SCRAP TIRE MANAGEMENT: TIRE DEMAND ESTIMATION

by

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ABSTRACT

The proper management of scrap tires is relatively resource-intensive. Two features of waste tires produce internal and external costs. Their donut-like shape occupies vast space on transportation vehicles and in general landfills. It also allows the breeding of disease-carrying mosquitoes in populated areas. Their rubber and steel composition makes them durable and at the same time costly to reduce in size. Tire rubber can also generate air and ground pollutants during fires. Mosquito and fire outbreaks are associated with scrap tire stocks of any size. Faced with increasing flows of scrap tires (and other solid and hazardous waste), local officials consider a policy to decrease the waste tire generation rate, i.e., source-reduction. To implement such a policy, a critical first step is to determine, theoretically and empirically, the factors that influence tire demand.

Consequently, this thesis applies basic consumer theory to specify important economic determinants of tire demand. Their empirical counterparts form the basis of the explanatory variables in the econometric demand model. Tire sales quantities are derived from state revenue collections of a per unit tire tax on new tire purchases. Measurement errors in the dependent variable and lack of explanatory data motivate the use of the generalized least-squares fixed effects estimator in a pooled tire demand model comprising 28 states.

The qualitative results of the econometric estimation are in conformity with economic theory. Quantitatively, the model produces an income elasticity of 0.4; a ten percent increase in real per capita income increases tire sales per vehicle by four percent, ceteris paribus. This effect is very likely to measure increased gasoline consumption, i.e., vehicle utilization. The calculated own price elasticity of tire demand is about -15, which is too large to reflect a pure price effect. Unless statistical problems generate this estimate, it probably captures a movement of and along the tire demand curve.

CHAPTER 1

INTRODUCTION

Problem Statement

As of the year 2000, 48 states had introduced regulatory guidelines for scrap tire disposal, which indicates that tire disposal received much attention from policy-makers in recent decades (Scrap Tire Management Council n.d.b). Since there is no federal legislation in place with regard to scrap tire management, state policies substantially vary with respect to sources of funding, degree of regulations, recycling activities, and educational programs.[1] Depending on particular state legislation, laws thus include complete bans on whole tires and rubber chips from general landfills and monofills, storage requirements, mandatory licenses for scrap tire recipients, and tracking systems for waste tire flows. Yet, a distinction can be made between states that passed regulations and those that provide continuous subsidies for the clean-up of existing tire piles and the extension of end-use markets.[2] The latter are commonly referred to as state scrap tire management programs.

Waste tire disposal is costly. The full social burden of waste tires stems from the internal waste management system and from potential externalities. Two main characteristics of scrap tires contribute to their relatively resource-intensive disposal. First, scrap tires consume considerable space on transportation vehicles and in general

[1] Unless noted otherwise, information on specific features of state waste tire laws was obtained from the agencies listed in Appendix A.
[2] The Recycling Research Institute (2002) provides an up-to-date summary on scrap tire management policies in individual states.

landfills because of their bulky shape. Second, the rubber and steel that comprise whole tires are nondegradable and costly to reduce in size.[3]

External costs mainly derive from whole tires in *stocks*. This form of tire disposal raises both environmental and health concerns. Arson and lightning can initiate tire fires that are very costly to control and extinguish. Frequently, the rubber material of tires burns for months releasing toxic chemicals into the air and run-off oil into the ground. Moreover, the shape of whole tires presents ideal harbors for snakes, rats, and disease-carrying mosquitoes. Mosquito control can have important effects on animal and human health. Measures to prevent severe tire fires and mosquito outbreaks, i.e., to prevent externalities, add to the internal costs of scrap tire disposal.

Because of their external costs, the use of tires poses a greater disposal challenge than the consumption of commodities that generate ordinary solid waste. From the standpoint of economic efficiency, optimal levels of scrap tire recycling and landfilling must vary within and across geographical areas in accordance with local resource constraints. Thus, communities that record relatively high landfill tipping fees may find it cost-effective to reduce the number of tires in landfills through recycling policies. In other areas, high levels of monofilling may act as the least expensive alternative because of the abundance of land and limited volumes of scrap tires.

In addition, competing uses of public funds, tight fiscal budget constraints, and taxpayers' concerns about excessive spending force local governments to practice fiscal scrutiny. In view of rising scrap tire *flows*, these communities might therefore consider source-reduction as optimal alternative to recycling and landfilling policies. Importantly,

[3] See Snyder (1998, 19) for details on the technical difficulties associated with tire chopping.

lower waste tire generation rates do not only decrease expenses on waste management services, but on fire-control, mosquito surveillance, and health-care. If source-reduction is efficient in some regions, local policy-makers should find it informative to learn about the determinants of tire demand as critical first step in setting optimal reduction policies.

Objectives

The primary objectives of this thesis are to (1) discuss the economic determinants of tire demand, (2) specify state level econometric demand equations, and (3) estimate a pooled model of tire demand. To meet the financial challenge of proper waste tire management, states collect funds from various sources. Some have introduced fees on new vehicle registrations, title transfers, or new automobile sales, whereas others entertain a joint budget for solid waste and scrap tire management with the help of property taxes. About two-thirds have had a tax on tire replacement purchases at some point.[4] These revenue collections are used for the empirical part of this research.

[4] The terms pre-disposal charge, user fee, advanced fee, and product charge are interchangeably used in this thesis.

CHAPTER 2

PRESENT AND PAST SCRAP TIRE MANAGEMENT CHALLENGES

Introduction

The following chapter outlines in detail why scrap tires have become a waste disposal issue over the years. As mentioned, state legislative action with regard to proper tire storage and disposal has been high. The qualitative consequences of some of these policies are analyzed within the framework of basic economic theory. The primary attempt of the subsequent discussion is, however, to make the reader appreciate that the consumption of tires entails resource-intensive waste disposal. For that reason, some communities might find it advantageous to adopt source-reduction policies.

Waste tire management presents a problem of dual nature. This is expressed well by the Scrap Tire Management Council:

> All parties involved in scrap tire management understand that there are actually two separate but interrelated aspects to sound scrap tire management. The first aspect is dealing with the newly generated scrap tires, the 266 million or so …created [in the nation at an annual rate] by the normal process of use of tires. The second problem is dealing with the legal and illegal stockpiles of tires which are the residue of past (and some current) methods of handling scrap tires. (California Integrated Waste Management Board 1999, 12)

Since wide-spread car ownership is unlikely to be replaced soon by an alternative means of transportation, scrap tire disposal will pose a significant challenge to communities and states in the years to come.

There are various reasons why proper waste tire management is costly. Scrap tires occupy large amounts of void space and are therefore undesirable components of general

landfills. They are also very difficult to chop or shred because their rubber and steel ingredients are designed to be durable. Nonetheless, size reduction may be cost-effective because pieces of whole tires utilize less space and lower the risk of tire fires and mosquito outbreaks.

Fires and mosquito breeding are the most important externalities associated with improper waste tire disposal. In the absence of markets for externalities, however, it is challenging to measure their costs. With regard to tire fires, fire fighting and pollution control expenditures present one possible estimate. These expenditures can be quite high because the nature of tire fires necessitates vast resources from fire departments. In addition to posing a fire hazard, whole tires offer ideal breeding sites for some species of mosquitoes that carry disease. Researchers claim that these mosquitoes breed about 4,000 times faster in tire piles than in forests (Grady 1987, 34). Many scrap tires are generated in densely populated areas, in which they are often stored and disposed to avoid high transportation costs. As a result, waste tire piles produce and support colonies of mosquito species in close proximity to large human populations.

These mosquitoes can transmit viral diseases to animals and humans although causing deaths far more frequently among the former than the latter. The loss of animal and human life reflects an important real cost in the wake of mosquito outbreaks. In most human cases, however, mosquito-borne diseases lead to mild, flu-like symptoms that go undiagnosed and hence unreported. The costs due to mosquito bites are therefore very difficult to quantify. Measurement problems also arise in the context of mosquito annoyance, the economic cost of which could perhaps be approximated by state budget allocations to mosquito surveillance and control. Contingent valuation studies on

residents' willingness to pay for reduced mosquito bite rates could produce another rough measure.

Trend of Scrap Tire Generation

Household demand for tires is a derived demand for transportation. The automobile has become the standard item of mobility for a majority of consumers over the past century. Rising real incomes from economy-wide productivity gains have allowed middle-class families to own multiple cars and have made the automobile accessible to large numbers of low-income consumers. Roughly speaking, this development has been reinforced by a 50 percent decline in the real price of passenger cars, a 70 percent drop in the real price of tires, and a 70 percent increase in population in 50 years.[5] One consequence has been an increasing annual stream of scrap tires (Table 2.1).

Table 2.1. Scrap Tires in Municipal Solid Waste.

Year	Waste Tires in thousands of tons[6]	Waste Tires per capita [7]	Percent of total MSW by weight[8]	Percent of total MSW by volume[9]
1960	1,120	0.62	1.3 %	5.2 %
1970	1,890	0.93	1.6	6.4

[5] National tire and vehicle price indexes are deflated by the consumer price index for all goods and services to calculate these real price changes over fifty years. See Appendix B for data sources.
Resident population *source*: United States Environmental Protection Agency. 1999. Characterization of Municipal Solid Waste in The United States: 1998 Update, 141.

[6] *Source*: United States Environmental Protection Agency. 1999. Characterization of Municipal Solid Waste in The United States: 1998 Update, 58.

[7] It is assumed that tires under 20 inches in diameter weigh on average 20 pounds. Note that these per capita figures include scrap tires generated by the commercial, household, and government sector.

[8] *Source*: see footnote 2.

[9] A report by the Californian Integrated Waste Management Board (1992, 11) assumes that 1000 pounds of MSW and 10-15 tires are in one cubic yard. If one again maintains that the average weight of a passenger tire is 20 pounds, one calculates 200 to 300 pounds for one cubic yard or an average of 250 pounds. Dividing 1000 by 250, one obtains a factor of 4 which is then multiplied with column four to compute column five.

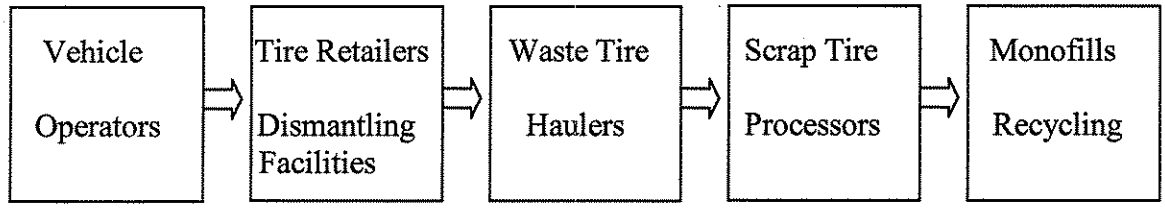
1980	2,720	1.20	1.8	7.2
1990	3,610	1.44	1.8	7.2
1994	4,080	1.60	1.9	7.6
1995	3,770	1.40	1.8	7.2
1996	3,910	1.47	1.9	7.6
1997	4,260	1.60	2.0	8.0

Since scrap tires contain up to 75 percent of void space (CIWMB 1992, 10), the volume-based percentages are calculated to portray more accurately the magnitude of scrap tires in the municipal solid waste stream. It is also important to note that no adjustments have been made for technological change reflected through increased tire durability over the decades.[10]

Decision-Makers

Generators, collectors, transporters, processors, and end-users are the main agents steering the scrap tire stream. In some cases, whole tires are directly transported to landfills that run their own processing facilities in connection with disposal operations. In other instances, independent tire haulers are not contracted because processors pick up scrap tire loads directly from retailers. Different disposal arrangements can exist within individual states of which Figure 2.1 represents the most general scenario.

Figure 2.1. Agents in Scrap Tire Stream.



[10] Some research suggests that durability improvements are overestimated due to simultaneous changes in road quality (see Hamilton and Macauley (1999) for the case of automobiles).

Table 2.2. Tire Pile Inventories by State (million tires).

State	1994	1996	1998	State	1994	1996	1998
AL	N/A	N/A	N/A	**MT**	N/A	0.5	0.6
AK	N/A	N/A	N/A	**NE**	2	1.6	0.45
AZ	4.8	N/A	N/A	**NV**	1.95	1	0.45
AR	5	3	2	**NH**	N/A	1.1	0.2
CA	42	N/A	N/A	**NJ**	5.5	5	10
CO	N/A	N/A	N/A	**NM**	1	1.4	0.75
CT	6	6	N/A	**NY**	30	30	22
DE	N/A	2	2.5	**NC**	8.3	1	0.27
DC	N/A	N/A	N/A	**ND**	N/A	0.64	0.5
FL	7.2	5	0.3	**OH**	100	100	35
GA	8	2	2	**OK**	9-15	1.9	0.22
HI	0.15	N/A	0.95	**OR**	3	6	0.5
ID	1.1	0.25	0.75	**PA**	34	21	17
IL	15-20	4	N/A	**RI**	34	33	7
IN	20	15	N/A	**SC**	N/A	5.7	N/A
IA	6.4	7.3	4	**SD**	2	2	0.92
KS	N/A	2.5	N/A	**TN**	16	N/A	N/A
KY	10	8	N/A	**TX**	69	85	N/A
LA	40	6.2	0.25	**UT**	5.6	0.5	0.6
ME	30-60	60	26	**VT**	1	N/A	0.25
MD	10-15	12	N/A	**VA**	6.5	14	10.5
MA	5-10	6	10	**WA**	18	N/A	N/A
MI	20	25	25	**WV**	6.8	6.8	10
MN	0.75	0.1	N/A	**WI**	4	1	0.1
MS	0.7	1	0.25	**WY**	0.25	N/A	0.38
MO	10	4.7	6.5				

Sources: Scrap Tire Management Council. 1995, 1997. 1-7, 12.
Brown et al. 2001. 12.

Internal Costs

Stockpile Clean-Ups

Although the eyesore of abandoned tires across streams and woods may have been one point of concern, the risk of pollution from burning tires and viral infections from disease-carrying mosquitoes have been the primary reason for state governments to seek

the removal of scrap tire piles. As Table 2.2 shows, the rate of discovery has been tremendous in some states throughout the 1990s.

