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16. Abstract <p>This report was prepared in order to evaluate the impacts that tire debris on state highways produces in Arizona and the Phoenix metropolitan area. Estimates of debris collected in metro Phoenix were reported along with an analysis of the safety implications that roadway debris and tire defects have for Arizona motorists. In order to assess the causes of tire debris in metropolitan Phoenix, a sample of tires and tire fragments was taken at several ADOT maintenance yards in the metro area. These fragments were classified according to type of vehicle, retread or original tire, and probable cause of failure.</p> <p>The study revealed that, relative to the state as a whole, tire debris is a maintenance problem of greater magnitude in the Phoenix metropolitan area. However, roadway debris in general was not found to be a significant highway safety hazard in either the Phoenix metropolitan area or statewide. Tire defects and tire failures were also found to have a negligible effect on highway safety in terms of accidents reported in Arizona.</p> <p>Truck tires, particularly retread tires, were found to be over-represented among the samples of tire fragments collected in metropolitan Phoenix. Tires for light trucks and sport utility vehicles were also over-represented relative to these vehicles' configurations and share of travel. For all types of tires, under-inflation and damage due to roadway hazards and debris were the most common causes of tire failure.</p> <p>Due to the minimal safety hazard posed by tire debris, the over-representation of different tire types in the Phoenix sample, and the attribution of most tire failures to driver negligence or infrequent maintenance, it is not recommended that a policy be adopted targeting specific types of tires at this time.</p>					
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# Table of Contents

<b>SUMMARY OF KEY FINDINGS .....</b>	<b>iv</b>
<b>I. INTRODUCTION.....</b>	<b>1</b>
RETREAD TIRES .....	2
OUTLINE OF APPROACH.....	3
<b>II. SCOPE OF ARIZONA DEBRIS COLLECTION AND TIRE MARKET SEGMENTS .....</b>	<b>4</b>
METROPOLITAN PHOENIX AND ARIZONA TIRE DEBRIS STATISTICS .....	4
ADOT MAINTENANCE PROCEDURES (METRO PHOENIX).....	5
TIRE SALES BY VEHICLE TYPE AND MARKET SEGMENT .....	10
<b>III. TYPES AND CAUSES OF TIRE DEBRIS AND RELATIVE SAFETY RISKS .....</b>	<b>14</b>
PRIMARY CAUSES OF TIRE FAILURE .....	14
PREVIOUS TIRE DEBRIS STUDIES .....	17
TRAFFIC ACCIDENT DATA ANALYSIS .....	23
<b>IV. METROPOLITAN PHOENIX TIRE SAMPLES .....</b>	<b>31</b>
SAMPLING METHODS .....	31
LIMITATIONS OF THIS SAMPLING METHOD.....	32
TIRE IDENTIFICATION METHODS.....	33
METRO PHOENIX SAMPLE STATISTICS .....	35
METRO PHOENIX SAMPLE DETAIL.....	37
METRO PHOENIX SAMPLE DISCUSSION .....	44
<b>V. ASSESSING THE SOURCES AND IMPACTS OF TIRE DEBRIS .....</b>	<b>45</b>
DISCUSSION AND CONCLUSIONS .....	45
OPTIONS FOR FURTHER ACTION .....	49
<b>APPENDIX A: TIRE ANALYSIS.....</b>	<b>54</b>
<b>APPENDIX B: RESULTS OF THE METROPOLITAN PHOENIX TIRE SAMPLE .....</b>	<b>62</b>
<b>APPENDIX C: COMMON CAUSES OF TIRE FAILURE.....</b>	<b>81</b>

## List of Tables

Table 1: Highways Served by ADOT Maintenance Yards in Metro Phoenix	6
Table 2: Estimated Weekly Collection of Tire Materials by ADOT Maintenance District, 1998	9
Table 3: TMC Tire Debris Sample Size by Location, 1995 and 1998	18
Table 4: Sample Size by ADOT Maintenance Yard	36
Table 5: Distribution of Fragments by Location and Tire Type	37
Table 6: Distribution of Retread and Original Tires	38
Table 7: Cause of Failure by Location	38
Table 8: Cause of Failure by Type of Tire	39
Table 9: Manufacturer Issues Detail (Percentage of All Tire Failures by Type)	40
Table 10: Average Tread Depth by Tire Type and Cause of Failure	41
Table 11: Share of Travel versus Share of Debris on U.S. Highways	46
Table 12: Share of Travel versus Share of Debris on Urban Arizona Highways	47
Table 13: Medium/Heavy Truck Tire Sales and Share of Debris	48

