606	4,065	
Plant Capacity	7,875	33,336	5,998	
Processing Capacity	9,423	39,909	6,098	
Processed Material	5,780	24,478	3,740	
Annual Ownership Cost	$9,514.70	$40,297.57	$6,156.57	
$/ton/mile				$0.45
Profit/ton				$25

The formula for converting units of total tires generated to tons is based on the Waste Tire Management Council's 1994 estimate that 90 percent of tires generated are passenger car tires and 10 percent are truck tires, and the Oklahoma DEQ per passenger tire equivalent of 18.7 pounds and the WTMC truck tire equivalent of 100 pounds. Thus,

$$\text{Tons} = (\text{Total number of scrap tires}) \times [(0.90 \times 18.7) + (0.10 \times 100)] \div 2000$$

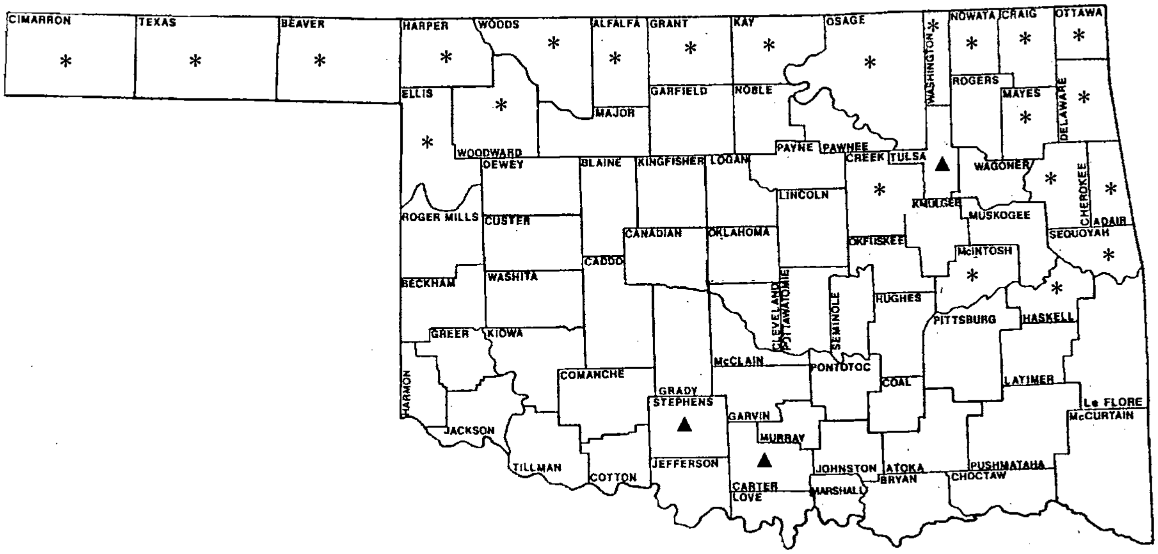
5.1 Model Experiment: Magnitude Choices

The model assumes that parameter estimates on which experiments are conducted are known with certainty. The parameters considered are cost/ton/mile, profit/ton. The first scenario considers the impact of three magnitudes of cost/ton/mile, $0.45, $0.34 and $0.29 on the least-cost transportation model, decreasing because of a 25 and a 35 percent subsidy assumption. Two conditions of scrap tire transportation are investigated by changing the quantity limit constraint. In the first condition it is assumed that total tires transported from the counties cannot exceed the amount of tires generated. For the second condition total tires transported are assumed to be equal to the amount of tires generated.

Transportation costs are significant as scrap tire transportation distances between the points of origin and the facilities increase. The information provided by the results of transportation analysis could assist in the development of a subsidy for transporting scrap tires or in choosing the size of the subsidy. For example, a regulator may choose different subsidy levels for different mile radius instead of a flat rate for all points of origins.

Results show that an optimal plan for transporting tires using the inequality constraint is achieved by shipping scrap tires from fifty-four counties out of the seventy-seven. Counties from which tires could not be transported include Adair, Alfalfa, Beaver, Cherokee, Cimarron, Craig, Creek, Delaware, Ellis, Grant, Harper, Haskell, Kay, McIntosh, Mayes, Muskogee, Nowata, Osage, Ottawa, Sequoyah, Texas, Wagoner, Washington, Woods, and Woodward. Figure 2 shows the optimal transportation pattern and approximately 9,113.1 tires are not transported. The reader must note that counties like Creek, Muskogee, McIntosh, and Mayes are not far from Frontier Recycling Corporation in Tulsa, the problem may be the size of the capacity for this facility. It is the smallest out of the three. A higher subsidy level may be required to transport tires from the other counties, most of which are very far from the waste tire facilities.

Figure 2
The Optimal Transportation Pattern – Three Facilities



* Counties from which tires are not transported under the first condition
▲Waste tire facilities

The optimal transportation pattern of the tires is also shown in Table 13. The marginal cost of transporting additional units (tons) of tires from the counties that could not transport tires to the tire facilities according to the optimal transportation pattern also varies with each level of the cost/ton/mile. Reducing the cost/ton/mile or introduction of a subsidy reduces these marginal values by the percentages of the subsidy as shown in Table 14. However, the results for the transportation pattern are not affected by the changes in cost/ton/mile; only the values of the objective function are affected. The cost of receiving one more unit (ton) of tires is high for all three tire facilities; $82.44 for Four D, $92.12 for Safe Tires, and $12.65 for Frontier.

The assumption of transporting all the tires generated (strict equality constraint or second condition) results in the increase in the value of minimum transportation cost (objective function). The optimal transportation pattern also changes, for example under the previous scenario tires from Garfield and Tulsa were distributed between Safe Tires and Frontier but are now transported one facility. Tables 13 and 14 show the optimal transportation pattern and the changes in marginal values for this scenario. Changes in the shadow prices for the second case are very low compared to the first case. Table 9 illustrates these changes in the value of the objective function for the transportation model for the two conditions.

Table 9

Objective Function Value for Transportation - Three Tire Facilities

\$/ton/mile	**Supply Constraint**	**Objective Function Value**
\$0.45	$\sum_j X_{ij} \leq T_i$ **(1st Cond.)**	\$1,711,848.00
\$0.34		\$1,293,395.00
\$0.29		\$1,103,191.00
\$0.45	$\sum_j X_{ij} = T_i$ **(2nd Cond.)**	\$2,623,665.00
\$0.34		\$1,982,325.00
\$0.29		\$1,690,806.000

The second scenario examines maximization of net profits from processed material. The study assumes that only tire chips are produced through tire processing. In 2000 ninety two percent of waste tires were processed in Oklahoma. The experiments are conducted by varying the magnitude of profit per ton (\$25 and \$30), the three levels of cost/ton/mile (\$0.45, \$0.34 and \$0.29) for transportation cost, and the amount of processed material per unit of tires received at the tire facilities (92 and 100 percent). The two supply constraint conditions hold. Results from all the combinations of the above mentioned profit margins show that tire processors generate no profits.

The model was then run at different levels of profit per ton and \$0.29 cost/ton/mile to investigate the levels at which tire processors start generating profits. For the first condition, tire processors begin generating profits at \$35.10/ton profit margin when ninety-two percent tires received are processed and at \$30.18 /ton profit margin when all tires received are processed. For the second condition, profit generation begins at \$41.61/ton profit level when ninety-two percent tires received are processed and at \$36.04 when all tires received are processed. These results are shown in Table 10.

Table 10
Objective Function Value – Net Profit Maximization

\$/t/m	Profit/ton	Supply Constraint	a_j	Obj. (F) Value
\$0.45	\$25	$\sum_j X_{ij} \le T_i$	.92	-\$1,087.611.00
			1	-\$806,358.00
\$0.34	\$25		.92	-\$595,927.00
			1	-\$383,424.00
\$0.29	\$25		.92	-\$372,434.00
			1	-\$191,182.00
\$0.45	\$30	$\sum_j X_{ij} = T_i$	.92	-\$1,832,125.00
			1	-\$1,432,050.00
\$0.34	\$30		.92	-\$1,101,272.00
			1	-798,994.00
\$0.29	\$30		.92	-\$769,067.00
			1	-\$511,241.00

Because a higher profit margin is necessary, results from this study tend to confirm the perceptions that profit margins for tire chip producers are very low for tire processors. The inclusion of other costs may change the conclusions of this study. However, there are other factors and concerns such as declining demand (discussed in chapter two) that affect the market for tire chip production, which need to be considered.