Tire stockpiles at illegal disposal sites and abandoned scrap tire processing facilities reflect a misdirection of portions of past and current waste tire streams. It is very difficult to know to what extent newly generated tires contribute to existing piles and/or create new ones because the magnitude of illegal dumping does not usually become apparent to state officials until new sites are discovered. Direct state comparisons should be undertaken with great caution for various reasons. These figures are very rough since it is difficult to count accurately the number of tires in a given pile. Also, waste officials across states use different survey models to derive their estimates. And some states have high numbers of tires in stockpiles because they have historically received scrap tires from multiple states. The STMC (1999, 4) estimates that the national stockpile was reduced from 700-800 million scrap tires in 1994 to approximately 500 million at the end of 1998.

The removal of scrap tires from open field sites is labor-intensive because tires are awkward to handle. Often, they are retrieved from piles and loaded individually on trucks. Transportation costs also make up a substantial portion of the costs. In some cases, transportation costs can be so prohibitive that the facility is moved to the pile. A good example is the tires-to-energy plant near Modesto, California. At one point in the late 1980s, a scrap tire pile contained about 40 million tires which was at the time probably the largest in the world. Since 1987, the plant generates heat to produce steam providing enough electricity for a town of 15,000 people (Mattheis 1988, 46).

Ceteris paribus, the closer the site is to a tire disposal facility, the lower the per unit cost of tire clean-up. Snyder (1998, 7) writes that it takes roughly one dollar to transport a new tire, which is close in weight to a scrap tire, 100 miles.

Landfilling

Scrap tires consume relatively much landfill capacity. Unless they are mixed with small waste, whole tires occupy about 75 percent of void space due to their low density. Moreover, their durable rubber material is non-degradable and hard to compress by other landfill components. In addition, the presence of waste tires can increase landfill operating costs in two ways. First, void space within a single or group of tires creates an unstable landfill component creating differential settlement of landfill covers when large enough. Second, the fact that tires do not degenerate allows them to float upwards as surrounding material decomposes. This, too, heightens the likelihood of cap repairs (CIWMB 1992, 10).

As of fall 2000, 37 states had banned whole tires from general-purpose landfills (STMC 2001). Although further research might shed more light on what exactly motivated lobbying efforts to ban tires from general solid waste landfills, tight environmental regulations of landfills, high standards on opening new sites, increased public aversion to new landfill openings, and temporarily reduced landfill space (Jenkins 1991, 10) might partially explain state action.

It is noteworthy that the majority of states allows the storage of tires in monofills and mixed-use landfills. Whereas mixed-use landfills permit the disposal of tires with other waste, monofills are exclusively designed for scrap tire disposal. In both types of

landfills, operators are generally required by law to shred or cut tires into pieces before covering them with dirt. While 14 states grant the disposal of whole tires, 12 states even restrict the landfilling of shredded tires (Brown et al. 2001, 13). Even when size reduction through cutting or shredding eliminates numerous problems associated with landfilling whole tires, it entails processing expenses. The relative price difference between general and tire waste in Table 2.3 reflects these costs and the private opportunity cost of land. However, these prices are not representative because California's landfill disposal charges rank below the national average (CIWMB 1999, 5).

Table 2.3. Solid Waste and Tire Landfill Disposal Fees.

1998 Survey	Solid Waste $/Ton	Shredded Tires $/Ton	Whole Tires $/Ton
Lowest	3.5	9.2	75
Highest	110	500	1400
Median	33.25	100	200
Average	37.94	95.80	246
Weighted Average (Landfills Only)	31.07	59.39	373
Weighted Average (All Facilities)	33.07	60.07	365
1999 Survey	Solid Waste Comp Rate $/Ton	Shredded Tires $/Ton	Whole Tires $/Ton
Lowest	3.5	3.5	95
Highest	110	280	1500
Median	35.85	84.5	200
Average	39.64	87.01	281
Weighted Average (Landfills Only)	31.91	65.9	406
Weighted Average (All Facilities)	34.37	67.4	400
2000 Survey	Solid Waste Comp Rate $/Ton	Shredded Tires $/Ton	Whole Tires $/Ton
Lowest	2.5	42	75
Highest	85.3	280	1465

Median	36	95	200
Average	39.62	102.7	261
Weighted Average (Landfills Only)	35.14	67.67	355
Weighted Average (All Facilities)	37.72	71.41	353

Source: California Integrated Waste Management Board. 2001a, 2001b. The original data source reports dollar costs per tire. If one assumes that one scrap tire weighs 20 pounds, one can compute disposal charges per ton as in the right-hand column.

Regulations

In order to address proper short-term storage practices, states have enacted new waste tire standards. Although legislation differs in particular details, common regulatory approaches can readily be noted. As of 2001, 46 states require license or permit systems for scrap tire storage (STMC 2001). Mostly processing and landfill facilities hold these permits because they frequently store large numbers of whole tires for some period of time.[11] These permits allow waste tire agencies to record scrap tire storage locations and to impose rules on fire prevention and vector control. Fire regulations may include lanes for easy access of firefighting equipment and limits on the height and horizontal dimension of individual piles. Commonly, the law also sets minimum spacing among piles and quotas on the total number of tires at any given storage site. North Carolina, for instance, places the total number at the maximum of 60,000, whereas Nebraska puts the limit at 300,000 with the requirement that no single tire remains longer than 18 months at a given location (U.S. EPA 1999).

[11] Minnesota exempts landfills that store no more than 10,000 tires, whereas Florida requires any disposal facility to possess a permit. In Kentucky, no one is allowed to store more than 100 tires without state permission. Under Georgian law, retailers can collect up to 3,000 tires (U.S. EPA 1999b).

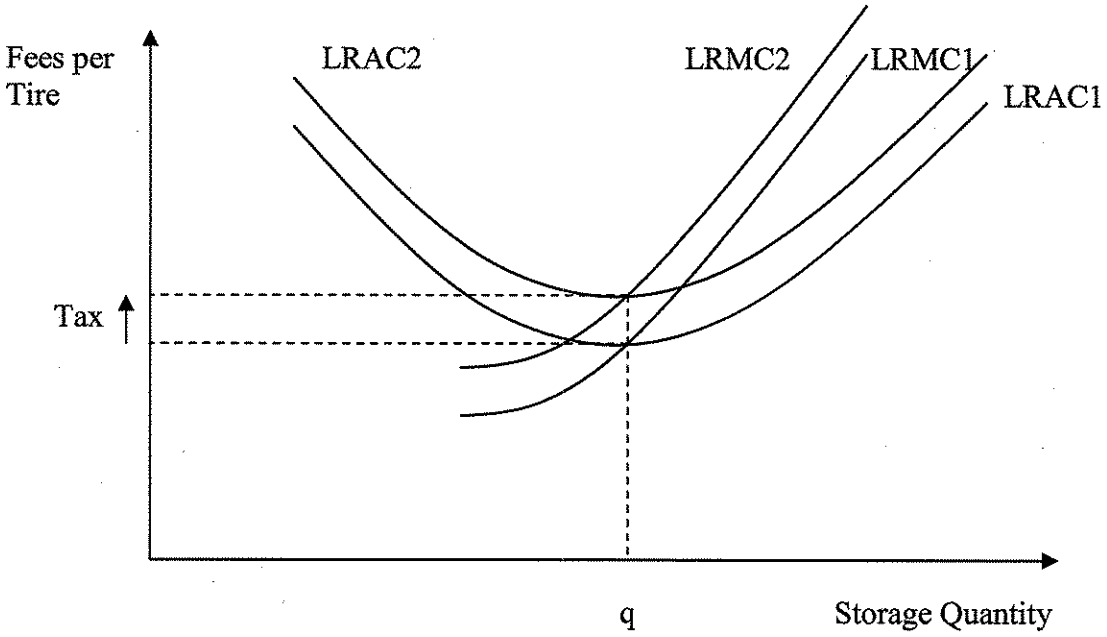
Moreover, the limited number of tires at individual storage sites allows better control of mosquito outbreaks, while statutory law can require additional measures to be undertaken to reduce the extent of mosquito breeding, such as the spraying of pesticides and larvacides. Other practices involve the covering of tires to avoid the accumulation of rainwater. In many states, even non-permit holders must comply with proper storage practices. For instance, Ohio, as most other states, does not require collectors of small numbers of waste tires, such as tire retailers, fleet maintenance garages, and automobile salvage dealers to hold permits (Ohio State University Extension 2001a). They are usually excluded because their primary course of business is not scrap tire disposal, and it is therefore in their interest to remove tires in a timely manner. Nonetheless, fire and pest prevention mandates do apply to these enterprises. Figure 2.2 treats state regulations as if they were a per unit tax shifting long-run storage costs upward.[12]

It is assumed that the cost function displays both economies and diseconomies of scale. Thus, average costs may decline because the production technology displays increasing returns to scale up to a certain storage level due to standard gains in specialization. The opportunity cost of additional land in urban areas can then be large enough to force an upward sloping cost curve when storing high quantities of scrap tires. For processors, another reason for such diseconomies are rising transportation costs the

[12] Due to imperfect monitoring efforts, the cost curves of individual recipients are expected to shift upwards to differing degrees albeit equally at all storage levels. Hence, it is assumed that the marginal cost of regulation is constant. This might even be a reasonable assumption in the context of adulticide and larvicide sprayings for modest-size scrap tire piles even if adult mosquitoes and larvaes are difficult to reach at the bottom of piles where they tend to locate. Hence, the larger the pile, the higher *total* pesticide expenditures are. The result of one study placed the material cost at 2.43 dollars per 100 tires excluding capital and labor expenses (Faget, Perdew, and Yates 1992, 8).

farther the supply of scrap tires is from the facility. For that reason, processors are likely to enter local markets when a sufficient stream of scrap tires is within proximity.

Figure 2.2. Representative Long-Run Cost Function for Tire Collectors.



Furthermore, 34 states permit the transportation of scrap tires only by registered haulers. Retailers and other entities are thus required by law to use exclusively transporters that possess a valid identification number. Ten states even require manifests for the collection and disposal of scrap tires (STMC 2001).[13] One can imagine that extensive tracking systems for scrap tires through manifests is resource-intensive for both private and government agents. As Brown et al. (2001) point out, however, such systems

[13] The regulations put forward by the Mississippi Department of Environmental Quality (1992) provide a representative example. By law, scrap tire collectors, such as tire retailers, must certify the place of collection, quantity, and destination of their scrap tires. Registered haulers are then required to complete and sign the manifest, whereas retailers are mandated to keep a copy of the transaction for at least three years. At the point of destination, transporters present the original manifest to the processing or disposal site. Again, the recipient must sign and retain a copy of the manifest for three years. The records of all three agents are subject to the inspection of state enforcement personnel. In addition to keeping a copy, the waste tire hauler must file an annual report with the department. The report must state the approximate number of waste tires hauled, origin, and final destination.

assure that registered haulers transport their tires to proper waste facilities. In addition, they argue that they provide surveillance for government officials on prescribed storage requirements and make the enforcement of regulations visible to all agents. Inconsistent monitoring places legitimate businesses into a disadvantage and provides incentives to circumvent rules and consequently the costs of tightened regulations in a competitive business environment (CIWMB 1999, 25). Increased illegal dumping incidents might be the immediate consequence.

Recycling

Market Volume. Government subsidies and private enterprise have extended end-use markets for recycled scrap tires and guaranteed that whole tires are processed in a timely manner. [14] Nation-wide, the percentage of scrap tires with new markets has risen from eleven percent in 1990 to 55 percent in 1994, gaining roughly ten percent every year (STMC 1997, 4).

Table 2.4. Total Scrap Tire Market (million tires).[15]

	1998	1996	1994
Fuel	114	152.5	101
Civil Engineering	20	10	9
Products (e.g. ground rubber)	23	20.5	12.5
Miscellaneous	5.5	4	3.5
Export	15	15	12.5
Subtotal	177.5	202	138.5

[14] See CIWMB (1992, Section 2) and Snyder (1998, Chapter 5-12) for numerous applications of recycled scrap tires.

[15] It is noteworthy that the STMC changed its estimation method in 1998 (1999, 5). Previously, market shares were based on capacity rather than actual usage. For instance, the capacity of all permitted fuel users comprised 132 million tires in 1998 as opposed to the actual 114 million tires used. The numbers for 1996 were 153 million in capacity and 135 million in burned tires. If one adjusts the 1998 fuel figure, 72 percent of all tires generated found market applications.

Total Generation	270	266	252
Market as % of total generation	65.7%	75.9%	54.9%

Source: Scrap Tire Management Council. 1995, 1997, 1999. WA, DC.

Tire Derived Fuel (TDF). The largest use of scrap tires is as fuel. Particularly cement kilns, paper mills, and to some extent electric power plants utilize tire chips. Thirty-six cement kilns burned 55 million scrap tires in 1996, and 30 kilns used 38 million tires in 1998 (STMC 1999, 6). Scrap tires are attractive to cement producers because the manufacture of cement uses large amounts of energy. In order to generate one ton of Portland cement, roughly 500 pounds of coal are required rendering energy expenses a large share of input costs in cement production (Snyder 1998, 53). Since tire chips are high in energy content relative to other fuels, kiln operators view them as low cost energy alternative (Table 2.5). Indeed, kiln owners charge small tipping fees of around ten cents per tire because they predominately use whole tires in production eliminating potential shredding costs for their suppliers (CIWMB 1999, 9).

Table 2.5. Typical Combustion Heat of Various Materials.

Fuel	BTU/lb
Anthracite coal	12,000-14,000
Newspaper	7,975
MSW	3,500-5,500
Bituminous coal	11,000-13,000
Fuel oil	18,000-18,500
Sawdust	7,800-9,600
Wet wood	4,000-5,500
Tire chips	12,000-16,000

Source: California Integrated Waste Management Board. 1992. 12.

In addition to lowering the private costs of cement production, whole tires have the potential to decrease external costs, as well. The standard sulfur content of a tire is about

1.2 percent. In contrast, Midwestern coals may contain up to four percent, and Montana and Western coals roughly 0.5 percent of sulfur, where the latter possess fewer BTU per pound (e.g. 6,000 versus 13,500), and hence on an equivalent BTU basis they contain approximately 1 percent (Snyder 1998, 47-48).