## List of Figures

Figure 1: Debris Billed to Durango Maintenance Yard, 1998 to 1999	7
Figure 2: Metro Phoenix Estimated Monthly Debris Collections, 1998 to 1999	8
Figure 3: Percentage of Total Tire Sales, 1998	10
Figure 4: Percentage of Tire Sales and Retread Market by Type, 1998	11
Figure 5: Automobile and Truck Tire Sales, 1969 to 1998	12
Figure 6: Number of Tires Retreaded by Type, 1985 to 1998	13
Figure 7: TMC Tire Samples by Type of Tire, 1995 and 1998	19
Figure 8: Causes of Failure Identified for Retreaded Truck Tires	21
Figure 9: Causes of Failure Identified for New Truck Tires	21
Figure 10: Accidents Attributed to Roadway Debris	24
Figure 11: Maricopa County Accident Injury Rates, 1991 to 1998	25
Figure 12: Arizona Accident Injury Rates, 1991 to 1998	26
Figure 13: Maricopa County Accident Fatality Rates, 1991 to 1998	27
Figure 14: Arizona Accident Fatality Rates, 1991 to 1998	28
Figure 15: Accidents Attributed to Tire Defects	29
Figure 16: Average Share of Arizona Traffic Accidents by Cause, 1991 to 1998	30
Figure 17: Cause of Tire Failure by Type of Tire	40
Figure 18: Distribution of Tread Depth - Passenger Auto Tires	42
Figure 19: Distribution of Tread Depth - Light Truck Tires	42
Figure 20: Distribution of Tread Depth - Medium/Heavy Truck Original Tires	43
Figure 21: Distribution of Tread Depth - Medium/Heavy Truck Retread Tires	43
Figure 22: Tire Composition Cutaway View	55
Figure 23: Tire Repair Failure	81

Figure 24: Improper / Missed Repair	82
Figure 25: Bond Failure - Tread Leaving Casing	82
Figure 26: Excessive Shoulder Wear	83
Figure 27: Improper Repair	83
Figure 28: Sidewall Impact Break	84
Figure 29: Sidewall Impact Break	84
Figure 30: Road Hazard - Puncture	85
Figure 31: Road Hazard - Puncture	85
Figure 32: Retread Bond Failure	86
Figure 33: Retread Bond Failure	86
Figure 34: Under-inflation	87
Figure 35: Run-flat Belt Leaving Belt	87

## Summary of Key Findings

Tire debris on state highways in metropolitan Phoenix has been targeted as a potential safety hazard, as well as a burden on the Arizona Department of Transportation (ADOT) maintenance budget. However, much of the evidence to support these perceptions is anecdotal. Few statistics exist that measure the impact of tire debris on highway safety and the state maintenance budget.

This study was prepared with several goals in mind. The first was to estimate the impacts of highway tire debris on the Arizona Department of Transportation, in terms of quantities collected and costs of collection and disposal. Second, the question of whether tire debris on Arizona highways represents a significant safety risk to motorists was addressed. Finally, a sample of tire debris at various maintenance yards in metropolitan Phoenix was collected and compared to previous tire debris studies to ascertain the distribution of tire types and causes of failure. Sampling and identification techniques were developed with the assistance of industry experts to ensure the comparability of results.

The following general conclusions were reached as a result of this research:

- Tire debris is primarily a maintenance problem. The removal of debris from state highways consumes roughly 3 percent of the Arizona Department of Transportation's roadway maintenance budget. The problem is more pronounced in the metro area. Removal of debris from metropolitan Phoenix highways consumes over 7 percent of ADOT's Phoenix Maintenance District roadway budget, with roughly 6 percent dedicated to litter removal contracts. Phoenix District employees remove an estimated 3.3 tons of tire debris from state highways in metropolitan Phoenix each week. The quantity of tire debris collected varies with seasonal traffic volumes, changes in temperature and the share of different types of vehicles found on the roadway.
- Tire debris is not a significant safety hazard in Maricopa County or Arizona as a whole. From 1991 to 1998, an annual average of 79 traffic accidents were caused by debris of any kind on Arizona highways. This count represents only 0.07 percent of all Arizona accidents recorded for this period. Traffic accidents attributable to road debris averaged 0.02 percent of all traffic accidents in Maricopa County. Accidents attributable to debris also tend to have lower rates of injuries and fatalities than nearly all other types of traffic accidents. There were no deaths recorded in Maricopa County traffic accidents due to road debris from 1991 to 1998. Similar findings were made for traffic accidents caused by tire defects or failures. Tire defects were found in 0.6 percent of Maricopa County traffic accidents and 0.8 percent of Arizona traffic accidents between 1991 and 1998.
- Tire debris is primarily caused by large truck traffic. After taking into account the greater distances traveled by large trucks and the greater number of tires generally

found on these vehicles, the amount of tire debris caused by these vehicles remained disproportionately high. In the metropolitan Phoenix sample, large truck tires made up 31 percent of all tire fragments counted. In contrast, these vehicles make up an estimated 9 percent of urban traffic in Arizona. Light truck tires from pick-up trucks and SUVs were similarly over-represented in the metro Phoenix sample, comprising an estimated 31 percent of traffic but 43 percent of debris counted.