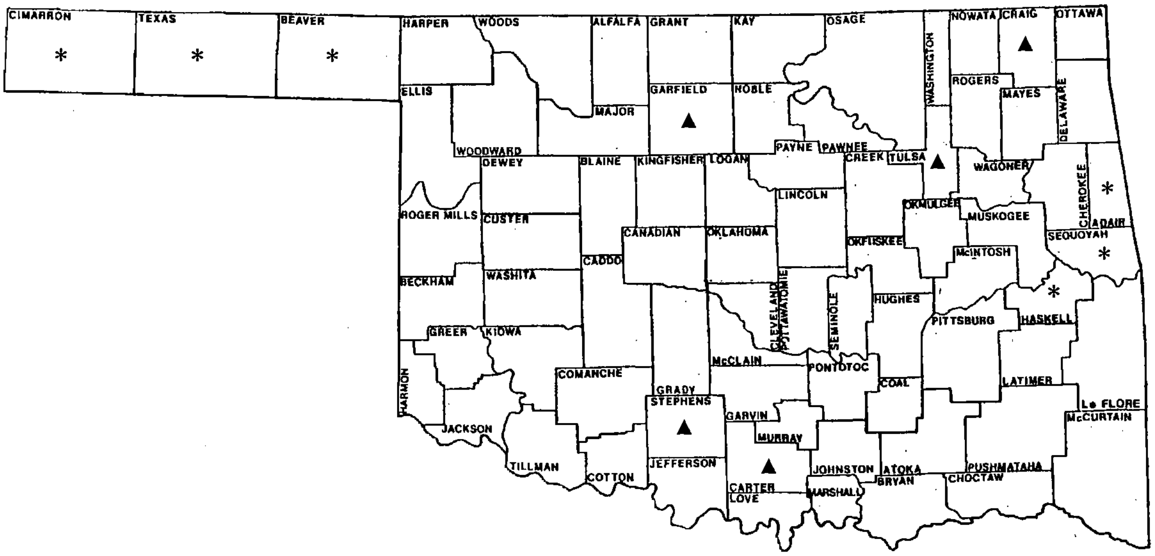
The third scenario considers the option of constructing new facilities in Enid and Vinita. The model treats facility location as a discrete variable and the objective is to minimize transportation costs and annualizes ownership costs. We assume that the three existing tire facilities operate at their current capacities (specified in the base scenario estimates). The capacities for the two potential facilities are varied between 4,000 and 6,000 tons of tires. First we assume equal capacities of 4,000 tons for each potential facility, then 4,000 and 6,000 tons for each facility for different cases, and finally 6,000 tons for both potential facilities. The experiment is conducted at $0.29/ton/mile only and the supply limit constraints hold. Table 11 illustrates the results.

Table 11
Objective Function Value – Transportation and Location Model

$/ton/mile	**WTF-cap**	**Supply Constraint**	**Obj. F Value**
$0.29	VN 4000 EN 4000	$\sum_j X_{ij} \leq T_i$	$1,326,595.00
$0.29	VN 6000 EN 4000		$1,267,671.00
$0.29	VN 4000 EN 6000		$1,174,536.00
$0.29	VN 6000 EN 6000		$1,179,942.00
$0.29	VN 4000 EN 4000	$\sum_j X_{ij} = T_i$ (**2nd Cond.**)	$1357,478.00
$0.29	VN 6000 EN 4000		$1,280,141.00
$0.29	VN 4000 EN 6000		$1,219,242.00
$0.29	VN 6000 EN 6000		$1,224,638.00

According to the results it is economical to construct both facilities. Changing capacities and cost/ton/mile does not change the optimal transportation pattern, only the objective and marginal values change. However, changes of the supply limit constraint produce changes in optimal transportation pattern, objective value and marginal values of transporting tires. For the first condition, about 1,353 tires are not transported from Adair, Beaver, Cimarron, Haskell, Sequoyah and Texas, this is illustrated in Figure 3.

Figure 3
Optimal Transportation Pattern – Five Facilities



* Counties from which tires are not transported under the first condition
▲Waste tire facilities

Comparing the minimum cost of transporting tires between three and five facilities, transportation cost is lower for the three facilities under the first condition. However, if all tires generated are transported, the transportation cost is lower for the five facilities. Table 12 shows the objective function values for five facilities.

Table 12
Objective Function Value – Transportation Model – Five Facilities

$/ton/mile	Supply constraint	Objective function value
$0.45	$\sum_{j}$ Xij $\leq$ Ti (1st cond.)	$1,958,765.00
$0.34		$1,479,955.00
$0.29		$1,1262,315.00
$0.45	$\sum_{j}$ Xij = Ti (2nd cond.)	$2,015,746.00
$0.34		$1,523,008.00
$0.29		$1,299.036.00

Tables 13–20 show the optimal transportation patterns and marginal costs of transporting one more unit (ton) of tires from each county for the transportation models and transportation and location models as different experiments are conducted. For optimal transportation pattern tables, blanks indicate that no tires are transported to respective tire facilities. For marginal cost tables, blanks represent the facilities to which scrap tires were optimally transported.

Table 13
Optimal Transportation Pattern for Tires *in Tons* for Three Facilities Under the First Condition or Inequality Constraint

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
ATOKA		186.2	
BECKHAM	265.6		
BLAINE	160.7		
BRYAN		490.1	
CADDO	404.5		
CANADIAN		1,176.5	
CARTER		621.0	
CHOCTAW		205.8	
CLEVELAND		2,790.5	
COAL		81.0	
COMANCHE	1,542.7		
COTTON	88.7		
CUSTER	350.7		
DEWEY	63.6		
GARFIELD	745.4	30.2	
GARVIN		365.0	
GRADY	610.6		
GREER	81.3		
HARMON	44.0		
HUGHES		189.9	
JACKSON	381.5		
JEFFERSON	91.5		
JOHNSTON		141.0	
KINGFISHER	186.8		
KIOWA	137.2		
LATIMER		143.4	
LEFLORE		645.4	

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
LINCOLN		430.4	
LOGAN		455.1	
LOVE		118.5	
MCCLAIN		372.1	
MCCURTAIN		461.5	
MAJOR		100.5	
MARSHALL		176.9	
MURRAY		169.3	
NOBLE		153.1	
OKFUSKEE		158.5	
OKLAHOMA		8,860.0	
OKMULGEE		523.4	
PAWNEE	222.8		
PAYNE		914.8	
PITTSBURG		576.2	
PONTOTOC		471.4	
POTTAWATOMIE		879.0	
PUSHMATAHA		56.5	
ROGER MILLS	46.1		
ROGERS			746.6
SEMINOLE		334.0	
STEPHENS	579.3		
TILLMAN	124.6		
TULSA		4,238.3	3,318.6
WASHITA	154.4		

Table 14
Marginal Cost of Transporting Tires for Three Facilities at $0.45 and $0.29*/Ton/Mile *in Dollars*- First Condition or Inequality Constraint. Values in Parenthesis are for $0.29/Ton/Mile, Others are for $0.45/Ton/Mile

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
ADAIR	$41.58 *($26.80)*	$30.39 *($19.58)*	$31.95 *($20.59)*
ALFALFA	18.72 *(12.06)*	20.43 *(13.66)*	63.45 *(40.89)*
ATOKA	39.74 *(25.61)*		103.91 *(66.96)*
BEAVER	48.33 *(31.15)*	53.46 *(34.45)*	113.67 *(73.25)*
BECKHAM		24.21 (15.60)	108.54 *(69.95)*
BLAINE		11.25 *(7.20)*	96.48 *(62.18)*
BRYAN	38.88 *(25.06)*		129.78 *(83.64)*
CADDO		21.42 *(13.80)*	116.37 *(74.99)*
CANADIAN	1.035 (0.67)		83.48 (53.80)
CARTER	25.11 *(16.18)*		139.95 *(90.19)*
CHEROKEE	28.08 *(18.08)*	23.58 *(15.20)*	21.11 *(13.60)*
CHOCTAW	42.48 *(18.10)*		104.49 *(67.34)*
CIMARRON	93.56 *(60.29)*	121.95 *(78.59)*	162.00 *(104.40)*
CLEVELAND	12.33 *(7.95)*		98.37 *(63.40)*
COAL	38.84 *(25.03)*		94.27 *(60.76)*
COMANCHE		21.69 *(13.98)*	141.57 *(91.23)*
COTTON		12.26 (7.92)	149.54 (96.37)
CRAIG	30.69 *(19.78)*	32.49 *(20.94)*	16.16 *(10.41)*
CREEK	22.41 *(14.42)*	17.78 *(11.46)*	6.80 *(4.38)*
CUSTER		10.76 (6.93)	94.23 *(60.73)*
DELAWARE	44.15 *(28.45)*	47.43 *(30.57)*	28.35 *(18.27)*
DEWEY		11.25 *(7.25)*	85.95 *(55.39)*
ELLIS	10.56 *(6.82)*	22.37 *(14.41)*	93.87 *(60.94)*
GARFIELD			43.73 *(28.19)*
GARVIN	16.07 *(10.35)*		133.11 *(85.78)*
GRADY		21.42 (13.80)	116.51 *(75.08)*
GRANT	13.73 *(8.85)*	5.22 *(11.08)*	47.75 (30.77)
GREER		21.42 *(13.80)*	158.49 *(102.14)*
HARMON		21.42 *(13.80)*	162.05 *(104.43)*
HARPER	18.90 *(12.18)*	5.67 *(3.65)*	96.30 *(62.06)*
HASKELL	35.10 *(22.62)*	22.23 *(14.33)*	35.24 *(22.71)*
HUGHES	11.48 (7.40)		68.81 (44.34)
JACKSON		21.42 *(13.80)*	139.86 *(90.13)*
JEFFERSON		0.68 *(0.44)*	151.61 (97.70)
JOHNSTON	34.07 *(21.95)*		133.83 *(86.25)*
KAY	9.90 *(6.38)*	4.95 *(3.19)*	35.78 *(23.06)*
KINGFISHER		10.13 (6.53)	88.70 *(57.16)*
KIOWA		21.38 (13.78)	148.14 *(95.47)*
LATIMER	$57.38 *($36.98)*		$64.49 *($41.56)*