To appreciate the mitigation of external costs, it is critical to realize, however, that the chemical process in kiln furnaces utilizes almost all the sulfur content of tires and converts it first into sulfur dioxide which it then turns into calcium sulfate as ingredient for cement (Snyder 1998, 54). As a result, only minor amounts of sulfur dioxide are left to escape into the atmosphere placing a negligible burden on the environment. Snyder (1998, 50) further notes the advantage of tires over coal with respect to carbon dioxide emissions. This is in stark contrast to the external consequences of incomplete combustion in open-field tire fires to be described in the next section.[16]

The pulp and paper industry is very energy intensive, too, because the production of paper requires tremendous quantities of steam for the heating and drying process. Although wood wastes produced during cutting and chipping are used in boilers as energy resource, branches and sawdust have relatively low heat energy (Table 2.5). TDF therefore serves as suitable fuel supplement in combination-fuel boilers, which establishes its wide use in the forest products industry (Snyder 1998, 52).

Utility boilers use whole tires or TDF in combination with coal to generate electricity. At the end of 1998, eleven facilities consumed 25 million tires (STMC 1999, 8). There are currently two utility facilities in the United States that exclusively use tires, absorbing

[16] Between 1996 and 1998, six cement kilns stopped using TDF or their entire operation. Interestingly, environmental damage was never a reason (STMC 1999, 5).

16 million tires each year (STMC 1999, 10). The Modesto facility, the previously mentioned tire-to-energy facility in California, incinerates whole tires to supply a turbine with high-pressure steam. Five million tires produce 14 MW of electricity annually (STMC 1997, 29).

In conclusion, the application of rubber chips as energy input is quite prevalent in some industries. Albeit emissions are likely to vary depending on the type and design of facilities, kind of primary fuel burned, percentage of primary fuel replaced with tires, and air pollution control equipment (CIWMB 1992, 39), excessive concerns about the burning of waste tires on public health and the environment are largely misguided. More importantly, the extensive use of whole tires or tire chips as energy input may significantly decrease the internal and external costs of production, e.g., cement, and scrap tire disposal. This appears to be particularly true when the energy alternative is coal and the scrap tire stream is nearby. Ironically, the lack of reliable, nearby, and large supplies of scrap tires is the main reason why the use of whole tires or TDF as a sole fuel is not wide-spread (Snyder 1998, 51).[17] Similarly, for tire-to-energy facilities, this limits the size of the plant. As mentioned, the Modesto facility is a 14.4 MW unit. In contrast, large coal-fired power plants can have a capacity of 500 MW (Snyder 1998, 51).

Ground Rubber Applications. Rubber Modified Asphalt is a potentially large volume outlet for scrap tires. If crumb rubber were universally adopted at the moderate rate of 60

[17] Moreover, many industrial and utility boilers use a boiler technology that is designed to burn fuel in powder (pulverized coal), liquid (oil), or gaseous (natural gas) form (Brown et al. 2001, 12). Rubber particles that are free of wire are available on the market and are called crumb or ground rubber. TDF of that fineness, however, calls for considerable processing costs which are reflected in the high price of crumb rubber per ton.

pounds of rubber per ton of asphalt, 28 billion pounds of crumb rubber would be required. Assuming that ten pounds of crumb rubber are obtained from an average passenger tire, RMA presents a disposal means for two billion tires in any given year (Snyder 1998, 62).

At one time, the US Congress recognized the capacity of this outlet for scrap tires and passed legislation. The Intermodal Surface Transportation Efficiency Act (ISTEA) mandated the use of scrap tires in road construction, which was soon repealed in 1995 due to durability and safety concerns about unproven technology raised by some states (Snyder 1998, 57-66). In the meantime, extensive research efforts have been directed to evaluate the properties of RMA, but more time will have to pass to see how states' experiences turn out. Presently, the blending of ground rubber with asphalt is prevalent in Florida, California, and Arizona (STMC 1999, 11). Wide adoption in the near future is unlikely because of the technological uncertainties surrounding RMC and because of the lower cost of unmodified asphalt. High processing expenses with ground rubber and additional mixture procedures in connection with RMA are largely responsible for the latter.

Crumb rubber has found low-scale miscellaneous applications in rubber mats. One interesting product is the agrimat for cow and horse barns. These commonly one inch thick mats provide a warm ground for animals and an increase in milk productivity on some farms by as much as ten percent (Snyder 1998, 73). Thick rubber mats also find applications under playground equipment lowering the risk of injuries for children (Snyder 1998, 74-75). Playturf containing loose rubber chips has replaced sand or wood chips on playgrounds in some regions. Public parks, golf courses, and various grass

sports fields utilize rubber turf as soil amendment. Other athletic and recreational applications may include running tracks, gym surfaces, and sports fields.

Civil Engineering. Using rubber chips in landfill construction and operation is a rather ironic and growing civil engineering use. As mentioned before, whole tires have been baned from general landfills in many states. Yet, tire shreds have proven to possess superior properties in landfills mainly because the friction they provide keeps them better in place on slopes than sand and other material (Snyder 1998, 99). Also, several states permit scrap tire shreds mixed with soil as landfill cover material. A few inches of tire chips in landfill caps provide excellent permeability and good drainage (STMC 1995, 2-24).

External Costs

Environmental Concerns

Arson and lightning are the primary causes of prolonged tire fires. Although whole tires do not ignite easily and combust spontaneously, once large tire piles catch fire they pose the primary environmental concern in connection with improper scrap tire disposal (Snyder 1998, 2). The polluting effects of these streams derive from the burning tires themselves and their impact on adjacent ones. Under controlled conditions in a furnace or boiler undesirable chemicals from burning tires are completely combusted without being able to escape the combustion zone (Snyder 1998, 47). In contrast, tires on fire in open air burn incompletely. Their uncontrolled burning produces dense smoke with a wide variety of decomposition products, among which hydrocarbons (CO), sulfur compounds

(SO, SO_2), nitrogen oxides (NO, NO_2), and benzene are the most prominent. Specific emissions usually depend on tire fire specifics and the surrounding climate, such as burn rate, tire types, pile size, humidity, and temperature (STMC n.d.a, 37). The black smoke generated by these fires can be 3,000 feet high, with a serious effect on neighboring areas (STMC n.d.a, 4).

Burning tires also release extreme heat, setting in motion a chemical change called pyrolysis in nearby tires. Pyrolysis is caused by heat alone in contrast to oxidation and burning (Snyder 1998, 2). Approximately two gallons of pyrolytic oil can be produced from a standard passenger tire. To place this into perspective, during the Exxon-Valdez incident on the Alaskan shore, eleven million gallons of oil spilled into the sea. If only half of a 14 million tire pile turns into oil, 14 million gallons of toxic substances can contaminate groundwater, near-by lakes, and soil (STMC n.d.a, 4). Sometimes, run-off oil can be contained, collected, and sold as fuel oil. Albeit spilled oil is much easier collected on the ground than in the sea, fire fighting and clean-up are nonetheless technically difficult.[18] In addition to generating large amounts of pyrolytic oil, this process adds to the gaseous chemicals that come from burning tires themselves and that escape in the air.

Tire fires can generate substantial costs even when the piles are small, drawing vast resources from fire departments (STMC n.d.a, 3).[19] According to the Maine Department

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[18] This is particularly the case when large amounts of oil are generated at low levels of the pile.

[19] There are two main reasons why burning tire piles are hard to combat. First, the intensive heat entertained by tire fires does not render water very suitable. Second, scrap tire piles trap fair amounts of oxygen. This is due to the low bulk density of tires and the fact that they are often loosely combined in piles. Consequently, even tires in large piles have access to a sufficient supply of oxygen making it hard to smother a fire with foam (STMC n.d.a, 33). A common difficulty with the use of both water and foam is that they cool burning tires down enough to generate oily water mixtures that can contaminate the surface

of Environmental Protection and Maine Department of Economic and Community Development (2000, 7), expenditures on firefighting and containing oil and contaminated water run-offs are up to 100,000 dollars per day for several weeks. In addition, polluted soil and water can entail a lengthy removal process with costs of about 5,000 per day for over six months (Maine DEP and Maine DECD, 7). The U.S. EPA maintains that cleaning up scrap tire stockpiles, including fire fighting costs, is ten times as expensive after a fire as before (STMC 2000, 20).

The agency also estimates that about 176 tire fires have burned nation-wide between 1971 and 1996 (Pennsylvania DEP 1996, 1). The three recent major tire fires in the United States occurred in Ohio, Syamore, and California, Tracey and Westley. In Syamore in 1998, five to seven million tires burned creating ten to twelve million dollars in clean-up and damage.[20] Albert Johnson, state official with the CIWMB, offered the following cost estimates for the two fires in California.[21] The Tracey fire ignited in 1998, and all six million tires in the pile were allowed to burn. After two and a half years, the California Integrated Waste Management Board did extinguish the remaining hot spots for about 400,000 dollars. The agency expects to spend an extra nine million dollars to free the soil from contamination. At Westley, in 1999, between two and three million tires out of a seven million pile burned. The U.S. EPA extinguished the fire in 34 days accumulating costs of about four million dollars. Johnson noted that the CIWMB had spent more than five million dollars to date on oil clean-ups. His agency intends to make

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and groundwater (Pennsylvania DEP 1996, 1-2). In order to cut off the oxygen supply, dirt and sand are therefore the preferred material by the United States Environmental Protection Agency (Pennsylvania DEP 1996, 2). Occasionally, tire fires take months to burn themselves out, whereas firefighting efforts are confined to isolate burning tires and to collect oil run-offs (STMC n.d.a, 33-34).

[20] Based on a telephone conversation with Mr. Blumenthal from the STMC.

[21] Telephone conversation.

available another eight million dollars to remedy all adverse environmental impacts from the fire.

Nuisance and Public Health

Tire piles are often hosts to pests. Rats and snakes find easy access to the loose structure of tire piles. If there is a surrounding food source, they infest the tires thus creating a nuisance for nearby neighborhoods. More critical, however, is the fact that scrap tires pool rainwater because some mosquito species favor these stagnant water accumulations as breeding places. Mosquitoes are commonly considered a nuisance pest, too, but some species transmit dangerous encephalitis strains to humans and animals. The La Crosse, St. Louis, and recently, the West Nile encephalitis are dominant causes of mosquito-transmitted viral infections in the United States (Centers for Disease Control and Prevention 2001a, 1).[22] The La Crosse strain was traced back to a tire pile in the town of La Crosse, Wisconsin, in 1963 (Snyder 1998, 4; HSPH 2000b, 1).[23]

Two mosquito species are the main carriers of these encephalitis strains. Unlike the majority of mosquitoes that reproduce in marshes, ditches, puddles, and such, these two

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[22] St. Louis encephalitis is the leading viral infection of its kind in the United States (CDC 2001a, 4). It is named after the city of St. Louis in which is was first detected in 1939 (HSPH 2000b, 1-2). The CDC receives an average of 193 reports each year, with the elderly at the highest risk to develop more severe symptoms (2001a, 4). The West Nile Virus originated in Africa, and it is unknown when it arrived in the United States (CDC 2001c, 1). No cases were reported until 1999 when in the New York area at least 62 citizens became severely sick, while seven of them died in the wake of an outbreak. Another 21 cases with two deaths occurred in New York City in the subsequent year (CDC 2001b, 1). In the meantime, the WNV has rapidly spread throughout the entire state and into New Jersey, the District of Columbia, Connecticut, North Carolina, and Pennsylvania (Ohio State University Extension 2001a, 1; NYDOH 2000c, 1). Health officials expect the virus to appear soon in some of the more humid Midwestern states.
Refer to Centers for Disease Control and Prevention, September 2001, for other encephalitis types. The strains in this section are mentioned because they are largely borne by tire pile breeders.

[23] Ohio, Wisconsin, Minnesota, Illinois, and Indiana form the La Crosse Belt because they report the largest number of cases (Walker 1992, 17). An average of 75 cases is reported to the CDC each year with children under 15 carrying the most severe symptoms (CDC 2001a, 3).

species prefer small collections of water as breeding sites. Any place that can hold one centimeter of water, such as tree holes, beverage cans, Styrofoam cups, or flower pots therefore acts as potential habitat. However, discarded tires have become the prime breeding site for these species, giving them the nicknames "Tire Pile Mosquito" and "Container Breeder" (Walker 1992; Ohio State University Extension 2001b, 1-2).[24] Public insecticide-sprayings are common pest control measures during mosquito seasons in urban areas (ABC News 2000).[25]

An estimated 25 million scrap tires are stockpiled throughout New York State in addition to the 18-20 million tires generated each year (STMC 2000, 2). A diverse group of interests comprised of waste management officials, tire industry representatives, environmental advocacy officials, among others, hence formed the New York State Roundtable for Consensus on Tire Management in late 1998. In a final draft, the Roundtable summarized its various findings and suggestions for sound scrap tire management. Since scrap tires have become the primary breeding source for disease-carrying mosquitoes, it is hardly surprising to read in this report that "Given the recent

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[24] The spread of mosquitoes within the United States has primarily been caused by shipments of used or waste tires. For that reason, some states restrict importation to new tires. Scrap tires offer ideal conditions for numerous reasons. Like all other mosquito species, the encephalitis carriers require warm, stagnant, stained, and sunlight-protected water as breeding habitat. Due to their shape and void space, tires accumulate stagnant pools of rainwater in any position in which they are stored. At the same time, they absorb large amounts of sunlight, while their form protects the stained water from direct light exposure. Hence, mosquitoes lay their eggs in water-filled tires, and the larvae and pupae mature in the water under almost ideal conditions (Pennsylvania DEP 1996, 3). Walker (1992, 17) writes that "In scrap tire yards, adults reach incredibly high numbers, as many as 60,000 females per acre in mid-summer".