- Retread truck tires were also disproportionately represented in all samples measured. In both the metropolitan Phoenix tire sample and nationwide samples conducted by The Maintenance Council, retreads comprised between 71 percent and 89 percent of all large truck tire debris. In contrast, retread tires made up roughly half of all large truck tire sales between 1995 and 1998.
- Poor tire maintenance, particularly running tires under-inflated, and punctures due to road hazards and debris made up the most frequent causes of failure in tires of *all* types. Collectively, these causal factors account for the majority (over 82 percent) of tire failures in the metropolitan Phoenix debris samples. An increase in the relative frequency of retread tire failures due to manufacturer defects was observed in each sample period. These defects increased from 5 percent of retread failures in the 1995 TMC study to 9 percent of retread failures in the 1998 TMC study. In the metropolitan Phoenix tire sample (1999), retread failures due to manufacturer defects comprised 23 percent of all retread failures.

While a variety of possible options for reducing the amount of tire debris on highways in the Phoenix metro area exists, the results of this analysis suggest that few options will be effective enough to warrant action. Because the vast majority of tire failures are caused by poor tire maintenance or neglect by individual drivers, the effectiveness of any efforts at debris reduction depends in large measure upon changes in driver behavior. Insofar as tire debris does not pose a significant highway safety risk, legislation aimed at driver behavior (e.g. fines for poor maintenance, etc.) may be politically unpalatable and very difficult to enforce. A reduction of the state speed limit would reduce tire wear, but is unlikely to garner favorable support. A ban on retread tires would unnecessarily burden trucking companies without addressing the root causes of most tire failures.

It appears feasible that a significant portion of the tire debris problem will be solved without government action. Given the considerable costs that tire failures impose on the trucking industry, several technological advances have been developed to help fleets properly maintain their tires. The most influential of these devices appears to be a system that constantly monitors and adjusts air pressure in truck tires while the vehicle is in motion. With over 60 percent of tire failures attributed to under-inflation, widespread adoption of such systems stands to reduce the amount of tire debris on the roadway considerably.

## I. Introduction

As the number of drivers and vehicles has increased over the past several decades, discarded tires have become a policy concern of increasing magnitude. Tires left on the roadway after failure or simply discarded as litter pose more than an aesthetic problem. Waste tires are difficult to transport and dispose of efficiently, pose certain health and environmental problems, and are an added cost for highway maintenance departments. Tire debris on the highway is also frequently mentioned as a safety hazard, creating an added risk for motorists. This report has been prepared to investigate the sources of tire debris on metropolitan Phoenix roadways, and to estimate the impact of this debris on the Arizona Department of Transportation and highway safety in metropolitan Phoenix and Arizona.

Studies estimate that between 0.8 and 1.0 tires per person end up in scrap piles every year (Wiekierak, *et.al.*, 1991). An assessment of litter on Pennsylvania highways in 1991 concluded that tire fragments were the fifth most prominent type of debris, and the most frequent type of accidental debris found on Pennsylvania roads. Tire shreds made up 6 percent of the litter count on 138 highways sampled.<sup>1</sup> According to the Pennsylvania study, most litter complaints are generated by large pieces of very visible and unsightly debris such as tires (TriLine Associates, 1992).

In addition to its frequency as an eyesore, tire debris also poses environmental and health issues. Because tires decompose very slowly and migrate upward as landfills compact, they disrupt the landfill cap and are thus forbidden from many licensed landfills. As a result, many used tires end up in above-ground dumps, creating fire hazards (Wallace, 1990). Stockpiled whole tires also retain water, providing a suitable breeding ground for mosquitoes and other pests (Wiekierak, *et.al.*, 1991).

The collection and disposal of debris on state highways poses an ongoing challenge for departments of transportation. According to a survey of state transportation departments (Andres, 1993), the cost of collection and disposal of highway litter exceeded \$120 million annually in 1990 and 1991. An average of 3.3 percent of each state maintenance budget was spent on roadside debris cleanup. Rubber and leather materials together comprised 4.4 million tons of waste discarded in municipal solid wastes (MSW) in 1990. These materials made up 2.7% of total MSW by weight and 6.1% of MSW by volume. Tire debris was the most frequently mentioned debris collection problem, indicated as such by 65 percent of states responding.