ORIGIN	FOUR D		SAFE TIRES		FRONTIER	
LEFLORE	43.11	*(27.78)*			47.75	*(30.77)*
LINCOLN	4.86	*(3.13)*			45.00	(29.00)
LOGAN	5.00	*(3.22)*			73.31	*(47.24)*
LOVE	37.53	*(24.19)*			175.55	*(113.13)*
MCCLAIN	8.46	*(5.45)*			115.56	*(74.47)*
MCCURTAIN	38.43	*(24.77)*			103.82	*(66.90)*
MCINTOSH	16.43	*(10.59)*	1.35	(0.87)	27.00	*(17.40)*
MAJOR	1.89	*(1.22)*			59.04	*(38.05)*
MARSHALL	38.57	*(24.85)*			146.34	*(94.31)*
MAYES	21.42	*(13.80)*	27.72	*(17.86)*	6.93	*(4.47)*
MURRAY	20.16	*(12.99)*			130.50	(84.10)
MUSKOGEE	17.24	*(11.11)*	1 2.74	*(8.21)*	13.23	(8.53)
NOBLE	5.00	*(3.22)*			44.10	*(28.42)*
NOWATA	25.20	*(16.24)*	20.75	*(13.46)*	9.99	*(6.44)*
OKFUSKEE	4.50	*(2.90)*			37.76	*(24.33)*
OKLAHOMA	4.19	*(2.70)*			83.88	*(54.06)*
OKMULGEE	4.50	*(2.90)*			9.05	(5.83)
OSAGE	25.70	*(16.56)*	28.26	*(18.21)*	17.42	*(11.22)*
OTTAWA	42.08	*(27.12)*	43.61	*(28.10)*	27.89	*(17.95)*
PAWNEE			0.32	*(0.20)*	15.62	*(10.06)*
PAYNE	4.86	(3.13)			37.94	*(24.45)*
PITTSBURG	56.16	*(36.19)*			64.53	*(41.59)*
PONTOTOC	7.07	*(4.55)*			92.39	*(59.54)*
POTTAWATOMIE	21.24	*(13.69)*			81.41	*(52.46)*
PUSHMATAHA	23.76	*(15.31)*			93.15	*(60.03)*
ROGER MILLS			20.97	*(13.51)*	102.69	*(66.18)*
ROGERS	14.76	*(9.51)*	10.22	*(6.58)*		
SEMINOLE	13.91	*(8.96)*			70.52	(45.44)
SEQUOYAH	35.96	*(23.17)*	20.88	*(13 .46)*	25.02	*(16.12)*
STEPHENS			7.38	*(4.76)*	143.19	*(92.28)*
TEXAS	68.45	*(44.11)*	73.62	*(47.44)*	143.19	*(86.30)*
TILLMAN			7.25	*(4.67)*	140.67	*(90.65)*
TULSA	6.03	*(3.89)*				
WAGONER	21.69	*(13.98)*	17.19	*(11.08)*	7.25	*(4.67)*
WASHINGTON	24.66	*(15.89)*	20.03	*(12.91)*	9.09	*(5.86)*
WASHITA			32.94	(21.23)	132.98	*(85.70)*
WOODS	15.17	*(9.77)*	30.83	*(19.87)*	74.61	*(48.08)*
WOODWARD	4.05	*(2.61)*	19.62	*(12.64)*	78.75	*(50.75)*

Table 15
Optimal Transportation Pattern for Tires *in Tons* for Three Facilities Under the Second Condition or Equality Constraint

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
ADAIR		282.2	
ALFALFA	81.9		
ATOKA		186.2	
BEAVER	78.6		
BECKHAM	265.6		
BLAINE	160.7		
BRYAN		490.1	
CADDO	404.5		
CANADIAN		1,176.5	
CARTER		621.0	
CHEROKEE		570.4	
CHOCTAW		205.8	
CIMARRON	42.2		
CLEVELAND		2,790.5	
COAL		81.0	
COMANCHE	1,542.7		
COTTON	88.7		
CRAIG			200.6
CREEK			903.7
CUSTER	350.7		
DELAWARE			497.4
DEWEY	63.6		
ELLIS	54.6		
GARFIELD	775.6*		
GARVIN		365.0	
GRADY	610.6		
GRANT		69/0	
GREER	81.3		
HARMON	44.0		
HARPER		47.8	
HASKELL		158.2	
HUGHES		189.9	
JACKSON	381.5		
JEFFERSON	91.5		
JOHNSTON		141.0	
KAY		645.0	
KINGFISHER	186.8		
KIOWA	137.2		
LATIMER		143.4	
LEFLORE		645.4	

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
LINCOLN		430.4	
LOGAN		455.1	
LOVE		118.5	
MCCLAIN		372.1	
MCCURTAIN		461.5	
MCINTOSH		261.0	
MAJOR		100.5	
MARSHALL		176.9	
MAYES			514.7
MURRAY		169.3	
MUSKOGEE		931.7	
NOBLE		153.1	
NOWATA			141.8
OKFUSKEE		158.5	
OKLAHOMA		8,860.0	
OKMULGEE		523.4	
OSAGE	577.7		18.4
OTTAWA			445.3
PAWNEE	222.8		
PAYNE		914.8	
PITTSBURG		576.2	
PONTOTOC		471.4	
POTTAWATOMIE		879.0	
PUSHMATAHA		56.5	
ROGER MILLS	46.1		
ROGERS			947.6*
SEMINOLE		334.0	
SEQUOYAH		522.8	
STEPHENS	579.3		
TILLMAN	124.6		
TULSA		7,556*	
WAGONER			771.2
WASHINGTON			657.3
WASHITA	154.4		
WOODS	121.9		
WOODWARD	248.0		

* Indicates changes in transportation pattern for the previous experiment

Table 16
Marginal Cost of Transporting Tires for Three Facilities at $0.45 and $0.29*/Ton/Mile *in Dollars* - Second Condition or Equality Constraint. Values in Parenthesis are for $0.29/Ton/Mile, Others are for $0.45/Ton/Mile

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
ADAIR	$10.17 *($6.55)*		$8.82 *($5.68)*
ALFALFA		2.75 *(1.77)*	53.01 *(34.16)*
ATOKA	38.70 *(24.94)*		111.15 *(71.63)*
BEAVER		6.62 *(3.97)*	73.62 *(47.44)*
BECKHAM		25.25 *(16.27)*	116.82 *(75.28)*
BLAINE		12.29 *(7.92)*	104.76 *(67.51)*
BRYAN	37.85 *(24.39)*		137.03 *(88.31)*
CADDO		22.46 *(14.47)*	124.65 *(80.33)*
CANADIAN			90.72 *(58.46)*
CARTER	24.08 *(15.52)*		147.20 *(94.86)*
CHEROKEE	3.47 *(2.23)*		4.77 *(3.07)*
CHOCTAW	41.45 *(26.71)*		111.74 *(72.01)*
CIMARRON		29.43 *(18.97)*	76.73 *(49.45)*
CLEVELAND	11.30 *(7.28)*		105.62 *(68.06)*
COAL	37.80 *(24.36)*		101.52 *(65.42)*
COMANCHE		22.74 *(14.65)*	149.85 *(96.57)*
COTTON		13.32 *(8.58)*	157.82 *(101.70)*
CRAIG	6.26 *(4.03)*	9.09 *(5.86)*	
CREEK	7.34 *(4.73)*	3.74 *(2.41)*	
CUSTER		11.79 *(7.60)*	102.51 *(66.06)*
DELAWARE	7.52 *(4.83)*	11.84 *(7.63)*	
DEWEY		12.29 *(7.92)*	91.56 *(60.73)*
ELLIS		12.83 *(8.27)*	91.56 *(59.02)*
GARFIELD		1.04 *(0.67)*	52.02 *(33.52)*
GARVIN	15.03 *(9.69)*		140.36 *(90.45)*
GRADY		22.46 *(14.47)*	124.79 *(80.42)*
GRANT	7.47 *(4.81)*		49.77 *(32.07)*
GREER		22.46 *(14.47)*	166.77 *(107.47)*
HARMON		22.46 *(14.47)*	170.33 *(109.77)*
HARPER	12.20 *(7.86)*	5.67	97.88 *(63.08)*
HASKELL	11.84 *(7.63)*		20.25 *(13.05)*
HUGHES	10.44 *(6.73)*		76.05 *(49.01)*
JACKSON		22.46 *(14.47)*	148.14 *(95.47)*
JEFFERSON		1.71 *(1.10)*	159.89 *(103.04)*
JOHNSTON	33.03 *(21.29)*		141.08 *(90.92)*
KAY	3.92 *(2.52)*		38.07 *(24.53)*
KINGFISHER		11.16 *(7.19)*	96.98 *(62.50)*
KIOWA		22.41 *(14.44)*	156.42 *(100.80)*
LATIMER	56.34 (36.31)		71.73 *(46.23)*