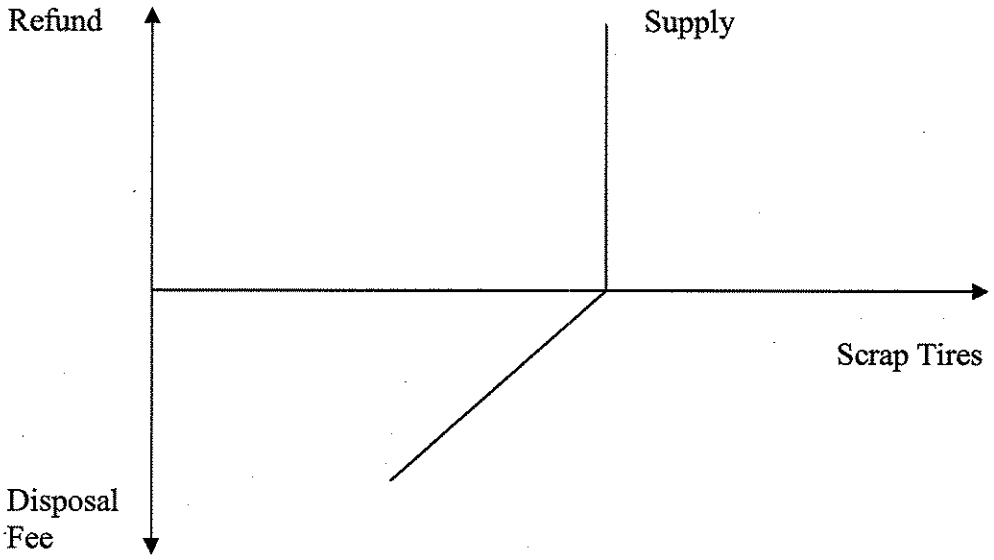
[25] As opposed to tire fires that have occurred all over the nation, the public health threat associated with mosquito outbreaks is geographically confined to the humid rather than semi-arid or arid climates. Take California and New York as examples. Both stockpile large numbers of scrap tires within their borders (Table 2.2). While New York has experienced fatalities in the wake of mosquito-outbreaks and ten tire fires since 1994, improper tire disposal practices have alerted Californian officials largely because of devastating fires (STMC 2000, 20).

episodes of mosquito borne diseases in the State, the urgency for scrap tire stockpile abatement in New York has heightened" (STMC 2000, 20).

Some Basic Economics of Tire Disposal Policy

Further application of economic theory can help illuminate other interesting effects of state scrap tire policies. In the majority of states that charge user fees, retailers levy both a pre-disposal and disposal fee on consumers. As of 2001, six of those states, however, do not permit retailers to charge consumers extra for tire disposal services (STMC 2001).[26]

Figure 2.3. Scrap Tire Supply Function for Households.



Individual consumers undoubtedly comprise the largest proportion of the demand for replacement tires which makes them important agents in proper waste tire disposal. In this context, it is critical to realize that most consumers do not change tires themselves,

[26] Five of which are part of the sample.

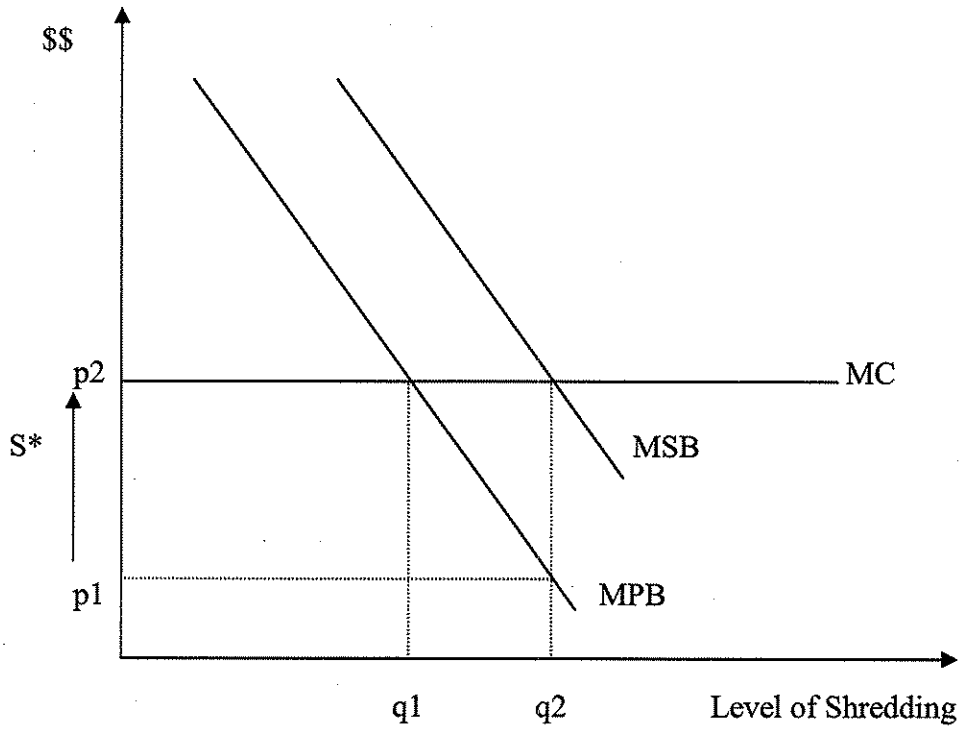
but return them at almost zero inconvenience to their source regardless of a refund option (Figure 2.3).

Recall from Figure 2.2 that state regulations have pushed tipping fees upward. Retailers are likely to pass on increased disposal fees to consumers producing a possible dual effect at the margin. More specifically, some consumers will reduce their rate of new tire purchases and/or increase their level of illegal disposal practices assuming that the price of alternative collection services remains constant. One can therefore expect to encounter scrap tires in isolated sets of four as opposed to accumulated piles of thousands at a higher rate in the future.

Assuming that many consumers are law-abiding citizens and that licensed haulers deliver scrap tires to registered processors, processors might be regarded as the pivotal agent in the tire disposal process. If it is correct, as previously argued, that potential environmental and health hazards are most pronounced when tires are stockpiled, the marginal social benefits of proper disposal are expected to be largest when tires are reduced in volume by shredding, cutting, or chipping. Again, the reasoning is that shredded tires pose a lower fire hazard than whole tires and do not allow the accumulation of stagnant water in stockpiles, in addition to reducing transportation costs and the amount of landfill disposal space.

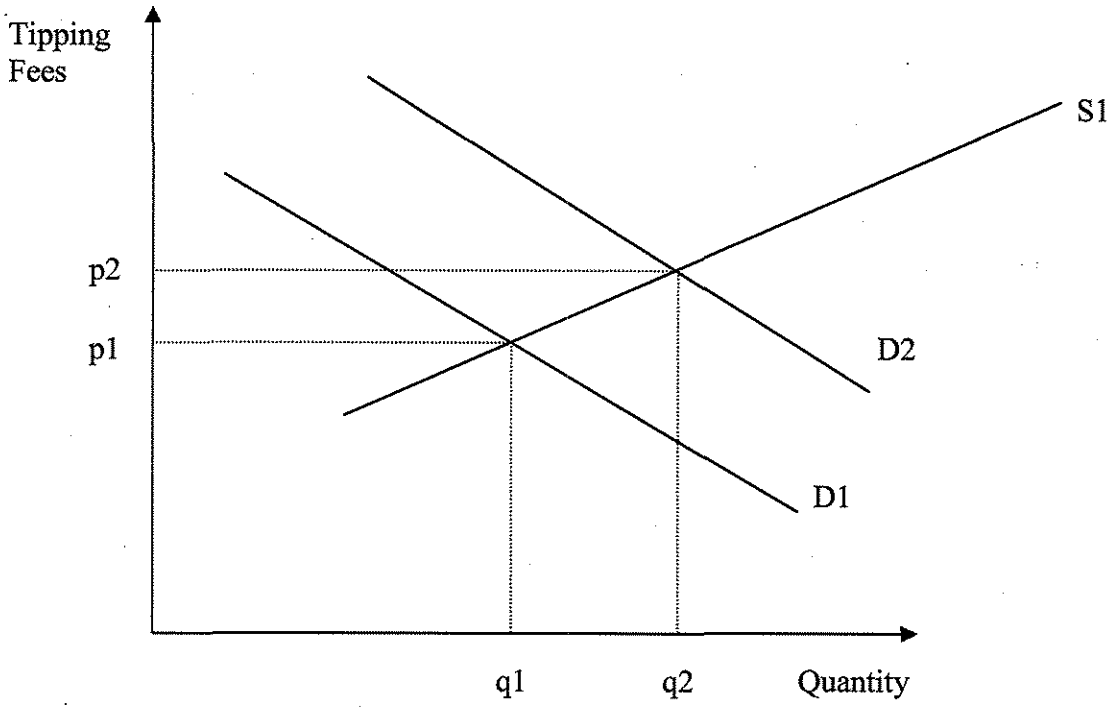
Significant external benefits could be derived from higher quantities of processed scrap tires. To equate marginal social and private benefits, one could install a subsidy S* paid by the government or tire industry as shown in Figure 2.4. Private benefits comprise potential sales in end-use markets, while social welfare includes, in addition, the benefits of avoided external costs.

Figure 2.4. Optimal Level of Shredding Services.



The legislative ban of tires from general landfills increased the quantity of whole tires that required alternative disposal options. The current outlet for whole tires primarily relies on processing facilities and monofill operators that accept them from tire retailers and haulers as inputs in their production process. One possibility for modeling the ban of whole tires in general landfills is to view it as an increase in the demand for collection services leading to higher tipping fees paid by retailers and haulers (Figure 2.5). Due to these profit opportunities, one would expect to see entry of scrap tire processors reflected by a move along and shift of the market supply curve. Brown et al. (2001, 16) suggest that entry indeed occurred placing downward pressure on tipping fees.

Figure 2.5. Market for Non-Landfill Collection Services.



Processors collect tipping fees from retailers and haulers when accepting their scrap tire loads. These fees are their major source of revenue (Brown et al. 2001, 16). Obviously, processors will only have an incentive to shred tires as they receive them if they face a steady demand from end-users willing to pay a price that covers at least their processing and transportation costs. Absent such recycling options, they weigh their marginal *private* costs against their marginal *private* benefits of stockpiling. Benefits primarily stem from tipping fee avoidance at monofills, whereas costs include expenditures on meeting storage regulations. The ban on whole tires in general landfills is likely to have significantly increased the number of whole tires in open air piles. It is not

clear with respect to the frequency and intensity of fires and mosquito outbreaks if this presents a superior disposal option to whole tires in general landfills.

A final note is in order with regard to the popularity of recycling programs. The STMC, for instance, has been promoting the three R's since its inception: reuse, recycle, or recover the inherent value in scrap tires (Rubber Manufacturers Association 2000, 56). The tone of some states' legislation clearly favors recycling, such as Georgia's disposal law:

> It is ... the intent of the General Assembly that every effort be undertaken to ensure the proper management of scrap tires from the point of generation to the ultimate point of reuse, recycling, or disposal and that every effort be made to ensure that, where possible, they be used or recycled rather than being disposed. (Brown et al. 2001, 12)

Without a doubt, some members of society view recycling as the superior disposal option, almost disconnected from relative prices. It is noteworthy that monofilled tire shreds allow for future recovery, and that they pose little danger to the environment and health by releasing insignificant levels of organics and metals into the ground(water) (STMC 1999, 16-17).

One potentially attractive policy would provide a simple subsidy and thus artificially stimulate demand in the rubber chip market. The advantages of such a price support are manifold. First, whole tires are processed in a timely manner, which reduces the external costs associated with tire fires and mosquito outbreaks. Second, it lowers the incentive to haulers and processors to dump tires illegally.

CHAPTER 3

DATA DESCRIPTION

Overview

This chapter explains the construction of the per unit tax variable, which is the independent variable of main interest, and the derivation of the quantity of tire purchases, which is the dependent variable. At the same time, it explains the asymmetric measurement errors in the sales data and describes the data sources for the state characteristics. States that have introduced a tire tax have done so mainly to establish a funding source for proper scrap tire disposal.

Data from a large number of different sources are often problematic because figures from one agency may not be comparable to another even if the variables of interest are conceptually the same. Since this paper utilizes tax revenue collections by fiscal year from 28 state agencies, it introduces inconsistencies in the derived tire sales data. For instance, variations exist among state tire laws with regard to the specific type of tire that is subject to the tax (i.e., the tax base), because some programs include taxes on used tires and tires for trailers, while others have exemptions for these cases. Only revenues from taxed tires can be collected; thus, exemptions for certain tires in some state laws render a different composition of tire types that generate the revenues, and hence the *measured* level of tire sales. It is important to discuss these non-uniformities despite the fact that all states in the sample place the fee on passenger and light truck tires, which together comprise 80 percent of the tire market.

Data on particular state characteristics are compiled from three agencies. The Federal Highway Administration collects vehicle registration data by individual states, the Bureau of Economic Analysis provides data series on per capita personal income, and the Bureau of Labor Statistics constructs numerous price indexes for public use. Data from all agencies are expected to be uniform among states.

Pre-Disposal Charge

In the majority of states, retailers are required by statute to list the user fee as a separate line item on the sales invoice at the point of purchase. The consumer is therefore aware of the charge when payment is made. Furthermore, it is conceivable that consumers had been aware of new tire laws going into effect through radio, television, and newspaper accounts before they purchased a set of tires.

Table 3.1. Tax Rate and Base for Individual States.

State	Revenues collected Fiscal year	Policy fee ($$ per tire)	Allowances for retailers	Net fee ($$)	Tax base
AZ	1994-00	2% of tire price with a max. fee of 2.00 per tire	N/A	1.10	All new tires and tires on new vehicles
AR	1992-97	1.50	10% of tax	1.35	All new auto and truck tires
CA	1991-00	0.00	N/A	0.00	All new tires
CO	1995-00	1.00	N/A	1.00	All new tires
CT	1994-97	2.00	N/A	2.00	All new, used, and retreaded tires
FL	1991-00	1.00	N/A	1.00	All new tires and tires on new vehicles
GA	1993-00	1.00	11% of fee	0.89	All new tires
IL	1993-00	0.90	0.10 per tire	0.90	All new and used tires

IN	1994-00	0.25	N/A	0.25	All new tires and tires on new vehicles
KS	1992-00	0.50	N/A	0.50	All new tires and tires on new vehicles
KY	1994-98	1.00	N/A	1.00	All new tires
LA	1993-95 1996-00	1.00 2.00	1.00 for tire disposal N/A	1.00 2.00	Passenger and truck tires
MD	1993-00	1.00	N/A	0.99	All new tires and tires on new vehicles
MS	1993-96 1997-00	1.00 1.00 < 24" 2.00 ≥ 24"	5% of fee 5% of fee	0.95 mean of 0.99	All new tires
MO	1996-00	0.50	6% of tax	0.47	All new tires
NE	1992-00	1.00	N/A	1.00	All new tires and tires on new vehicles
NV	1994-00	1.00	5% of tax	0.95	All new tires
NC	1991-93 1994-00	1% of tire price 2% < 20" 1% ≥ 20"	N/A	0.75 mean of 1.35	All new tires
OH	1995-99	0.50	N/A	0.50	All new tires
OK	1990-95	1.00	N/A	1.00	Auto and light truck
OR	1989-92	1.00	0.15 per tire	0.85	All new tires
RI	1995-98	0.75	N/A	0.75	All new tires
SC	1993-00	2.00	1.00 for tire received plus 3% of fee	0.94	All new tires
TN	1993-00	1.00	0.10 per new tire	0.90	All new tires
TX	1993-97	2.00 < 17.5" 3.50 ≥ 17.5" 1.00 used tires	N/A	Mean of 2.15	All new and used tires
UT	1994-96 1997-99 2000	1.00 0.50 0.85	2.5% of tax	0.98 0.48 0.83	All new tires and tires on new vehicles
VA	1991-00	0.50	5% of fee	0.48	All new and used tires
WA	1991-94	1.00	10% of fee	0.90	All new tires

In addition to the state-wide user fee on new tires, consumers in almost all instances pay a disposal fee. This charge is entirely by the discretion of the retailer and partially dependent

upon local disposal costs. An interesting exception is the program in California which levies a fee on replacement tires only if a scrap tire remains with the retail business. In effect, California's charge of $0.25 is a state disposal fee and not a tax on new tires. Simultaneously, Californians pay private retailers an additional disposal fee. This study assumes that the quantity of scrap tires left with retailers is a good approximation for the number of tires purchased in California.

North Carolina and Arizona apply a proportional fee based on tire price, while a few states have differential tax rates according to tire size. North Carolina is the only state in the sample with a differential and a proportional charge. Moreover, only Ohio places the fee at the wholesale level. All the other states in the sample levy a per-unit fee on every new tire purchased at the retail level.

The construction of the effective per tire tax rate follows in a straightforward manner. Whether retailers retain a fixed dollar amount or a certain proportion of the tax as compensation for administrative costs, it is simply deducted from the policy fee stated in the waste tire law. In quite a few instances in which retailers are not granted any deductions, the net fee turns out to be equivalent to the policy fee.

The computation of the net fee is somewhat complicated by the existence of a proportional tax and/or by the tire size tax base. The state of Arizona forms a nice exception in this respect because venders must submit the actual number of tires sold with their tax returns. This allows an easy computation of the net fee by dividing the tax payment by the number of tires sold. The effective average tire tax amounts to $1.10 for all fiscal years. In contrast, retailers in North Carolina merely include collected funds with their returns. In order to approximate the average tax rate, it is assumed that the

average tire is sold at a price of $75. A further complication arises for the years 1996 through 2000 insofar that North Carolina changed to a differential fee based on tire size. Officials at the North Carolinan Department of Environment, Health, and Natural Resources however suggest an average market share of 80 percent for tires up to 20" (passenger and light truck tires) and 20 percent for tires larger in diameter (medium and heavy truck tires).[27] The average fee for fiscal year 1996 through 2000 is then weighted accordingly: $0.02\times0.8\times75 + 0.01\times0.2\times75 = 1.35$. Similar calculations for Texas and Mississippi assume that tires up to 24" in diameter comprise 95 percent of the market share while large tires are mostly heavy truck tires with a small purchase volume.

Revenue Data

Private tire retailers are reluctant to disclose actual sales figures. An indirect method to calculate sales takes collected state fiscal revenue receipts from tire fees and divides them by the corresponding tax rate. When state law does not grant retailers any deductions for administrative expenses associated with tax collection and transfer, aggregate revenue numbers are simply divided by the policy fee. In cases where retailers retain part of the per unit fee, the collected amount is net of certain deductions requiring the use of the calculated effective fees. For example, retailers in Virginia keep five percent of every fifty cents; thus, one divides total revenue receipts by $0.475 to derive a measure of the number of tires. This follows from economic principles for analyzing tax

[27] A similar estimate can be obtained by computing the relative number of passenger and light car vehicles in North Carolina and then taking the average over a five year period.

incidence, as illustrated in Figure 5.1. Matters are similar in cases in which fees are based on tire size, so one again divides total revenues by the weighted fee in Table 3.1.

Sources of Inconsistencies

Tax Base

The demand for new tires presents a derived demand because the good consumers desire is transportation. Since certain tires are designed for certain vehicles, state waste tire laws define tires with regard to the vehicle they serve. Commonly, these laws place vehicles into two broad categories: *on-road* motorized and unmotorized; *off-road* motorized and unmotorized.

On-road vehicles travel on public roads and highways. Motorized on-road vehicles include automobiles, motorcycles, light trucks, medium-trucks, semi-trucks, and so forth. On-road unmotorized vehicles are trailers or mobile homes, for example. Some states tax tires for motorcycles and/or mobile homes, while others do not.

Off-road motorized equipment is primarily used by the commercial sector. Farm vehicles, aircraft, and mining vehicles fall in this group. The off-road unmotorized category comprises heavy farm and construction equipment. Again there are minor variations across states as to which tires are taxed. Oregon law exempted farm equipment but not farm trucks, while the state of Georgia includes tires on all farm and construction devices. A number of states include aircraft tires in their tax base and/or tires on new vehicle sales, others do not. As a general rule, tires on motorized vehicles are subject to the tax because they wear out faster than tires on non-mobile devices. In addition, every state excludes tires on human-powered devices, such as bicycles.

It is also the case that in some states the market for retreaded and used tires is relatively large.[28] Sometimes they are taxed, but frequently they are not. Evidently, different types of tires in the tax base across states generate some degree of non-uniformity in the derived quantity data. However, every state in the sample levies a user fee on passenger and light truck tires. This means that all states in the sample share a considerable proportion of the same tire types in their sales in any given year.

Collecting and Reporting Practices

Sometimes, state waste management agencies are directly involved in the collection of tax receipts, whereas in other cases revenue departments happen to be solely responsible for collecting and accounting funds for the waste tire program. At first, this might appear to be peripheral to the derivation of tire sales. However, it creates an important source of inconsistency within the quantity data.

The revenue agency is compensated for administrative expenses in various forms across states when assigned collection responsibility. In some states, collectors take a proportion (2-5%) and/or a fixed dollar amount ($100,000-$1,000,000) of the total receipts, and in other states, they are compensated through their own general budgets. When deductions are allowed from total tire fee collections, state revenue departments either reported gross or net figures in their statistical records to the public.

Importantly, the use of net revenue numbers can substantially underestimate the number of tires sold in a given state. Utah illustrates this point nicely. Its tax agency, the

[28] According to Mr. Blumenthal, the market for used tires is somewhat gray. It is difficult to obtain estimates of used tire sales in any given state. Tire retreads used to be prevalent among all sorts of tires. Today, few tires except those for large trucks are retreaded. This means that in states in which fleet operators of trucks are present, the sale of retreads is relatively large, as in California and Arkansas.

Utah State Tax Commission, reports net revenue actually available for the waste tire program. In fiscal year 2000, the available tax collections were $1,791,601. However, the actual amount received from retailers was $1,837,540. If one were to use the former number to calculate sales, one would miscalculate tire purchases by 55,431, or by 2.5 percent of total sales in that year.

Moreover, legislation in a number of states demands late fee penalties from retailers when tax returns exceed the specified deadline. As a consequence, late submission charges are likely to end up with tax revenue collections. Californian law, for example, enacts a ten percent penalty on the amount due. Roughly 20 million tires are sold in California annually by 4,000 retailers who file their fee returns on a quarterly basis. On average, then, a retailer sells 1,250 tires per quarter and a penalty on the collected fees from these sales translates into an average charge of thirty dollars. If a substantial number of retailers, for example ten percent (400), postponed payments every quarter, fiscal tire sales would be overestimated by 192,000 tires, or one percent of total annual sales in California. It should be noted that tire fees are often filed with general sales tax returns, which also levy late submission penalties. It is unlikely that profit-maximizing retailers fail to submit tire tax returns on a large scale when using the same tax form for their sales tax collections.

State Characteristics

Preliminary Remarks

Whenever monthly or quarterly numbers are available, one constructs fiscal year variables by averaging them. A fiscal year runs from July through June comprising twelve months of

two calendar years. Personal income and the price indexes are in fiscal year units. Monthly or quarterly data are unavailable for vehicle registrations and population accounts, albeit population numbers are usually measured in mid-year.

Income and Population

The SQ5 data series maintained by the Bureau of Economic Analysis provides the data on personal income. It consists of income from production, private and governmental transfer payments, and government interest. In order to match the fiscal sales variable with fiscal income, one sums up quarterly income data and divides the aggregate by four.

Population estimates come from The Consolidated Federal Funds Report which is available from the Census Bureau's QuickFacts web page. This fiscal report records the federal government's expenditures on state and local governments. Every document includes state population measures.

Vehicle Registration

Although registered vehicles are not necessarily driven vehicles, the number should be reasonably close. The data for vehicle registrations by calendar year are drawn from various editions of Highway Statistics published by the Federal Highway Administration. To calculate the aggregate number of motorized devices in a given state, one combines the columns total automobiles, buses, trucks, and motorcycles in the vehicle registration

table.[29] Thus four major categories thus include all private, commercial, and publicly owned vehicles.

The truck category consists of farm trucks, truck tractors, light trucks, such as pickup trucks, panel trucks, minivans, station wagons, and delivery vans. Publicly owned vehicles do not include vehicles of the military service, but civilian branches of the federal, state, county, and municipal government (FHWA 1990, 17).[30] In addition, the FHWA data series does not include any unmotorized devices. Although Highway Statistics contains an extra table on trailer registrations, these figures are not added to the other categories. The main reason for that is that tires on trailers and mobile homes form a very small percentage of total tire sales and in some states they are not even subject to the tire tax.

The FHWA collects data from 50 state sources. Since states vary in their definition of private, commercial, and public vehicles, the FHWA's data recording guidelines mandate states to specify the exact vehicle type and registration category. To derive uniform registration measurements, the agency must account for the fact that some states define a tractor and trailer as a single unit while others register both devices separately. It is also true that a few states count a minivan as a truck and others as a passenger car. The FHWA's data series records minivans and utility-type vehicles as trucks regardless of the registration category of the original state (FHWA 2000).

As a result, the vehicle registration series displays a large degree of uniformity, but its econometric use not without difficulties. Both economic and econometric reasoning

[29] Table MV-1 in Highway Statistics.
[30] Charity and government entities are exempted from sales taxes in many states; however, they are frequently subject to the pre-disposal tire tax.

justify the computation of per vehicle tire sales. Their accurate calculation requires that the classes of vehicles in the registration data are reasonably related to the ones that are represented in the tire consumption data. Although all effort is made to match them up as closely as possible, some inconsistencies are yet unavoidable. For instance, remember that not all scrap tire programs include truck tires in their tax base, which slightly reduces the per vehicle variable in these cases.

A further complication arises from the fact that registration data are only available by calendar year. Tire sales per vehicle therefore reflect fiscal and calendar year variables. This is theoretically far from ideal, but it must be noted that vehicle registration does not change dramatically over a year within states. Thus, calendar year observations are good proxies for the corresponding fiscal year running from July through June.

Price Indexes

The United States Bureau of Labor Statistics publishes all three price indexes used in this study.[31] The regional price index for all goods and services measures the spending habits of consumers in the Northeast, Midwest, South, and West on a monthly basis. The states in the sample are assigned to these major regions as the BLS distributes them.[32] To match and deflate the nominal fiscal tire fee variable, one constructs fiscal year regional

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[31] They are contained in the All Urban Consumers (CPI-U) group series. "The CPI-U represents about 87 percent of the total US. Population. It is based on the expenditures of almost all residents of urban or metropolitan areas, including professionals, the self-employed, the poor, the unemployed, and retired persons as well as urban wage earners and clerical workers. Not included in the CPI are the spending patterns of persons living in rural non-metropolitan areas, farm, families, persons in the Armed Forces, and those in institutions, such as prisons and mental hospitals" (U.S. BLS n.d., 2).

[32] Northeast: RI, MD, CT; Midwest: NE, KS, MO, IL, IN, OH; South: TX, OK, LA, MS, TN, GA, FL, SC, NC, AR, VA, KY; West: WA, OR, UT, CO, AZ, NV, CA.

indexes by averaging their corresponding monthly values. As in the case of the nominal personal income variable, economic theory justifies the deflation. The use of a state specific deflator for both variables is desirable, but such a price index does not exist. As an important secondary effect for econometric estimation, the deflation produces changes in the real tax rate over time even when the nominal rate has remained constant since the inception of the fee in most programs. The variation of the real tire tax is indispensable within the fixed effects framework.

Since changes in the real tax rate are exclusively driven by the deflator in most states, it is important to see how sensitive the estimates are to the use of a particular price index. For that reason, nominal tax rates are alternatively deflated by the national consumer price index.

The tire index is a national price index and is meant to control for overall tire price changes. Besides measuring the price of new tires, it contains the costs of balancing and installation services. Since most consumers do not change tires themselves, this price index reflects the full costs of tire replacement.

CHAPTER 4

ECONOMETRIC ISSUES

Introduction

The econometric equation presents a panel data tire demand model whose coefficients will be estimated with the aid of the fixed effects estimator. The cross-sectional units i relate to individual states and the time-series units m identify (fiscal) years. As Chapter 3 outlined, computed tire sales differ among states partially due to measurement errors. Moreover, several state characteristics that account for varying levels of tire sales are excluded from the model. The following discussion shows why the fixed effects framework is appropriate for the given data set. First, however, it outlines the general and specific economic demand model, and some important econometric assumptions for unbiased and efficient fixed effects estimation.[33] In doing so, potential sources of estimation bias and non-spherical error terms are analyzed.

General Demand Model

To estimate the tire demand equation, this thesis will use the following general function:

(4.1) Per vehicle sales = f(price(tax, price supplied), income)

The inclusion of these three main theoretical variables becomes clear with the aid of the following simple identity:

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[33] Appendix C shows a derivation of the generalized least-squares fixed effects estimator.

$$(4.2.1)\quad Sales \equiv \frac{Miles}{Vehicles} \times \frac{Sales}{Miles} \times Vehicles$$

or rearranged as:

$$(4.2.2)\quad \frac{Sales}{Vehicles} = \frac{Miles}{Vehicles} \times \frac{Sales}{Miles}$$

There are of course certain simplifying assumptions underlying this identity and hence the general demand model. First, the vehicle stock is assumed to be exogenous, which allows the definition of the dependent variable in sales per vehicle with only the sales variable being endogenous. Second, tire durability, i.e., level of technology, is held constant for all tire categories throughout the sample period. Third, any cross-effects between variables are neglected (e.g., sales per mile being a function of miles driven), suggesting that the utilization rate of automobiles and the replacement rate of tires additively influence tire sales per vehicle. For the purpose of specifying an economic relationship, the general demand model thus includes income and tire price measures as fundamental determinants of these rates.