ORIGIN	FOUR D	SAFE TIRES	FRONTIER
LEFLORE	$42.08 *($27.16)*		$54.99 *($35.44)*
LINCOLN	3.83 *(2.47)*		52.25 *(33.67)*
LOGAN	3.96 *(2.55)*		80.55 *(51.91)*
LOVE	36.50 *(23.52)*		182.79 *(117.80)*
MCCLAIN	7.43 *(4.79)*		122.81 *(79.14)*
MCCURTAIN	37.40 *(24.10)*		111.06 *(71.57)*
MCINTOSH	14.04 *(9.05)*		32.90 *(21.20)*
MAJOR	0.86 *(0.55)*		66.29 *(42.72)*
MARSHALL	37.53 *(24.19)*		153.59 *(98.98)*
MAYES	6.21 *(4.00)*	13.55 *(8.73)*	
MURRAY	19.13 *(12.33)*		137.75 (88.77)
MUSKOGEE	3.47 *(2.23)*		7.74 *(4.99)*
NOBLE	3.96 *(2.55)*		51.35 *(33.09)*
NOWATA	6.93 *(4.47)*	3.51 *(2.26)*	
OKFUSKEE	3.47 *(2.23)*		45.00 *(29.00)*
OKLAHOMA	3.15 (2.03)		91.13 (58.73)
OKMULGEE	3.47 *(2.23)*		16.29 *(10.50)*
OSAGE		3.60 *(2.30)*	
OTTAWA	5.94 *(3.83)*	8.51 *(5.48)*	
PAWNEE		1.35 *(0.87)*	23.90 *(15.40)*
PAYNE	3.83 *(2.47)*		45.18 *(29.17)*
PITTSBURG	55.13 *(35.53)*		71.78 *(46.26)*
PONTOTOC	6.03 *(3.89)*		99.63 *(64..21)*
POTTAWATOMIE	20.21 *(13.02)*		88.65 (57.13)
PUSHMATAHA	22.73 *(14.65)*		100.40 *(64.70)*
ROGER MILLS		22.01 *(14.18)*	110.97 *(71.51)*
ROGERS	6.48 *(4.18)*	2.97 *(1.91)*	
SEMINOLE	12.87 *(8.30)*		77.76 *(50.11)*
SEQUOYAH	14.04 *(9.05)*		11.39 *(7.34)*
STEPHENS		8.42 *(5.42)*	151.47 *(97.61)*
TEXAS		6.21 (4.00)	73.76 *(47.53)*
TILLMAN		8.28 (5.34)	148.95 *(95.99)*
TULSA	4.99 *(3.22)*		7.25 *(4.67)*
WAGONER	6.17 *(3.97)*	2.70 *(1.74)*	
WASHINGTON	7.29 *(5.05)*	3.69 *(2.79)*	
WASHITA		33.98 (21.90)	141.26 *(91.03)*
WOODS		16.70 *(10.76)*	67.73 (43.65)
WOODWARD		16.61 *(10.70)*	82.98 (53.48)

Table 17
Optimal Transportation Pattern – Transportation and Location Model with Five Facilities at $0.29/Ton/Mile- First Condition or Inequality Constraint

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
ADAIR					
ALFALFA				81.9	
ATOKA		186.2			
BEAVER					
BECKHAM	265.6				
BLAINE	160.7				
BRYAN		490.1			
CADDO	404.5				
CANADIAN	1031.8*	144.7*			
CARTER		612.0			
CHEROKEE					556.9*
CHOCTAW		205.8			
CIMARRON					
CLEVELAND		2790.5			
COAL		81.0			
COMANCHE	1542.7				
COTTON	88.7				
CRAIG					200.6
CREEK			83.1*	820.6*	
CUSTER	350.7				
DELAWARE					497.4
DEWEY				63.6*	
ELLIS				54.6*	
GARFIELD				775.6	
GARVIN		365.0			
GRADY	610.6				
GRANT				69.0	
GREER	81.3				
HARMON	44.0				
HARPER				47.8*	
HASKELL					
HUGHES		189.9			
JACKSON	381.5				
JEFFERSON	91.5				
JOHNSTON		141.0			
KAY				645.0*	
KINGFISHER	186.8				
KIOWA	137.2				
LATIMER		143.4			

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
LEFLORE		645.4			
LINCOLN		430.4			
LOGAN		455.1			
LOVE		118.5			
MCCLAIN		372.1			
MCCURTAIN		461.5			
MCINTOSH		261.0			
MAJOR				100.0	
MARSHALL		176.9			
MAYES					514.7
MURRAY		169.3			
MUSKOGEE		931.7*			
NOBLE				153.1	
NOWATA					141.8
OKFUSKEE		158.5			
OKLAHOMA		8,860.0*			
OKMULGEE		523.4			
OSAGE				596.1	
OTTAWA					445.3
PAWNEE				222.8	
PAYNE		914.8*			
PITTSBURG		576.2			
PONTOTOC		471.4			
POTTAWATOMIE		879.0			
PUSHMATAHA		156.6			
ROGER MILLS	46.1				
ROGERS			732.8		214.8*
SEMINOLE		334.0			
SEQUOYAH					
STEPHENS	579.3				
TEXAS					
TILLMAN	124.6				
TULSA		4,307.6*	3,249.1*		
WAGONER					771.2
WASHINGTON					657.3
WASHITA	154.4				
WOODS				121.9	
WOODWARD				248.0	

* Indicates changes optimal quantities as capacities are varied transported changes

Table 18
Marginal Cost of Transporting Tires for Five Facilities at $0.29/Ton/Mile *in Dollars* – First Condition or Inequality Constraint and Different Capacity Levels for Vinita and Enid (*explanation notes below the Table)*