Specific Demand Model

The particular demand equation for individual consumers in a given state takes the following linear form:

$$(4.3.1)\quad \frac{y_{jim}}{v_{jim}} = \beta_{1ji} x_{1jim} + \beta_{2ji} x_{2jim} + \beta_{3ji} x_{3jim}$$

$(j = 1,2,.....n_{im}; i = 1,2,.....n; m = 1,2,.....M)$

where the left-hand side measures per vehicle tire sales, and vector $\mathbf{x}'_{jim}$ contains the tire tax, the income level, and the tire price for consumer j in state i during (fiscal) year m.

Potential Sources of Bias

Aggregation Problem

One could think about an aggregate tire demand function as if it were the demand function of a representative consumer. However, there are certain assumptions that must hold when constructing an aggregate state demand relationship. It is important to be explicit about these conditions because if they are unreasonable, estimated coefficients on totals can be subject to aggregation bias.[34]

Rewriting equation (4.3.1)[35] as estimating relation with the disturbance terms α_{jim} and η_{jim}, one can state for consumer j in state i during year m the following:

(4.3.2) $y_{jim} = \beta_{1ji} x_{1jim} + \beta_{2ji} x_{2jim} + \beta_{3ji} x_{3jim} + \alpha_{jim} + \eta_{jim}$

$(j = 1,2,....., n_{mi}; i = 1,2,.....,28; m = 1,2,...M)$

State level totals for a given year are calculated by summing over all consumers in state i at time m where the state idiosyncratic error is simply the sum of all individual errors. Without making any further assumptions, one can similarly define the quantity variable for tires and the aggregate time-invariant parameter, so that:

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[34] For further discussion regarding aggregation bias see Theil (1971).
[35] The dependent variable is not stated in per vehicle terms at the individual level for simplicity.

(4.4.1) $\eta_{jim} = \sum_{j=1}^{v_{im}} \eta_{jim}$; $Y_{im} = \sum_{j=1}^{v_{im}} y_{jim}$; $\alpha_i = \sum_{j=1}^{n_{im}} \alpha_{jim}$ where $\alpha_{im} = \alpha_i$ by definition.

However, the transformation of individual demand functions into one representative market demand calls for further conditions with respect to the tax and income variable. If retailers in state i comply with the waste tire law and charge every consumer the full rate, one can readily conclude that the user fee is a state-wide and identical charge. Imposing this fairly weak condition on the model, one writes the sum over all n_{im} consumers in a given state i at time m:

(4.4.2) $\beta_{1i} X_{1im} = x_{1im} \sum_{j=1}^{n_{im}} \beta_{1ji} = \sum_{j=1}^{n_{im}} \beta_{1ji} x_{1jim}$ where $x_{1jim} = x_{1im}$; $X_{1im} \equiv x_{1im}$ by assumption.

The aggregation of n_{im} consumers is more problematic for the income variable because consumers vary greatly in their income levels. Evidently, it is unrealistic to assume equal distribution of income over n_{im} agents, i.e. $x_{2jim} = x_{2im}$. A less rigid yet still strong condition imposes the existence of equivalent response coefficients among individual units, such that $\beta_{2ji} = \beta_{2i}$. Parallel Engel curves suggest that the response of tire demand to income changes is the same for all consumers. There is a high probability that this coefficient varies across agents, while it is hoped that the condition of equal slope parameters presents a reasonable approximation. To derive the state-level income variable, one again sums over all n_{im}:

(4.4.3) $\beta_{2i} X_{2im} = \beta_{2i} \sum_{j=1}^{n_{im}} x_{2jim} = \sum_{j=1}^{n_{im}} \beta_{2ji} x_{2jim}$

The tire index measures overall tire price changes over time. Since this price index is an aggregate and national variable by construction, $x_{3jim} = X_{3m}$. Consequently, total tire sales for each state i as decision variable in year m is written as:

(4.3.3) $Y_{im} = \beta_{1i} X_{1im} + \beta_{2i} X_{2im} + \beta_{3i} X_{3m} + \alpha_i + \eta_{im}$.

Omitted Variables

For unbiased estimation it is critical that the zero conditional mean assumption holds $E(\eta_{im} | \mathbf{x}_i, \alpha_i) = 0$.[36] One thus asserts that the independent variables in each state equation are strictly exogenous. Put differently, the population disturbance terms are uncorrelated with the explanatory variables at any time m. It is very likely that the tire demand model is misspecified due to omitted variables. First, the model does not account for tire disposal charges by retailers. As mentioned in the previous chapter, retailers in many of the sample states charge both a pre-disposal and disposal fee per tire. If the disposal fee is correlated with the user fee, the model is likely to suffer from omitted variable bias. Recall from Chapter 2 that storage regulations increased waste tire disposal fees. Since the scrap tire management programs in the sample introduced user fees on new tire purchases simultaneously to new regulations, the failure to control for actual disposal fees introduces upward bias.

[36] This is a finite sample assumption which can be relaxed to contemporaneous uncorrelatedness at time m if the sample size is sufficiently large. In addition, it is not necessary to condition on the entire data matrix due to the random sampling assumption across i. See Wooldridge (2000, 459) for a complete set of econometric assumptions for fixed effects estimation.

Pooling Procedure

Importantly, each state i must have the true linear tire demand model (4.2.3), which maintains that all 28 states share the same conceptual dependent and independent variables. Moreover, the model assumes that all behavioral differences among the 28 decision units are captured by their state specific effects, i.e., $\alpha_i \neq \alpha$, which further suggests that the response coefficient parameters are identical across states, i.e., $\boldsymbol{\beta}_i = \boldsymbol{\beta}$. The violation of the latter entails the same sort of aggregation bias discussed previously with the exception that it can be subjected to econometric testing.

Selectivity Bias

Two main reasons lead to an unbalanced panel data set in which observations on some states are missing. First, states simply did not introduce the user fee on new tire purchases all at the same time. Second, observations on a few states must be dropped for important econometric reasons. The technical adjustments necessary to apply the fixed effects estimator to unbalanced data sets are straightforward. One can easily define a dummy variable vector $\mathbf{d}_i$ that assigns zeros to missing observations and ones to available sample points.

A more critical point with respect to missing observations, however, is the question of their absence from the sample (Wooldridge 2000, 448). Selectivity bias is avoided if the factors causing missing data points are not correlated with the idiosyncratic error η_{im}. It is difficult to imagine for this study how selectivity bias enters the model because the political process leading to the final passage of a law is enduring. Whether a waste tire

law passes at a planned date or later can thus depend on a multitude of decisions and often random events. Although some states in the sample conceivably introduced waste tire laws in early years in the wake of strong environmental lobbying efforts, any time-invariant differences across states are captured by the fixed effects parameter.

Potential Sources of Non-Spherical Errors

Within Cross-Sections

Heteroskedasticity is commonly a minor problem for time-series observations primarily because variables do not sufficiently change over time. The average number of time observations on each state in this sample is only about seven years, which is too short for the independent variables to raise any serious concerns. On the other hand, serially correlated errors can pose a problem with observations over time, but they are less likely to do so with annual rather than monthly or weekly data sets. It is thus reasonable to assert that the idiosyncratic errors of each state i satisfy the conditional moment assumption $E(\boldsymbol{\eta}_i \boldsymbol{\eta}_i' | \mathbf{x}_i, \alpha_i) = \sigma_\eta^2 \mathbf{I}_M$.

Across Equations

To obtain a homoskedastic error structure in the pooled equation, it is necessary that all state equations share the same error variance. Unlike (other) systems of equations where unequal variances usually arise because of the presence of conceptually different dependent variables, cross-sectional heteroskedasticity in the fixed effects framework is only possible due to aggregated data issues. The cross-sections in the sample vastly differ in the size of their tire markets reflecting significant differences in population levels. One

can thus determine *a priori* that the error variances are inversely proportional to the true variance of the disturbance term:

$$(4.5)\ Var(\eta_{im}) = Var(Y_{im}) = Var(\frac{1}{v_{im}} \sum_{j=1}^{v_{im}} \eta_{jim})$$

$$= \frac{v_{im}}{v_{im}^2} \times Var(\eta_{jim})$$

$$= \frac{1}{v_{im}} \sigma_\eta^2 \qquad \text{by assumption constant variance at individual level}$$

$$\neq \sigma_\eta^2 \qquad \text{heteroskedasticity}$$

However, this error structure relies critically on homoskedastic errors at the individual level, so that individual consumers share the same error variance within states.

Serial correlation across equations is another source that can cause non-spherical error terms in the estimating equation. The random sampling assumption implies that cross-sections are identically and independently distributed, which necessarily rules out correlation of disturbance terms across equations. The current sample is not random because it exludes every state that has not funded its tire program through a per unit fee on new tire purchases. Nonetheless, there is no reason to believe that state errors are seriously correlated at any time period m.

Normalization

The pooling of cross-sectional and time series data across units of vastly different sizes requires the normalization of the dependent variable, and hence of the explanatory variables. For that reason, averaging tire sales is not only justified by the demand identity

(4.2.1) but also by econometric theory. To derive a relation of averaged variables, the last equation is divided by the total number of consumers n_{im}, or by total vehicle registrations v_{im}:

(4.3.4) $\overline{Y}_{im} = \beta_{1i}\overline{X}_{1im} + \beta_{2i}\overline{X}_{2im} + \beta_{3i}\overline{X}_{3m} + \alpha_i + \overline{\eta}_{im}$ where vector $\mathbf{x}'_{im} = \overline{\mathbf{x}}'_{im}$ by definition.

Empirical Model

Estimating Equation

To estimate the effects of price and income on tire sales, the following equation will be estimated:

$$(4.6)\quad \frac{Sales_{im}}{Vehicles_{im}} = \beta_1 \frac{Tax_{im}}{CPI_{im}} + \beta_2 \frac{Income_{im}}{CPI_{im}} \times \frac{1}{Pop_{im}} + \beta_3 \frac{TireIndex_m}{CPI_{im}} + \alpha_i + \varepsilon_{im}$$

$(i = 1,2,.....28; m = 1,2,....M)$ where

$Sales_{im}$ = the number of tires sold in state i in fiscal year m

$Vehicles_{im}$ = the number of automobiles, buses, trucks, and motorcycles registered in state i in calendar year m

Tax_{im} = per tire charge on new tire purchases in state i in fiscal year m

CPI_{im} = regional consumer price index for all items in state i in fiscal year m

$Income_{im}$ = personal income in state i in fiscal year m

Pop_{im} = population in state i in calendar year m

$TireIndex_m$ = national tire and replacement costs for fiscal year m

α_i = fixed effect for state i

ε_{im} = idiosyncratic error for state i and fiscal year m

$\beta_1;\beta_2;\beta_3$ = coefficients to be estimated

Data Issues

Remember from Chapter 3 that inconsistencies in the collected revenue data largely exist because of variations in the tax base across states. Importantly, almost all non-uniformities in measured tire sales occur over states, and not fiscal years. Although measurement errors in the dependent variable might not be perfectly constant, strongly asymmetric errors still warrant the use of state specific effects to capture data inconsistencies among cross-sectional units. Illinois, for example, places a tax on used tires, whereas Georgia exempts them from its tax base. Ceteris paribus, measured tire sales in Illinois are expected to be consistently higher than in Georgia assuming that the market share of used tires is fairly constant in Illinois over time.

This reasoning is also important for the derivation of tire sales in those states in which a proportional and/or differential tax rate is in place. North Carolina presents a good example. It is not crucial to the estimation procedure whether tires up to 20" comprise exactly 80 percent of the market share or more. The important assumption is that the relative market shares of passenger and truck tires is fairly constant over time in North Carolina. The same holds true for the average tire price of 75 dollars. Since this amount is consistently applied over time, it influences the level of tire sales through the fixed effects coefficient.

In contrast, one must drop observations from the pooled sample when the tax base of an individual state experienced revisions over time. Oklahoma, for instance, amended its

waste tire law for fiscal year 1996 to include truck and motorcycle tires. Before, it taxed only passenger and light truck tires. It is hence not possible to use all observations from 1990 through 2000. Notice that North Carolina changed its uniform tax rate to a differential one beginning of fiscal year 1994. Importantly, this switch did not accompany a change in the tax base because the same types of tires have been subject to the pre-disposal fee since the inception of the law. It is therefore appropriate to include all observations on North Carolina.

State Heterogeneities

It has been argued that random measurement errors in the dependent variable violate the zero conditional mean assumption, whereas fairly constant biases are captured by α_i and are hence eliminated prior to estimation. Similar reasoning applies to omitted variables that reflect heterogeneities among states. If these variables vary over time, they end up in the idiosyncratic error η_{im} and cause biased estimation if correlated with the explanatory variables in the model.

Fleet operators, for instance, are expected to have a greater demand for replacement tires than average households. As mentioned, all states in the sample collect the tax at the retail level except for the state of Ohio. This implies that households and small businesses are responsible for the bulk of tax payments. States differ in the number of fleet operators that reside within their borders. Although their member vehicles are counted in the vehicle registration data, total vehicle registrations do not indicate whether registered vehicles belong to a few large operators or to numerous small, independent businesses.

This is a relevant point because large trucking fleets normally purchase directly from manufacturers and wholesalers for two reasons. They might obtain quantity discounts, and they are able to purchase tires at wholesale prices. As a result, unlike small business purchases, wholesale tire orders by large fleet operators are not accounted for by taxation at the retail level. It is assumed that the presence of predominantly large or small fleet operators is fairly constant over a seven year period. The effects on measured tire sales should then again work through the intercept term.

No inference can be drawn from the following table as to the relative number of large and small operators in a given state; yet, it does dampen concerns about serious estimation bias because of the small relative size of fleet vehicles in the overall vehicle stock of a given state.

Table 4.1. Relative Number of Fleet Vehicles for 1998 by State.