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
ADAIR	16.59 *(14.53)* ***19.26*** (23.49)	11.45 *(11.46)* ***16.18*** (19.66)	11.02 *(11.02)* ***15.77*** (19.23)	22.48 *(21.72)* ***26.45*** (25.67)	8.44 *(8.44)* ***5.89*** (8.44)
ALFALFA	26.01 *(24.71)* ***24.71*** (29.73)	27.75 *(28.51)* ***28.51*** (32.77)	55.54 *(56.29)* ***56.29*** (60.55)		60.73 *(61.48)* ***54.20*** (57.54)
ATOKA	24.97 *(22.91)* ***22.91*** (23.66)		66.96 *(66.96)* ***66.96*** (66.96)	71.71 *(70.96)* ***70.96*** (66.70)	75.81 *(75.81)* ***68.53*** (67.60)
BEAVER	20.94 *(18.88)* ***23.61*** (27.84)	24.88 *(28.88)* ***29.61*** (33.09)	63.68 *(63.68)* ***68.41*** (71.89)	9.92 *(9.16)* ***13.89*** (13.11)	85.14 *(85.14)* ***82.59*** (85.14)
BECKHAM		16.24 *(18.30)* ***18.30*** (17.55)	70.56 *(72.65)* ***72.65*** (71.89)	27.78 *(29.09)* ***29.09*** (24.07)	98.40 *(100.46)* ***93.18*** (91.50)
BLAINE		7.89 *(9.95)* ***9.95*** (9.19)	62.81*(64.87)* ***64.87*** (64.12)	8.03 *(9.34)* ***9.34*** (4.32)	74.59 *(76.65)* ***69.37*** (67.69)
BRYAN	24.42 *(22.36)* ***22.36*** (23.11)		83.64 *(83.64)* ***83.64*** (83.64)	88.89 *(88.13)* ***88.13*** (83.87)	93.18 *(93.18)* ***85.90*** (84.97)
CADDO		14.44 *(16.50)* ***16.50*** (15.75)	75.63 *(77.69)* ***77.69*** (76.94)	52.78 *(54.09)* ***54.09*** (49.07)	91.21 *(93.26)* ***85.99*** (84.30)
CANADIAN		*(2.06) 2.06* (1.31)	53.80 *(55.85)* ***55.85*** (55.10)	30.45 *(31.76)* ***31.76*** (26.74)	70.15 *(72.21)* ***64.93*** (63.25)
CARTER	15.54 *(13.49)* ***13.49*** (14.24)		90.19 *(90.19)* ***90.19*** (90.19)	77.20 *(76.44)* ***76.44*** (72.18)	120.67 *(120.67)* ***113.39*** (112.46)
CHEROKEE	7.89 *(5.83)* ***13.11*** (14.79)	5.63 (5.63) ***12.91*** (13.83)	4.03 *(4.03)* ***11.31*** (12.24)	15.57 *(14.82)* ***22.10*** (18.76)	
CHOCTAW	24.13 *(22.07)* ***22.07*** (22.82)		67.34 *(67.34)* ***67.34*** (67.34)	84.33 *(83.58)* ***83.58*** (79.32)	76.79 *(76.79)* ***69.51*** (68.59)
CIMARRON	50.08 *(48.02)* ***52.75*** (56.99)	69.02 *(69.02)* ***73.75*** (77.23)	94.83 *(94.83)* ***99.56*** (103.04)	39.94 *(39.15)* ***43.88*** (43.09)	110.20 *(110.20)* ***107.65*** (110.20)
CLEVELAND	*(5.25)* ***5.25*** (6.00)		63.39 *(63.39)* ***63.69*** (63.39)	39.73 *(38.98)* ***38.98*** (34.71)	85.93 *(85.93)* ***78.65*** (77.72)
COAL	24.39 *(22.33)* ***22.33*** (23.08)		60.76 *(60.76)* ***60.76*** (60.76)	8.35 *(7.60)* ***7.60*** (3.34)	75.11 *(75.11)* ***67.83*** (66.90)
COMANCHE		14.62 *(16.68)* ***16.66*** (15.92)	91.87 *(93.93)* ***93.93*** (93.18)	67.95 *(69.25)* ***69.25*** (64.24)	106.49 *(108.55)* ***101.27*** (99.59)
COTTON		8.56 *(10.61)* ***10.61*** (9.86)	*(99.06)* ***99.06*** (98.31)	*(75.95)* ***75.95*** (70.93)	120.50 *(122.55)* ***115.275***(113.59)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
CRAIG	21.92 *(19.87)* ***27.14*** (28.83)	23.72 *(23.72)* ***31.00*** (31.93)	13.20 *(13.20)* ***20.47*** (21.40)	24.80 *(24.04)* ***31.32*** (27.99)	
CREEK	9.43 *(8.12)* ***8.12*** (13.14)	7.08 *(7.83)* ***7.83*** (12.09)	*(0.75)* ***0.75*** (5.02)		6.53 *(7.28)* (3.34)
CUSTER		7.57 *(9.63)* ***9.63*** (8.87)	61.36 *(63.42)* ***63.42*** (62.67)	15.66 *(16.97)* ***16.97*** (11.95)	75.08 *(77.14)* ***69.86*** (68.18)
DELAWARE	27.74 *(24.68)* ***31.96*** (33.64)	29.49 *(29.43)* ***36.77*** (37.70)	17.20 *(17.20)* ***24.48*** (25.04)	26.19 *(25.43)* ***32.71*** (29.38)	
DEWEY	1.25 (4.96)	9.14 *(9.95)* ***9.95*** (14.15)	57.28 *(58.09)* ***58.09*** (62.29)	*(0.06)* ***0.06***	78.50 *(79.32)* ***72.04*** (75.31)
ELLIS	0.96 (4.67)	9.14 *(10.30)* ***10.30*** (14.21)	57.28 *(56.38)* ***56.38*** (60.29)	*(0.35)* ***0.35***	78.50 *(71.14)* ***63.86*** (66.85)
GARFIELD	17.43 *(16.12)* ***16.12*** (21.14)	18.07 *(18.82)* ***18.82*** (23.08)	46.26 *(47.01)* ***47.01*** (51.27)		61.36 *(62.12)* ***54.84*** (58.17)
GARVIN	9.72 *(7.66)* ***7.66*** (8.41)		85.78 *(85.78)* ***85.78*** (85.78)	62.58 *(61.83)* ***61.83*** (57.57)	100.49 *(100.49)* ***93.21*** (92.29)
GRADY		14.44 *(16.50)* ***16.50*** (15.75)	75.72 *(77.78)* ***77.78*** (77.02)	52.58 *(53.88)* ***53.88*** (48.87)	91.12 *(93.18)* ***85.90*** (84.22)
GRANT	28.01 *(26.71)* ***26.71*** (31.73)	23.17 *(23.93)* ***23.93*** (28.19)	50.58 (51.33) ***51.33*** (55.60)		56.26 *(57.01)* ***49.74*** (53.07)
GREER		14.44 *(16.50)* ***16.50*** (15.75)	102.78 *(104.84)* ***104.84*** (106.37)	46.78 *(48.08)* ***48.08*** (43.01)	117.25 *(119.31)* ***112.03*** (110.35)
HARMON		14.44 *(16.50)* ***16.50*** (15.75)	105.07 *(107.13)* ***107.13*** (106.37)	55.68 *(56.99)* ***56.99*** (51.99)	107.13 *(109.19)* ***101.91*** (100.22)
HARPER	5.95 *(4.64)* ***4.64*** (9.66)	13.72 *(14.76)* ***14.47*** (18.73)	56.46 *(57.22)* ***57.22*** (61.48)		73.02 *(73.78)* ***66.50*** (69.83)
HASKELL	12.41 *(10.35)* ***15.08*** (19.31)	4.76 *(4.76)* ***9.48*** (12.96)	13.14 *(13.14)* ***17.86*** (21.34)	24.07 *(23.32)* ***28.04*** (27.26)	11.75 *(11.75)* ***9.19*** (11.75)
HUGHES	6.58 *(4.70)* ***4.70*** (5.45)		44.34 *(44.34)* ***44.34*** (44.34)	45.70 *(44.95)* ***44.95*** (40.69)	59.28 *(59.28)* ***52.00*** (51.07)
JACKSON		14.42 *(16.50)* ***16.50*** (15.75)	90.77 *(92.83)* ***92.83*** (92.08)	53.36 *(54.67)* ***54.67*** (49.65)	108.52 *(110.58)* ***103.30*** (101.62)
JEFFERSON		1.07 *(3.13)* ***3.13*** (2.38)	98.34 *(100.40)* ***100.40*** (99.64)	75.05 *(76.36)* ***76.36*** (71.34)	123.95 *(126.01)* ***118.73*** (117.04)
JOHNSTON	21.32 *(19.26)* ***19.26*** (20.01)		86.25 *(86.25)* ***86.25*** (86.25)	82.94 *(82.19)* ***82.19*** (77.92)	101.85 *(101.85)* ***94.57*** (93.64)
KAY	11.63 *(10.32)* ***10.32*** (15.34)	9.08 *(9.83)* ***9.83*** (14.09)	28.94 *(29.70)* ***29.70*** (33.96)		33.47 *(32.22)* ***26.94*** (30.28)
KINGFISHER		7.16 *(9.22)* ***9.22*** (8.47)	57.80 *(59.86)* ***59.86*** (59.10)	3.7 *(5.02)* ***5.02***	70.27 *(72.33)* ***65.05*** (63.37)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
KIOWA		14.41 *(16.47)* ***16.47*** (15.72)	96.11 *(98.17)* ***98.17*** (97.41)	41.04 *(42.34)* ***42.34*** (37.32)	111.51 *(113.56)* ***106.29*** (104.60)
LATIMER	36.34 *(34.28)* ***34.28*** (35.03)		41.56 *(41.56)* ***41.56*** (41.56)	50.46 *(49.71)* ***49.71*** (45.44)	49.76 *(49.76)* ***42.46*** (41.56)
LEFLORE	27.14 *(25.09)* ***25.09*** (25.84)		30.77 *(30.77)* ***30.77*** (30.77)	42.14 *(41.38)* ***41.38*** (37.12)	32.97 *(32.97)* ***25.69*** (24.77)
LINCOLN	2.49 *(0.44)* ***0.44*** (1.19)		29.00 *(29.00)* ***29.00*** (29.00)	19.17 *(18.42)* *18.42* (14.15)	43.76 *(43.76)* ***36.48*** (35.55)
LOGAN	2.58 *(0.52)* ***0.52*** (1.277)		47.24 *(47.24)* ***47.24*** (47.24)	13.89 *(13.14)* ***13.14*** (8.87)	63.64 *(62.64)* ***55.36*** (54.43)
LOVE	23.55*(21.49)* ***21.49*** (22.24)		113.13*(113.11)* ***113.13*** (113.13)	85.38*(84.62)* ***84.62*** (80.36)	127.25*(127.25)* ***119.97*** (119.05)
MCCLAIN	4.81 *(2.76)* ***2.76*** (3.51)		74.47 *(74.47)* ***74.47*** (74.47)	49.36 *(48.06)* *48.06* (44.34)	87.17 *(87.26)* ***79.98*** (79.05)
MCCURTAIN	24.13 *(22.07)* ***22.07*** (22.82)		66.90 *(66.90)* ***66.90*** (66.90)	77.55 *(76.79)* ***76.79*** (72.53)	81.17 *(81.17)* ***73.89*** (72.96)
MCINTOSH	9.08 *(7.02)* ***7.02*** (7.77)		16.53 *(16.53)* ***16.53*** (16.53)	33.79 *(33.03)* ***33.03*** (28.77)	17.72 *(17.72)* ***10.44*** (9.51)
MAJOR	18.42 *(17.11)* ***17.11*** (22.13)	17.84 *(18.59)* ***18.59*** (22.85)	55.88 *(56.64)* ***56.64*** (60.90)		70.04 *(70.79)* ***63.51*** (66.85)
MARSHALL	24.22 *(22.16)* ***22.16***(22.91)		94.31 *(94.31)* ***94.31***(94.31)	84.91 *(84.16)* ***84.16*** (79.90)	108.12 *(108.11)* ***100.83*** (99.91)
MAYES	16.24 *(14.18)* ***21.46*** (23.14)	20.94 *(20.94)* ***28.22*** (29.15)	7.54 *(7.54)* ***14.82*** (15.75)	19.11 *(18.36)* ***25.64*** (22.30)	
MURRAY	12.35 *(10.30)* ***10.30*** (11.05)		84.10 *(84.10)* ***84.10*** (84.10)	74.99 *(74.24)* ***74.24*** (69.98)	106.23 *(106.23)* ***98.95*** (98.02)
MUSKOGEE	2.26*(0.20)* ***6.82*** (8.50)	****6.61***(7.54)	0.32*(0.32)* ***6.93*** (7.86)	9.92*(9.16)* ***15.78*** (12.44)	0.67*(0.67)*
NOBLE	6.59 *(5.28)* ***5.28*** (10.30)	4.00 *(4.77)* ***4.77*** (0.02)	32.42 *(33.18)* ***33.18*** (37.44)		47.50 *(48.26)* ***40.98*** (44.31)
NOWATA	17.40 *(15.34)* ***22.62*** (24.30)	15.17 *(15.17)* ***22.45*** (23.37)	8.24 *(8.24)* ***15.52*** (16.44)	17.23 *(16.47)* ***23.75*** (20.42)	
OKFUSKEE	2.26 *(0.20)* ***0.20*** (0.96)		24.33 *(24.33)* ***24.33*** (24.33)	30.74 *(29.99)* ***29.99*** (35.72)	39.70 *(39.30)* ***32.02*** (31.09)
OKLAHOMA	2.06 (0.75)		54.06 *(54.06)* ***54.06*** (55.06)	19.78 *(19.02)* ***19.02*** (14.76)	58.70 *(59.70)* ***51.42*** (50.49)
OKMULGEE	2.26 *(0.20)* ***0.20*** (0.96)		5.83 *(5.83)* ***5.83*** (5.83)	17.28 *(16.53)* ***16.53*** (12.27)	20.10 *(20.10)* ***12.82*** (11.89)
OSAGE	14.09 *(12.79)* ***12.79*** (17.81)	16.39 *(17.14)* ***17.14*** (21.40)	9.40 *(10.15)* ***10.15*** (14.41)		9.19 *(9.95)* ***2.67*** (6.00)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
OTTAWA	29.81 *(27.75)* ***35.03*** (36.71)	31.44 *(31.44)* ***38.72*** (39.64)	21.29 *(21.29)* ***28.57*** (29.48)	32.42 *(31.67)* ***38.95*** (35.61)	
PAWNEE	8.06 *(6.76)* ***6.76*** (11.77)	8.90 *(9.66)* ***9.66*** (13.92)	18.76 *(19.52)* ***19.52*** (23.78)		33.58 *(34.34)* ***27.06*** (30.39)
PAYNE	2.49 *(0.44)* ***0.44*** (5.45)	(4.26)	24.45 *(24.45)* ***24.45*** (28.71)	0.75	39.67 *(39.67)* ***32.39*** (35.73)
PITTSBURG	35.55 *(33.50)* ***33.50*** (32.25)		41.59 *(41.59)* ***41.59*** (41.59)	57.57 *(56.81)* ***56.81*** (52.55)	49.24 *(49.24)* ***41.96*** (41.04)
PONTOTOC	3.92 *(1.86)* ***1.86*** (2.61)		59.54 *(59.54)* ***59.54*** (59.54)	54.49 *(53.74)* ***53.74*** (49.47)	73.78 *(73.78)* ***66.50*** (65.57)
POTTAWATOMIE	13.02 *(10.96)* ***10.96*** (11.72)		52.43 *(52.43)* ***52.54*** (52.43)	41.91 *(41.15)* ***41.15*** (36.88)	67.28 *(67.20)* ***66.00*** (59.07)
PUSHMATAHA	14.67 *(12.62)* ***12.62*** (13.37)		60.03 *(60.03)* *60.03* (60.03)	76.36 *(75.60)* ***75.60*** (71.34)	68.79 *(68.79)* ***61.51*** (60.58)
ROGER MILLS		14.15 *(16.21)* ***16.21*** (15.46)	66.82 *(68.88)* ***68.88*** (68.12)	18.97 *(20.27)* ***20.27*** (15.25)	81.06 *(83.11)* ***75.84*** (74.15)
ROGERS	8.87 *(6.82)* ***14.09*** (15.78)	6.58 *(6.58)* ***13.86*** (14.79)	*7.28 (8.20)	11.46 *(10.70)* ***17.98*** (14.65)	
SEMINOLE	8.32 *(6.26)* ***6.26*** (7.02)		41.21 *(41.21)* ***41.21*** (41.21)	43.88 *(43.12)* ***43.12*** (38.86)	59.36 *(59.36)* ***52.08*** (51.16)
SEQUOYAH	12.30 *(10.90)* ***15.63*** (19.87)	3.87 *(3.89)* ***8.61*** (12.09)	10.79 *(10.79)* ***15.52*** (19.00)	21.61 *(20.85)* ***25.58*** (24.80)	12.47 *(12.47)* ***9.92*** (12.47)
STEPHENS		5.39 *(7.45)* ***7.45*** (6.70)	92.92 *(94.98)* ***94.98*** (94.22)	66.64 *(67.95)* ***67.95*** (62.93)	107.242*(109.30)* ***102.02***(100.34)
TEXAS	33.99 *(31.84)* ***36.57*** (40.80)	37.87 *(37.87)* ***42.60*** (46.08)	76.73 *(76.73)* ***81.46*** (84.94)	21.90 *(21.14)* ***25.87*** (25.09)	92.22 *(92.22)* ***89.67*** (92.22)
TILLMAN		5.31 *(7.37)* ***7.37*** (6.61)	91.29 *(93.35)* ***93.35*** (92.60)	59.03 *(59.33)* ***59.33*** (54.32)	106.87 *(108.92)* ***101.65*** (99.96)
TULSA	3.25*(1.19)* ***1.19*** (1.94)			5.02*(4.26)* ***4.26*** ()	8.21*(8.21)* ***0.93*** ()
WAGONER	9.34 *(9.48)* ***14.56*** (16.24)	7.8 *(9.19)* ***14.36*** (15.28)	0.67 *(0.67)* ***7.95*** (8.87)	11.48 *(10.73)* ***18.01*** (14.67)	
WASHINGTON	11.54 *(9.48)* ***16.76*** (18.44)	9.19 *(9.19)* ***16.47*** (17.40)	2.15 *(2.12)* ***9.43*** (10.35)	5.60 *(4.84)* ***12.12*** (8.79)	
WASHITA		21.87 *(23.93)* ***23.93***(23.17)	86.33 *(88.39)* ***88.39*** (87.64)	31.35 *(32.65)* ***32.65*** (27.64)	87.93 *(89.99)* ***82.71*** (81.03)
WOODS	17.81 *(16.50)* ***16.50*** (21.52)	28.53 *(29.29)* ***29.29*** (33.55)	56.75 *(57.51)* ***57.51*** (61.77)		60.78 *(61.54)* ***54.26***(57.59)
WOODWARD	6.44 *(5.13)* ***5.13*** (10.15)	17.11*(17.86)* ***17.86*** (22.13)	55.22 *(55.97)* ***55.97*** (60.23)		70.30 *(71.05)* ***63.77*** (67.11)