State	Total Fleets[37] (10+ Vehicles)	Fleet Vehicles	% of Total Veh. Reg.[38]	State	Total Fleets (10+ Vehicles)	Fleet Vehicles	% of Total Veh. Reg.
AZ	1,523	173,594	5.9	MO	2,751	255,795	5.8
AR	1,385	111,506	6.4	NE	1,302	106,573	7.0
CA	12,005	1,445,711	5.6	NV	685	64,113	5.3
CO	2,069	192,903	5.6	NC	3,821	392,410	6.7
CT	2,349	211,137	7.8	OH	5,418	532,653	5.3
FL	5,986	729,766	6.5	OK	1,728	154,487	5.3
GA	3,524	333,919	4.8	OR	1,790	169,533	5.7
IL	5,653	585,036	6.3	SC	1,772	176,874	6.1
IN	2,968	270,382	5.0	RI	548	45,365	6.3
KS	1,849	131,807	6.2	TN	2,510	277,609	6.2
KY	1,915	175,320	6.2	TX	8,851	878,714	6.6
LA	2,217	201,177	5.9	UT	918	86,134	5.6
MD	2,720	271,022	7.2	VA	3,025	329,710	5.7
MS	1,253	114,522	5.1	WA	2,496	230,502	4.8

[37] *Source*: Automotive Fleet 2000 records total number of fleets and vehicles.
[38] *Source*: Table MV-1 in the Highway Statistics 1998 published by Federal Highway Administration.

Another important difference among states is the relative market size of retreaded tires. Except for Connecticut, though, no state program places a user fee on retreads for obvious reason. Tire retreading reduces the rate at which scrap tires are generated. If these tires are taxed twice, tire programs will not set the right incentives for source reduction. Most of the demand for retreads comes from the commercial sector because tire retreading is common for truck tires and far less prevalent for passenger tires.[39] Consequently, the demand for retreads is closely related to the presence of fleet operators. If the assumption is correct that the number of small fleet operators is fairly stable within a state over time, state specific effects again capture unobserved numbers of fleet operators.

State heterogeneities exist with respect to state budgets for infrastructure expenditures, as well. The availability of alternative means of transportation, such as buses, trains, and subways reduces car ownership and usage, which is negatively correlated with tire sales. General road maintenance expenditures across states lead to differing tire replacement rates, too. As does the number of urban and rural road mileage. Freeways and highways in urban settings commonly have a better pavement quality than their rural counterparts. Evidently, poor roads increase tire wear. It is hoped that these factors are stable over time, otherwise they are likely to bias the income estimator.

Regional price indexes measure the overall price change within a geographic area. Thus, they capture price changes in gasoline, tires, public transportation, etc., within broad regions, while none of them can be interpreted as an indicator of change in relative

[39] Telephone conversation with Mr. Blumenthal (Winter 2002).

cost differences among geographic regions. State intercept terms, however, are expected to pick up consistent price differences with regard to the various goods and services that are needed to maintain and drive automobiles.

Conclusion

Observations on individual states are pooled to obtain reliable estimators because the sample points for each cross-sectional unit are not sufficient to warrant single equation estimators with small variances (Table 5.4). More importantly, this chapter has argued that uncontrolled state characteristics lead to biased estimation. Although alternative estimators, such as ordinary-least squares and random effects, have desirable efficiency properties, they do not prevent the estimation bias necessarily introduced by unmeasured state specific effects. In addition, they do not capture constant biases in the sales quantity data. From the standpoint of unbiasedness and efficiency, one must thus conclude that the fixed effects estimator is superior to any other linear estimator given the qualitative and quantitative nature of the data.

CHAPTER 5

EMPIRICAL ANALYSIS

Estimated Results

Remember that the model suffers from groupwise heteroskedasticity. The generalized fixed-effects estimator produces the following estimates (Appendix C). Again, all numbers are in real terms, whereby the tax variable is measured in dollars and the income variable in 100,000 units (Table 5.1). [40]

Table 5.1. Level-Level Estimates.

Per Vehicle Sales	Coefficient	Standard Error	95 % Confidence Interval	P>|T|
Per Unit Tax	-0.297	0.126	(-0.54; -0.05)	0.02
Per Capita Income	2.792	1.214	(0.41; 5.17)	0.023

Table 5.2. Pooled Averages.

	Sample Means
Per Vehicle Sales	1.01
Per Unit Tax	0.597
Per Capita Income	15,730

Number of observations: 197
Number of groups: 28

[40] Since the tire index is not state level, the table does not report its estimated coefficient.

Effects of Income

The sign of the estimated income effect conforms with theoretical expectations. Income influences the level of tire sales through the rate of car usage and tire purchases.[41] Overall higher income levels are likely to stimulate the number of vehicle miles traveled. Since vehicles only inflict tire wear when in motion, rising consumer incomes tend to have a positive indirect effect on tire sales in the form of increased vehicle utilization rates, and hence gasoline consumption. Conceivably, a heigh opportunity cost of time dampens this effect. Quantitatively, one expects a 10,000 dollar increase in real per capita income to push average sales up by 0.28 tires rendering an income elasticity of 0.4.

Effects of Prices

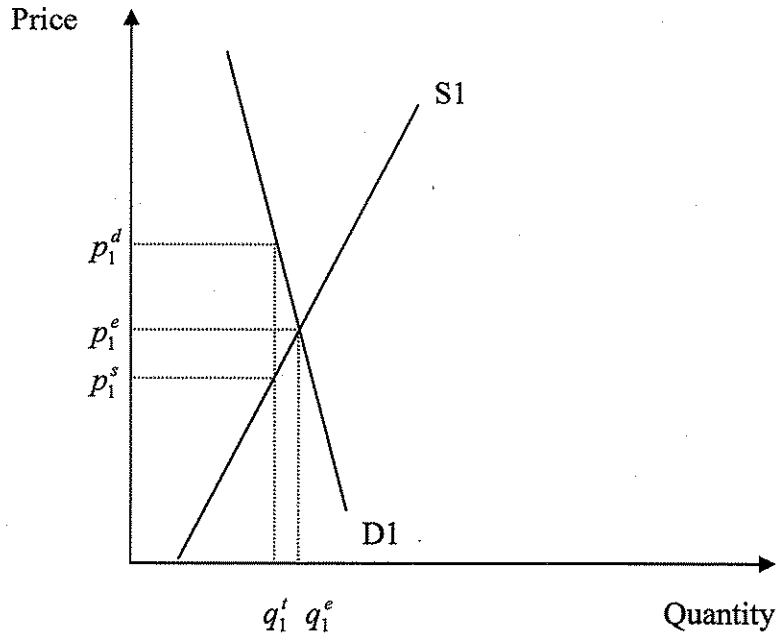
Overall, economic theory predicts a negative impact on aggregate tire sales as this study comprises all types and qualities of tires (Figure 5.1).[42] The estimated negative effect confirms this prediction. Its magnitude, however, is unrealistic. It suggests that a one dollar tax increase per tire reduces tire sales by 0.3 per vehicle per year in an average state. To appreciate the full size of this effect, it is helpful to calculate the point price

[41] Engel curves display different shapes depending on the initial income level. For instance, low-income consumers might view low-mileage tires as normal goods, yet regard them as inferior as their incomes rise. Consequently, they begin to substitute towards long-lasting tires rendering backward-bending Engel curves.

[42] The effects of the tax may vary for different quality categories. For instance, a per unit tax on both low-quality and high-quality tires reduces tire sales in the low-end market. It is conceivable that the same tax increases the sale of long-lasting tires because of substitution between tire types.

elasticity. Using the sample average of one tire purchase per car per year and an average real tire price of 50 dollars, one computes an elasticity of negative 15.[43]

Figure 5.1. Per-Unit Tax in Replacement Tire Market.



If this large elasticity reflects a true economic effect, it is likely to be of a dual nature. When specifying equation (4.1), it is implicitly assumed that consumer taste remains constant over the period of observation. As a practical matter, taste is evidently non-observable. At the same time, this study covers a time period for which the constant taste assumption is probably inappropriate mainly because the user fee presented a first-time

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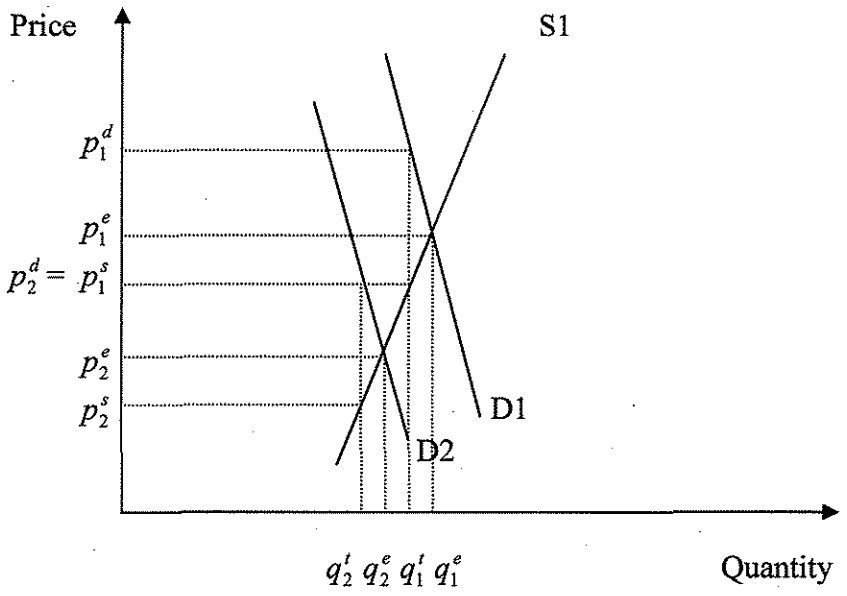
[43] Recall that Q = Q(P(t), …). Applying the chain rule with respect to the tax gives $\frac{\partial Q}{\partial t} = \frac{\partial Q}{\partial P}\frac{\partial P}{\partial t}$. If one assumes that consumers bear the full burden of the tax and that the average real retail price of a tire is 50 dollars, one can compute the price elasticity as follows: $\frac{\partial Q}{\partial P}\frac{\overline{P}}{\overline{Q}} = \frac{-0.3}{1} \times 50 = -15$ where the denominator measures $\frac{\partial P}{\partial t}$.

tax for consumers in almost every state. The mere presence of the tax might thus have signaled to some agents increased public concerns about scrap tire disposal. At the margin, they might have been induced to alter their tire replacement rates, while others might have gathered further information on the problems associated with scrap tire disposal. Consequently, heightened public awareness, modeled as a change in taste, might have shifted the tire demand function inwards. The large elasticity measure might thus reflect a simultaneous shift of and movement along the demand curve. Figure 5.2 illustrates how this dual effect reinforces the decline in tire sales.

Figure 5.2. Dual Effect in Tire Market.



Moreover, one cannot rule out that this large estimate is due to statistical problems. Chapter 3 talks much about measurement errors in the derived tire sales data. If these errors are symmetric or random, they are likely to be correlated with the tax variable. A

number of state officials, for instance, claim that some retailers do not consistently charge the tire tax, which introduces upward bias in the tax estimator. As discussed, omitted variables, e.g., disposal fees, can cause upward bias, as well.

Sensitivity Analysis

To control for time trends in tire prices, the pooled regression is also run with year dummy variables instead of the national tire price index without changing the point estimates. In addition, the results are not sensitive to the use of a particular deflator as the regional and national CPI generate identical estimates. Finally, the number of Democrats in state legislature are included to control for an inward shift of tire demand caused by environmental sentiments. As before, the results remain unaffected. The double-log functional specification gives the following constant elasticities (Table 5.3).

Table 5.3. Double-Log Estimates.

Per Vehicle Sales	Elasticity	95 % Confidence Interval	P>|T|
Per Unit Tax	-0.223	(-0.42; -0.03)	0.03
Per Capita Income	0.388	(-0.12; 0.89)	0.14

Random versus Fixed Effects

As noted, there exist significant interstate differences with respect to waste tire laws, road quality, geography, among others. A failure to control for these characteristics introduces estimation bias in both the price and income estimators. To confirm this empirically, one conducts the Hausman test under the following hypotheses:

$H_0 : \alpha_i$ are uncorrelated with independent variables

$H_1 : \alpha_i$ are correlated with explanatory variables

The results allow for the easy rejection of the null and the conclusion of systematic structural differences at practically zero level of significance.

Test for Constant Slope Coefficients

The two-dimensional nature of the data set makes it possible to test for structural differences in the slope coefficients across decision units:

$H_0 : R\boldsymbol{\beta} = \mathbf{r}$

$H_1 : R\boldsymbol{\beta} \neq \mathbf{r}$

For proper inference, it is important to derive sums of squared residuals that are robust to heteroskedasticity. For that reason, weighted least-squares is also used on the single equations. The weighted residuals then form the following test statistic:

$$F = \frac{\left(\tilde{\boldsymbol{\eta}}'\tilde{\boldsymbol{\eta}} - \sum_{i=1}^{i=n} \boldsymbol{\eta}_i'\boldsymbol{\eta}_i\right) \Big/ (n-1)}{\sum_{i=1}^{i=n} \boldsymbol{\eta}_i' \, \boldsymbol{\eta}_i / (Mn - 2n - K')} \approx F[(n-1, (Mn - 2n - K')]$$

As in the case of other panel data work, the validity of inter-equation slope coefficient restrictions is safely rejected. Yet, the pooled estimators by far outperform their single-equation counterparts in terms of precision, as Table 5.4 forcefully underlines.

Table 5.4. Individual demand equations.