Notes:

1. **First entry** – 4D,SF, and FR operating at original capacities, EN and VN with 4000 capacity each.
2. **Second entry** - 4D,SF, and FR operating at original capacities, EN and VN with 4000 capacity each.
3. **Third entry** - 4D,SF, and FR operating at original capacities, EN with 4000 and VN with 6000 capacity each.
4. **Fourth entry** - 4D,SF, and FR operating at original capacities, EN and VN with 6000 capacity each.

Table 19
Optimal Transportation Pattern - Five Facilities
($0.29/Ton/Mile) (Second Condition)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
ADAIR					282.2
ALFALFA				81.9	
ATOKA		186.2			
BEAVER				78.6	
BECKHAM	265.6				
BLAINE	160.7				
BRYAN		490.1			
CADDO	404.5				
CANADIAN	11.8				
CARTER		612.0			
CHEROKEE					570.4
CHOCTAW		205.8			
CIMARRON				42.2	
CLEVELAND		2,790.5			
COAL		81.0			
COMANCHE	1542.7				
COTTON	88.7				
CRAIG					200.6
CREEK*			335.4 *(315.6)* **907.9**	548.3	*(39.8)*
CUSTER	350.7				
DELAWARE					497.4
DEWEY*	63.6			**63.6**	
ELLIS*	54.6			**54.6**	
GARFIELD				775.6	
GARVIN		365.0			
GRADY	610.6				
GRANT				69.0	
GREER	81.3				
HARMON	44.0				
HARPER				47.8	
HASKELL*		158.2, **118.4**			**39.8**
HUGHES		189.9			
JACKSON	381.5				
JEFFERSON	91.5				
JOHNSTON		141.0			

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
KAY				645.0	
KINGFISHER	186.8				
KIOWA	137.2				
LATIMER		143.4			
LEFLORE		645.4			
LINCOLN		430.4			
LOGAN		455.1			
LOVE		118.5			
MCCLAIN		372.1			
MCCURTAIN		461.5			
MCINTOSH		261.0			
MAJOR				100.0	
MARSHALL		176.9			
MAYES					514.7
MURRAY		169.3			
MUSKOGEE*		931.7			*(931.7)*
NOBLE				153.1	
NOWATA					141.8
OKFUSKEE		158.5			
OKLAHOMA*	1,330.1 **(1,448.3)**	7,529.9 **(7,411.7)**			
OKMULGEE		523.4			
OSAGE				596.1	
OTTAWA					445.3
PAWNEE				222.8	
PAYNE*		914.8		**9,14.8**	
PITTSBURG		576.2			
PONTOTOC		471.4			
POTTAWATOMIE		879.0			
PUSHMATAHA		156.6			
ROGER MILLS	46.1				
ROGERS*			947.6		*(947.6)*
SEMINOLE		334.0			
SEQUOYAH		522.8			
STEPHENS	579.3				
TEXAS				269.7	
TILLMAN	124.6				
TULSA*		3842.6 *(2774.3)*	3714.1 *(4782.4)*		
WAGONER			80.9*		690.3 *(771.2)*
WASHINGTON					657.3
WASHITA	154.4				
WOODS				121.9	
WOODWARD				248.0	

*Indicates that tires are shared by 2 facilities,
Parentheses show changes when VN capacity is 6000
Bold shows changes when both EN and VN are operating at 6000 capacity.

Table 20
Marginal Cost of Transporting Tires for Five Facilities at $0.29/Ton/Mile *in Dollars* – Second Condition or Equality Constraint and Different Capacity Levels for Vinita and Enid (*explanation notes below the Table*)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
ADAIR	5.42 *(12.62)* ***13.08***	2.35 *(9.54)* ***10.00***	1.91 *(9.11)* ***9.57***	13.37 *(20.56)* ***16.01***	
ALFALFA	23.95 *(23.95)* ***28.97***	27.75 *(27.75)* ***32.77***	55.54 *(55.54)* ***60.55***		61.39 *(54.20)* ***58.75***
ATOKA	22.91 *(22.91)* ***22.91***		66.96 *(66.96)* ***66.96***	71.71 *(71.72)* ***66.70***	76.47 *(69.28)* ***68.82***
BEAVER	8.96 *(8.96)* ***13.97***	14.96 *(14.96)* ***19.98***	53.77 *(53.77)* ***58.78***		75.89 *(68.70)* ***73.25***
BECKHAM		18.30 *(18.30)* ***18.30***	72.65 *(72.65)* ***72.65***	29.84 *(29.84)* ***24.82***	101.12 *(93.93)* ***93.47***
BLAINE		9.95 *(9.95)* ***9.95***	64.87*(64.87)* ***64.87***	10.09 *(10.09)* ***5.08***	77.31 *(70.12)* ***69.66***)
BRYAN	22.36 *(22.36)* ***22.36***		83.64 *(83.64)* ***83.64***	88.86 *(88.86)* ***83.87***	93.84 *(86.65)* ***86.19***
CADDO		16.50 *(16.50)* ***16.50***	77.69 *(77.69)* ***77.69***	54.84 *(54.84)* ***49.82***	93.93 *(86.74)* ***86.28***
CANADIAN		2.06 *(2.06)* ***2.06***	55.85 *(55.85)* ***55.85***	32.51 *(32.51)* ***27.49***	72.88 *(65.69)* ***65.22***
CARTER	13.49 *(13.49)* ***13.49***		90.19 *(90.19)* ***90.19***	77.20 *(77.20)* **72.18**	121.34 *(114.14)* ***113.68***
CHEROKEE	5.16 *(12.35)* ***12.82***	4.96 (12.15) ***12.62***	3.36 *(10.56)* ***11.02***	14.91 *(22.10)* ***17.55***	
CHOCTAW	22.07 *(22.07)* ***22.07***		67.34 *(67.34)* ***67.34***	84.33 *(84.33)* ***79.32***	77.46 *(70.27)* ***69.81***
CIMARRON	8.12 *(8.12)* ***13.14***)	29.12 *(29.12)* ***34.13***	54.93 *(54.93)* ***59.94***		70.96 *(63.77)* ***68.32***
CLEVELAND	5.25 *(5.25)* ***5.25***		63.39 *(63.39)* ***63.69***	39.73 *(39.73)* ***34.71***	86.59 *(79.04)* ***78.94***
COAL	22.33 *(22.33)* ***22.33***		60.76 *(60.76)* ***60.76***	8.35 *(7.60)* ***3.34***	75.78 *(68.59)* ***78.93***
COMANCHE		16.68 *(16.68)* ***16.66***	93.93 *(93.93)* ***93.93***	70.00 *(70.00)* ***69.99***	109.21*(102.02)* ***101.59***
COTTON		10.61 *(10.61)* ***10.61***	99.06 *(99.06)* ***99.06***	76.71 *(76.71)* ***71.69***	123.22 *(122.03)* ***115.57***
CRAIG	19.20 *(26.39)*	23.06 *(30.25)*	12.53 *(19.72)*	24.13 *(31.32)*	

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
	26.85	***30.71***	***20.18***	***26.77***	
CREEK	7.37*(7.37)* ***12.38***	7.08 *(7.08)* ***12.09***)	***5.02***		7.19 ***4.55***
CUSTER		9.63 *(9.63)* ***9.63***	63.42 *(63.42)* ***63.42***	17.72 (*17.72*) ***12.70***	77.81 *(70.62)* ***70.15***
DELAWARE	24.01 *(31.20)* ***31.67***	28.83 *(36.02)* ***36.48***)	16.53 (*23.72*) ***24.19***	25.52 (*32.71*) ***28.16***)	
DEWEY	(4.96) ***4.21***	9.95 *(9.95)* ***14.15***	58.09 *(58.09)* ***62.29***	0.81*(0.81)* ***0.06***	79.98 *(72.79)* ***76.53***
ELLIS	(4.67) ***3.92***	10.30 (*10.30*) ***14.15***	56.38 *(56.38)* ***62.29***	1.10 *(1.10)*	71.80 *(64.61)* ***68.06***
GARFIELD	15.37 *(15.37)* ***20.39***	18.07 (*18.07*) ***23.08***	46.26 *(46.26)* ***51.27***		62.03 (*54.84*) ***59.39***
GARVIN	7.66 *(7.66)* ***7.66***		85.78 (*85.78*) ***85.78***	62.58 (*62.58*) ***57.57***	101.15 (*93.96*) ***93.50***
GRADY		16.50 (*16.50*) ***16.50***	77.78 *(77.78)* ***77.78***	54.64 (*54.64*) ***49.62***	93.84 *(86.65)* ***86.19***
GRANT	25.96 (*25.96*) ***30.97***)	23.17 *(2317)* ***28.19***	50.58 (50.58) ***55.59***		56.93 (*49.74*) ***54.29***
GREER		16.50 (*16.50*) ***16.50***	104.84 *(104.84)* ***104.84***	48.84 *(48.84)* ***43.82***	119.97 (*112.78*) ***112.32***
HARMON		16.50 (*16.50*) ***16.50*** (15.75)	107.13 *(107.13)* ***107.13***	57.74 (*57.74*) ***52.72***	109.85 *(102.66)* ***102.20***
HARPER	3.87 *(3.87)* ***8.90***	13.72 *(13.72)* ***18.73***	56.46 *(56.46)* ***61.48***		73.69 (*66.50*) ***71.05***
HASKELL	5.60 (*5.60*) ***5.60***		8.38 *(8.38)* ***8.38***	19.31 (*19.31*) ***14.30***	7.66 (*0.46*)
HUGHES	4.70 *(4.70)* ***4.70***		44.34 *(44.34)* ***44.34***	45.70 (*45.70*) ***40.69***	59.94 *(52.75)* ***52.88***
JACKSON		16.50 *(16.50)* ***16.50***	92.83 *(92.83)* ***92.83***	55.42 *(55.42)* ***50.40***	111.24 *(104.05*) ***103.59***
JEFFERSON		3.13 (*3.13*) ***3.13*** (2.38)	100.40 (*100.40*) ***100.40***	77.11 (*77.11*) ***72.09***	126.67 *(119.48)* ***119.02***
JOHNSTON	19.26 (*19.26*) ***19.26***		86.25 *(86.25)* ***86.25***	82.94 (*82.94*) ***72.92***	102.52 (*95.32*) ***94.85***
KAY	9.57 *(9.57)* ***14.59***	9.08 *(9.08)* ***14.09***	28.94 *(28.94)* ***33.96***		34.13 (*26.94*) ***31.49***
KINGFISHER		9.22 *(9.22)* ***9.22***	59.86 (*59.86*) ***59.86***	5.77 (*5.77*) ***0.75***	72.99 (*65.80*) ***65.34***
KIOWA		16.47 *(16.47)*	98.17 (*98.17*)	43.09 (*43.09*)	114.23 (*107.04*)

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
		16.47	***98.17***	***38.08***	***106.58***
LATIMER	34.28 *(34.28)* ***34.28***		41.56 *(41.56)* ***41.56***	50.46 *(50.46)* ***45.44***	50.43 *(43.24)* ***42.78***
LEFLORE	25.09 *(25.09)* ***25.09***		30.77 *(30.77)* ***30.77***	42.14 *(42.14)* ***37.12***	33.64 *(26.44)* ***25.98***
LINCOLN	0.44 *(0.44)* ***0.44***		29.00 *(29.00)* ***29.00***	19.17 *(19.17)* ***14.15***	33.43 *(37.24)* ***36.77***
LOGAN	0.52 *(0.52)* ***0.52***		47.24 *(47.24)* ***47.24***	13.89 *(13.89)* ***8.87***	63.31 *(56.12)* ***55.65***
LOVE	21.49*(21.49)* ***21.49***		113.13*(113.11)* ***113.13***	85.38*(85.38)* ***80.36***	127.92 *(120.73)* ***120.26***
MCCLAIN	2.76 *(2.76)* ***2.76***		74.47 *(74.47)* ***74.47***	49.36 *(49.36)* ***44.34***	87.93 *(80.74)* ***80.27***
MCCURTAIN	22.07 *(22.07)* ***22.07***		66.90 *(66.90)* ***66.90***	77.55 *(77.55)* ***72.53***	81.83 *(74.65)* ***74.18***
MCINTOSH	7.02 *(7.02)* ***7.02***		16.53 *(16.53)* ***16.53***	33.79 *(33.79)* ***28.77***	18.39 *(11.19)* ***10.73***
MAJOR	16.36 *(16.36)* ***21.37***	17.84 *(17.84)* ***22.85***	55.88 *(55.88)* ***60.90***		70.70 *(63.51)* ***68.06***
MARSHALL	22.16 *(22.16)* ***22.16***		94.31 *(94.31)* ***94.31***	84.91 *(84.91)* ***79.90***	108.179*(101.59)* ***101.12***
MAYES	13.51 *(20.71)* ***21.17***	20.27 *(27.46)* ***27.93***	6.87 *(14.07)* ***14.53***	18.44 *(25.64)* ***21.08***	
MURRAY	10.30 *(10.30)* ***10.30*** (11.05)		84.10 *(84.10)* ***84.10***	74.99 *(74.99)* ***69.98***	106.89 *(99.70)* ***99.24***
MUSKOGEE	0.20 *(6.06)* ***6.53***	***6.32***	0.32*(6.18)* ***6.64***	9.92*(15.78)* ***11.22***	1.33
NOBLE	4.52 *(4.52)* ***9.54***	4.00 *(4.00)* ***9.02***	32.42 *(32.42)* ***37.44***		48.17 *(40.98)* ***45.53***
NOWATA	14.67 *(21.87)* ***22.33***	14.50 *(21.69)* ***22.16***)	7.57 *(14.76)* ***15.23***	16.56 *(23.75)* ***19.20***	
OKFUSKEE	0.20 *(0.20)* ***0.20***		24.33 *(24.33)* ***24.33***	30.74 *(30.74)* ***25.72***	39.62 *(32.77)* ***32.31***)
OKLAHOMA			54.06 *(54.06)* ***54.06***	19.78 *(19.78)* ***14.76***	59.36 *(52.17)* ***51.71***
OKMULGEE	0.20 *(0.20)* ***0.20***		5.83 *(5.83)* ***5.83***	17.28 *(17.28)* ***12.27***	20.76 *(13.57)* ***13.11***
OSAGE	12.04 *(12.04)* ***17.05***	16.39 *(16.39)* ***21.40***	9.40 *(9.40)* ***14.41***		9.86 *(2.67)* ***7.22***
OTTAWA	27.09 *(34.28)*	30.77 *(37.96)*	20.62 *(27.81)*	31.76 *(38.95)*	