State	Per Unit Tax	T-Stat.	Per Capita Income	T-Stat.	Tire Index	T-Stat.	M
AZ	-4.227	-1.787	11.346	4.244	-0.001	0.022	7
AR	2.17	2.285	36.392	7.504	-0.013	0.035	6
CA	N/A	N/A	2.429	0.869	-0.032	-2.815	10
CO	0.439	0.069	1.936	0.678	-0.018	-0.412	6
CT	N/A	N/A	N/A	N/A	N/A	N/A	4
FL	-5.945	-3.603	11.705	10.384	0.056	0.047	10
GA	-3.585	-0.31	-4.651	-0.347	-0.092	-0.654	8
IL	9.73	1.173	-0.321	-0.038	-0.06	-0.835	8
IN	-21.773	-0.413	32.761	0.907	0.051	0.418	7
KS	-2.11	-0.732	-1.447	-0.447	-0.015	-0.832	9
KY	1.858	0.917	-40.71	-7.629	-0.122	-3.992	5
LA	-0.656	-2.012	-12.062	-0.578	-0.08	-1.519	8
MD	8.683	0.632	-5.122	-0.219	-0.077	-0.485	8
MS	-0.668	-0.418	2.996	0.637	-0.008	-0.588	8
MO	-7.984	-0.579	10.357	1.719	0.034	0.635	5
NE	-2.376	-0.305	-8.043	-0.407	-0.035	-0.332	9
NV	-4.159	-0.63	1.24	0.269	-0.015	-0.416	7
NC	-0.04	-0.099	2.581	0.173	0.007	0.156	10
OH	21.386	2.504	0.154	0.013	-0.039	-0.758	6
OK	-3.456	-5.064	-4.077	-1.844	0.017	2.701	6
OR	N/A	N/A	N/A	N/A	N/A	N/A	4
SC	4.172	0.487	-6.567	-0.327	-0.026	-0.238	8
RI	N/A	N/A	N/A	N/A	N/A	N/A	4
TN	0.315	0.171	-0.437	-0.142	-0.02	-1.323	8
TX	-0.699	-0.781	2.915	0.884	-0.017	-0.814	5
UT	-0.817	-2.231	-9.792	-0.501	-0.0009	-0.019	7
VA	-4.67	-3.624	1.412	1.194	0.01	1.309	10
WA	N/A	N/A	N/A	N/A	N/A	N/A	4

Note that although four individual equations are not identified, the fixed effects estimator utilizes all 28 groups in the sample. It is uniquely determined because of the a priori cross-equation restrictions. Moreover, some individual state equations might display positive tax effects due to omitted and time-invariant effects, e.g., tire price trends. In

other cases, the sample information might simply be too small to provide any meaningful estimates.

CHAPTER 6

CONCLUSION

Waste disposal has both a qualitative and quantitative dimension. By weight, scrap tires comprise roughly two percent of total solid waste in the United States and most other industrial countries. One might regard this to be a very modest amount. Instead, the difficulties with proper tire disposal originate from the shape and rubber material of tires. Their form and weight facilitate the breeding of extensive mosquito colonies near urban populations. Their rubber products and empty space support long-lasting tire fires releasing pollutants into the air, groundwater, and nearby lakes. Importantly, these externalities can occur at scrap tire stocks of almost any size. Further, tires consume space and entail high transportation costs.

As long as the full price of a tire reflects the marginal internal and external disposal costs, the level of scrap tire consumption is efficient. This paper emphasizes that externalities derive from stocks of scrap tires and not from generation per se. However, a reduction in the scrap tire generation rate lowers the rate at which existing stock piles grow and new ones emerge. It is thus conceivable that some communities regard it as cost-effective to reduce the burden of scrap tire stocks by promoting source-reduction policies. Knowledge of the determinants of tire demand forms an integral part for conducting these policies.

This thesis establishes the theoretical foundation for estimating an aggregate tire demand model. The qualitative effects of the tax and income variable confirm basic consumer theory. Unfortunately, the estimated magnitude of the tax coefficient is open to

interpretation. If the large elasticity measurement reflects a true underlying economic relation, it is likely to capture an inward shift and a movement along the tire demand curve. At the same time, statistical problems can be the cause of the estimated price effect.

Further research might want to use actual sales data from retailers in various urban areas if obtainable. Such a data set could provide more accurate quantitative results. In addition, it would be interesting to shed more light on states' motivation for passing particular scrap tire legislation. From a political economy perspective, one would therefore investigate the political forces behind the ban of scrap tires from general landfills, for example. In this context, one could also hypothesize about a link between landfill bans and the frequency of tire/mosquito outbreaks.

APPENDICES

APPENDIX A

DATA SOURCES FOR TIRE SALES DERIVATION

State	Fiscal year	Nominal gross fee	Revenue source and other information on waste tire law specifics, e.g. tax rates
Arizona	1994-00	2% on each tire with 2.00 dollar limit	Department of Revenue
Arkansas	1992-97	1.75	Department of Finance & Administration
California	1991-00	0.25	Board of Equalization
Colorado	1995-00	1.00	Office of Community & Local Govt. Services
Connecticut	1994-97	2.00	Office of Policy and Management
Florida	1991-00	1.00	Department of Revenue
Georgia	1993-00	1.00	Department of Natural Resources
Illinois	1993-00	1.00	Environmental Protection Agency
Indiana	1994-00	0.25	Department of Revenue
Kansas	1992-00	0.50	Department of Health and Environment
Kentucky	1994-98	1.00	Revenue Cabinet
Louisiana	1993-00 1996-00	2.00	Department of Environmental Quality
Maryland	1993-00	1.00	Comptroller's Office
Mississippi	1993-96 1997-00	1.00 1.00 < 24" 1.00 ≥ 24"	State Tax Commission
Missouri	1996-00	0.50	Department of Natural Resources
Nebraska	1992-00	1.00	Department of Revenue
Nevada	1994-00	1.00	
North Carolina	1991-93 1994-00	1% 2% < 20" 1% ≥ 20"	Department of Environment, Health, and Natural Resources
Ohio	1995-99	0.50	Environmental Protection Agency
Oklahoma	1990-95	1.00	Tax Commission
Oregon	1989-92	1.00	Department of Revenue
Rhode Island	1995-98	0.75	Department of Administration
South Carolina	1993-00	2.00	Department of Revenue
Tennessee	1993-00	1.00	Department of Environment and Conservation
Texas	1993-97	2.00 < 17.5" 3.50 ≥ 17.5" 1.00 used tires	Comptroller's Office
Utah	1994-96 1997-99 2000	1.00 0.50 0.85	Tax Commission
Virginia	1991-00	0.50	Department of Environmental Quality
Washington	1991-94	1.00	Department of Revenue

APPENDIX B

NATIONAL, STATE, AND REGIONAL DATA

Variable	Definition	Source	Period
Vehicle Registration	All private, commercial, and pub automobiles, buses, trucks, and motorcycles.	Federal Highway Administration, Highway Statistics Series: Table MV-1	Annually
Population		US Census Bureau; Consolidated Federal Funds Report (CFFR)	Fiscally
Personal Income	Income from production, private and governmental transfer payments, and government interest.	US Department of Commerce, Bureau of Economic Analysis (BEA): SQ5	Quarterly
Regional Consumer Price Index (CPI)	CPI for all urban consumers, all items (Base 1982-84): Northeast Midwest South West	US Department of Labor, Bureau of Labor Statistics (BLS): CUUS0100SA0 CUUS0200SA0 CUUS0300SA0 CUUS0400SA0	Monthly
National Consumer Price Index (CPI)	CPI for all urban consumers, all items (Base 1982-84): US city average	US Department of Labor, Bureau of Labor Statistics (BLS): CUUS0000SA0, CUUR0000SAO	Monthly
National Tire Price Index	Price index for all urban consume (Base 1982-84): Tire price, balancing and installin charges.	US Department of Labor, Bureau of Labor Statistics (BLS): CUUR0000SETC01	Monthly
National Vehicle Price Index	Price index for all urban Consumers (Base 1982-84): New vehicles	US Department of Labor, Bureau of Labor Statistics (BLS): CUUS0000SETA01, CUUR0000SETA01	Monthly

APPENDIX C

SUPPLEMENTAL PROOFS

Following Hayashi (2000), matrix notation is a convenient way to write the stacked model:

$$\begin{bmatrix} d_{i1}y_{i1} \\ \vdots \\ d_{iM}y_{iM} \end{bmatrix} = \begin{bmatrix} d_{i1}\mathbf{x}'_{i1}\boldsymbol{\beta} \\ \vdots \\ d_{iM}\mathbf{x}'_{iM}\boldsymbol{\beta} \end{bmatrix} + \begin{bmatrix} d_{i1} \\ \vdots \\ d_{iM} \end{bmatrix} \alpha_i + \begin{bmatrix} d_{i1}\eta_{i1} \\ \vdots \\ d_{iM}\eta_{iM} \end{bmatrix}$$

$$\mathbf{y}_i = \mathbf{F}_i + \mathbf{d}_i\alpha_i + \boldsymbol{\eta}_i \qquad \text{for i=1,2,.....28}$$

where $\mathbf{d}_i$ is a (M×1) dummy vector for 1 if m is in the sample and 0 otherwise to account for the unbalanced nature of the data set; $\mathbf{y}_i$ is the (M×1) observation vector on the dependent variable; $\mathbf{F}_i$ is (M×#β) matrix containing transpose vectors $\mathbf{x}'_{iM}$ for the independent variables and corresponding slope parameter vectors, $\boldsymbol{\beta}$; α_i is the time-invariant state parameter, and $\boldsymbol{\eta}_i$ is (M×1) vector of idiosyncratic errors. For notational ease, the dependent variables, explanatory variables, and unobservable errors are assumed to be state averages.

By transforming each state demand equation with the (M×M) matrix $\mathbf{P}_i$, one can efficiently pool all of the available data into one demand equation:

$$\begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{iM}} \end{bmatrix} \begin{bmatrix} d_{i1}y_{i1} \\ \vdots \\ d_{iM}y_{iM} \end{bmatrix} = \begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{iM}} \end{bmatrix} \begin{bmatrix} d_{i1}\mathbf{x}'_{i1}\boldsymbol{\beta} \\ \vdots \\ d_{1M}\mathbf{x}'_{iM}\boldsymbol{\beta} \end{bmatrix} +$$

$$\begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{iM}} \end{bmatrix} \begin{bmatrix} d_{i1} \\ \vdots \\ d_{iM} \end{bmatrix} \alpha_i + \begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{iM}} \end{bmatrix} \begin{bmatrix} d_{i1}\eta_{i1} \\ \vdots \\ d_{IM}\eta_{iM} \end{bmatrix}$$

$$\mathbf{P}_i\mathbf{y}_i = \mathbf{P}_i\mathbf{F}_i + \mathbf{P}_i\mathbf{d}_i\alpha_i + \mathbf{P}_i\boldsymbol{\eta}_i \qquad \text{i=1,2,.....28.}$$

Since $\mathbf{W}_i$ is a positive definite matrix of known weights, $\mathbf{P}_i'\mathbf{P}_i = \mathbf{W}_i$,

$$\begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{im}} \end{bmatrix}\begin{bmatrix} \sqrt{v_{i1}} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & \sqrt{v_{im}} \end{bmatrix} = \begin{bmatrix} w_{i1} & \cdots & 0 \\ \vdots & \ddots & 0 \\ 0 & 0 & w_{im} \end{bmatrix} = \mathbf{W}_i;$$

To derive the group-means estimator, one first premultiplies the pooled model with the (M×M) annihilator $\mathbf{Q}_i$ (Hayashi 2000):

$$\mathbf{P}_i\mathbf{y}_i = \mathbf{P}_i\mathbf{F}_i + \mathbf{P}_i\mathbf{d}_i\alpha_i + \mathbf{P}_i\boldsymbol{\eta}_i$$

$$\mathbf{Q}_i\mathbf{P}_i\mathbf{y}_i = \mathbf{Q}_i\mathbf{P}_i\mathbf{F}_i + \mathbf{Q}_i\mathbf{P}_i\mathbf{d}_i\cdot\alpha_i + \mathbf{Q}_i\mathbf{P}_i\boldsymbol{\eta}_i$$

$$\mathbf{Q}_i\mathbf{P}_i\mathbf{y}_i = \mathbf{Q}_i\mathbf{P}_i\mathbf{F}_i + \mathbf{Q}_i\mathbf{P}_i\boldsymbol{\eta}_i \qquad \text{since } \mathbf{Q}_i\mathbf{P}_i\mathbf{d}_i = \mathbf{P}_i\mathbf{Q}_i\mathbf{d}_i \text{ and } \mathbf{Q}_i\mathbf{d}_i = \mathbf{0}$$

$\tilde{\mathbf{y}}_i = \tilde{\mathbf{F}}_i + \tilde{\boldsymbol{\eta}}_i$ where $\mathbf{Q}_i = \mathbf{I}_M - \mathbf{d}_i(\mathbf{d}_i'\mathbf{d}_i)^{-1}\mathbf{d}_i = \mathbf{I}_M - \frac{1}{M_i}\mathbf{d}_i\mathbf{d}_i'$, and M_i is the total number of observations for each state. Subsequently, applying least-squares on the transformed equation, one obtains the generalized least-squares fixed effects estimator for the pooled sample:

$$\tilde{\boldsymbol{\beta}}_{FE} = (\tilde{\mathbf{F}}'\mathbf{W}\tilde{\mathbf{F}})^{-1}\tilde{\mathbf{F}}'\mathbf{W}\tilde{\mathbf{y}}$$

$$= (\frac{1}{n}\sum_{i=1}^{n}\mathbf{F}_i'\mathbf{Q}_i\mathbf{P}_i\mathbf{F}_i)^{-1}\frac{1}{n}\sum_{i=1}^{n}\mathbf{F}_i'\mathbf{Q}_i\mathbf{P}_i\mathbf{y}_i \qquad \mathbf{Q}_i \text{ and } \mathbf{P}_i \text{ are symmetric and idempotent}$$

where $\tilde{\mathbf{y}} \equiv \begin{bmatrix} \tilde{\mathbf{y}}_1 \\ \vdots \\ \tilde{\mathbf{y}}_n \end{bmatrix}; \mathbf{W} \equiv \begin{bmatrix} \mathbf{W}_1 \\ \vdots \\ \mathbf{W}_n \end{bmatrix}; \tilde{\mathbf{F}} \equiv \begin{bmatrix} \tilde{\mathbf{F}}_1 \\ \vdots \\ \tilde{\mathbf{F}}_n \end{bmatrix};$

(Mn×1) (Mn×M) (Mn×#β)

The homoskedastic variance-covariance matrix of the transformed equation is:

$$\mathbf{\Omega} = E(\tilde{\boldsymbol{\eta}}\tilde{\boldsymbol{\eta}}') = \sigma_\eta^2 \mathbf{Q}_{Mn}$$

(Mn×nM)

where $\mathbf{\Sigma} = E(\tilde{\boldsymbol{\eta}}_i \tilde{\boldsymbol{\eta}}_i') = \sigma_\eta^2 \mathbf{Q}_i$ $\quad \tilde{\boldsymbol{\eta}}_i \equiv \mathbf{Q}_i \boldsymbol{\eta}_i$ $\quad$ and $\boldsymbol{\eta} = \begin{bmatrix} \boldsymbol{\eta}_1 \\ \vdots \\ \boldsymbol{\eta}_n \end{bmatrix}$.

(M×M) $\qquad$ (M×1) $\qquad$ (Mn×1)

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