ORIGIN	FOUR D	SAFE TIRES	FRONTIER	ENID	VINITA
	34.74	***38.43***	***28.28***	***34.40***	
PAWNEE	6.00 *(6.00)* ***11.02***	8.90 *(8.90)* ***13.92***	18.76 *(18.76)* ***23.70***		34.25 *(27.06))* ***31.61***
PAYNE	0.44 *(0.44)* ***4.70***	***4.26***	24.45 *(24.45)* ***28.71***	0.75 *(0.75)*	40.34 *(33.15)* ***36.95***
PITTSBURG	33.50 *(33.50)* ***33.50***		41.59 *(41.59)* ***41.59***	57.57 *(57.57)* ***52.55***	49.90 *(42.72)* ***42.25***
PONTOTOC	1.86 *(1.86)* ***1.86***		59.54 *(59.54)* ***59.54***	54.49 *(54.49)* ***49.47***	74.44 *(67.25)* ***66.79***
POTTAWATOMIE	10.96 *(10.96)* ***10.96***		52.43 *(52.43)* ***52.43***	41.91 *(41.91)* ***36.89***	67.94 *(60.76)* ***60.29***
PUSHMATAHA	12.62 *(12.62)* ***12.62***		60.03 *(60.03)* *60.03*	76.36 *(76.36)* ***71.34***	69.46 *(62.26)* ***61.80***
ROGER MILLS		16.21 *(16.21)* ***16.21***	68.88 *(68.88)* ***68.88***	21.03 *(21.02)* ***16.01***	83.78 *(76.59)* ***76.13***
ROGERS	6.82 *(13.34)* ***13.80***	6.58 *(13.11)* ***13.57***	*(6.53)* ***6.99***	11.46 *(17.98)* ***13.43***	0.67
SEMINOLE	6.26 *(6.26)* ***6.26***		41.21 *(41.21)* ***41.21***	43.88 *(43.88)* ***38.86***	60.30 *(52.84)* ***52.37***
SEQUOYAH	7.02 *(7.02)* ***7.02***		6.90 *(6.90)* ***6.90***	17.72 *(17.72)* ***12.70***	9.25 *(2.06)* ***9.92*** ***1.60***
STEPHENS		7.45 *(7.45)* ***7.45***	94.98 *(94.98)* ***94.98***	68.70 *(68.70)* ***63.68***	109.97*(102.78)* ***102.31***
TEXAS	9.95 *(9.95)* ***14.96***	15.98 *(15.98)* ***21.00***	54.84 *(54.84)* ***59.86***	***25.87*** (25.09)	70.99 *(63.80)* ***68.35***
TILLMAN		7.37 *(7.37)* ***7.37***	93.35 (*93.35)* ***93.35***	60.08 *(60.09)* ***55.07***	109.59 *(102.40)* ***101.94***
TULSA	1.19 *(1.19)* ***1.19***			5.02*(5.02)* ***4.26***	8.87*(1.68)* ***1.22***
WAGONER	6.62 *(13.08)* ***14.27***	6.41*(13.60)* ***14.07***	*(7.19)* ***7.66***	10.82 *(18.01)* ***13.46***	
WASHINGTON	8.82 *(16.00)* ***16.47***	8.53 *(15.72)* ***16.18***	1.48 *(8.67)* ***9.14***	4.93 *(12.12)* ***7.57***	
WASHITA		23.93 *(23.93)* ***23.93***	88.39 *(88.39)* ***88.39***	33.41 *(33.41)* ***28.39***	90.65 *(83.46)* ***83.00***
WOODS	15.75 *(15.75)* ***20.76***	28.53 *(28.54)* ***33.55***	56.75 *(56.75)* ***61.77***		61.45 *(61.54)* ***58.81***
WOODWARD	4.38 *(4.38)* ***9.40***	17.11*(17.11)* ***22.13***	55.22 *(55.22)* ***60.23***		70.96 *(63.77)* ***68.32***

Notes:

1. First entry -- 4D,SF, and FR operating with full capacity, EN and VN with 4000 capacity each.
2. Second entry - 4D,SF, and FR operating with full capacity, EN with 4000 and VN with 6000 capacity each.
3. Third entry - 4D,SF, and FR operating with full capacity, EN and VN with 6000 capacity each.

CHAPTER VI

CONCLUSIONS AND IMPLICATIONS

In this chapter we outline the primary implications of the findings of this study. The need for scrap tire management programs is justified by the human health and environmental threats imposed by improper disposal. Scrap tire management programs are unique to each state because they are designed to address and to satisfy the needs, budgets and the objectives of individual state. Their primary objective is to support proper scrap tire disposal by creating incentives for recycling and reuse of scarp tires.

Waste tire programs operate in a way similar to the traditional deposit-refund system, the only exception being that refund is not paid for returning used tires or to the scrap tire generators. Instead, they generate revenues to undertake scrap tire recovery and reuse programs. Therefore, efficiency of any waste tire program would be to seek cost-saving alternatives to promote scrap tire recycling and reuse. The model developed for this study attempts to explore and investigate these options.

The model is designed to address the first two the components of waste tire recycling, transportation and processing plus the distribution of processing capacity by locating additional tire facilities in the region. The empirical application of the model is demonstrated by using data from Oklahoma Waste Tire Program. However, the study does not investigate the logistics involved in the determination or design of incentives for waste tire programs, it only attempts to explore alternative approaches or options that could be considered when designing policies for financial support of waste tire programs. Although the results of this analysis may be more useful to regions starting scrap tire programs, they also provide important information to already existing waste tire programs concerned with efficiency in markets and regional policies.

The sensitivity analysis for each scenario is implemented by changing base assumptions and/ or estimates, other things being equal. Therefore, the validity of the results will be greatly influenced by the quality of the key parameters whose changes may influence the results and the conclusions of this study.

Transportation costs are significant for the success of the scrap tire programs because points of collection are scattered all over the region. Of the many alternatives available for determining subsidy policies, the least–cost transportation approach could be considered an option. The transportation model applied in this study accounts for the distance the between scrap tire generating counties and the tire facilities with constant transportation rate ($/ton/mile), and results from provide insights that may be useful in determining the size of transportation subsidy form different points of origin. Tire transportation may be efficient within a certain distance radius, for example, a study in New York indicates that a 50- mile radius for tire hauling is good but beyond 100 miles is expensive (Brunswick Research Inc. 1998).

The results from the profit maximization sub-section of the model are significant especially in addressing the economic vulnerability scrap tire processors, especially tire chip processors whose revenues depend on inputs and tipping fees rather than output. Knowledge about the levels of profit margins at which waste tire processors start generating profits is valuable especially for waste tire programs promoting and providing incentives for tire chip production. For example, in Oklahoma processors are paid $53.48/ton of tires processed. This subsidy level is higher than the levels required for profit generation (see chapter five). Presently, there is a general concern about the future of tire chip processors 's revenue because of the shifts in demand in favor of crumb rubber. Among other things, the survival of tire chip processors depends upon technological advances or improvement. This requires financial support, and decision makers need to assess, evaluate and give special attention to the revenue problems facing tire chip processors.

With respect to locating additional plants, the results indicate that two tire facilities can be optimally located in Enid and Vinita. These locations were chosen to address the problem of not that not transporting and processing all tires generated in Oklahoma. These locations are in the northern part of the state that is serviced by a tire facility with the smallest capacity in the state, the possibility of increasing the capacity of this facility is another alternative. There are some gains in constructing two facilities, for example comparing the number of tires not transported under the assumption of inequality supply constraint, we observed that for the transportation model with three tire facilities, approximately 9,113.1 tons of tires are not transported from 23 counties. If five tire facilities exist, only 1,353.7 tons are not transported from 6 counties. Although transportation costs for three facilities are lower than for five facilities for the first condition, they are lower for five facilities if all tires generated are transported. See tables 9 and 12 in chapter five.

One implication of the model is that financial support for scrap tire recycling activities is necessary but the extent, methods and approaches implemented will depend upon the objectives and budgets of each program. The arguments for sustainability of waste tire programs favor financial support for end use markets, but the overall success of the waste tire programs should rely on policies that incorporate efficiency of the all activities and markets involved.

6.1 Limitations and Suggestions for Further Research

Scrap tire industry is very complex with a number of uncertainties. The study does not address all the components of scrap tire recycling; it excludes evaluation or assessment of scrap tire product markets. This is an important component for the long-term sustainability of scrap tire markets, which is a general concern of scrap tire management programs. To complete the waste tire recycling process, future research should consider markets for scrap tire products, tires from the historical dumps, welfare implications and enforcement cost of the scrap tire programs. It may be useful to consider factors like transportation rates ($/ton/mile) that vary by round trip; storage costs for unprocessed scrap tires and unsold processed material; and other factors that influence location such as infrastructures, access to markets. Whether these factors would change the results and conclusions of this study is subject to future research.

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VITA 2

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