In Arizona, the current cost of debris pick-up on state highways is estimated at slightly more than \$2 million annually, representing roughly three percent of the state's roadway maintenance budget (ADOT, 1999). While this represents a 33 percent increase over the estimated \$1.5 million spent in fiscal 1990 to 1991 (Andres, 1993), the percentage of the roadway maintenance budget has remained relatively constant. A substantially greater portion of the Phoenix Maintenance District roadway budget is allocated to sweeping and

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<sup>1</sup> In comparison, the most frequently observed litter material was paper, which represented 9 percent of debris counted in the sample.



debris removal. Over the past three years, over 7 percent of the Phoenix District's roadway budget has been allocated to highway sweeping and debris removal, with most of the funds (approximately 80 percent of the allocation) dedicated to litter removal contracts with private vendors. Costs attributed to debris removal by ADOT personnel in the Phoenix Maintenance District averaged \$225,000 annually over the past three years. Sweeping and debris removal contracts averaged another \$860,000 over the same period. The current year contract estimate for sweeping and debris removal activities by private vendors in metro Phoenix is over \$1 million.

Debris pick-up in Arizona was allocated among a number of entities, with approximately 30 percent of debris collected by regular state maintenance staff. Contractors collected the largest portion of debris on Arizona highways (63 percent), while Adopt a Highway (ADAH) program volunteers and convict laborers collected roughly 5 percent and 3 percent of highway debris respectively (Andres, 1993). Virtually all of the contractor activity occurs in the Phoenix and Tucson metropolitan areas.

Not only do discarded tires pose a problem in terms of collection and disposal, but tires also become a potential threat to driver safety when left on public roads. Whole tires and tire fragments left on the road create a perceived obstacle to motorists. While running over a piece of tire may or may not cause significant damage to a vehicle's undercarriage, a perception of risk associated with a large object in the road induces some drivers to swerve, thereby endangering both themselves and other motorists. Controversy exists regarding the types and causes of debris on the road, responsibility for highway debris, and the relative risk that tire debris poses to driver safety. Often mentioned in debates between safety groups and trucking and tire industry representatives is the role played by retread tires.<sup>2</sup>

### Retread Tires

Much of the public attention to tire debris has focused on potential hazards attributed to retreaded tires, which are essentially used tires that have been recapped with new tread material. Safety organizations see retread tire failures as a significant highway hazard. Citizens for Reliable and Safe Highways (CRASH) and Advocates for Highway and Auto Safety are among groups that have called for greater government oversight of retreading procedures (Cole, 1998 and Donaldson, 1998).

While consumer and highway safety groups have expressed speculation that retreaded tires are not as safe as original tires and are more susceptible to failure (Galligan, 1999), studies conducted by The Maintenance Council of the American Trucking Association have not identified an increased risk of tire failure in retreaded tires relative to original (new) tires (Laubie, *et. al.*, 1999). According to industry representatives, the materials used in modern retread tires ensure that casing integrity is maintained throughout not only the first tread life but also through one or more retreads, depending on service application, type of vehicle and operating conditions (Fleet Equipment, 1997). But tire

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<sup>2</sup> For a discussion of tire manufacturing and retreading procedures, refer to Appendix A.

casings are not an unlimited resource. Casings subject to regular use will eventually wear out. At issue is *how long* a casing will maintain its structural integrity.

Despite industry findings, public perception of retreads as unsafe continues, ostensibly due to the relatively large size and frequency of occurrence of truck tire debris on the highways. As a precautionary measure, CRASH has called for limitations on the number of times a tire could be retreaded (Donaldson, 1998). While such restrictions have been rejected to date, the potential exists for serious economic consequences to the retread industry, which generated over \$2 billion in sales in 1998 (Galligan, 1999), and the trucking industry, which derives substantial savings from the use of retread tires. Not only would such a change increase the cost of retreads, it also could expose manufacturers and users to legal action from damage and other claims (Brodsky, 1999).

An important component of this study was the identification of various tires and tire scraps collected on roadways in metropolitan Phoenix to determine the extent to which retreaded tires are represented in the tire debris collected. When possible, an effort was also made to determine the source of tire failure. Identification of the source of tire failure is important from a policy standpoint in that possible solutions to the perceived problem of escalating quantities of tire debris should address circumstances that may cause tire failure. If small car tires or retreaded tires are simply identified as problematic based on having a disproportionate representation in the tire sample, policy solutions aimed at these tire "types" may have little or no impact on the reasons for the disparity, and thus little impact on the problem itself. As an example, assume that a major source of tire failure is lack of adequate maintenance, more specifically -- under-inflation. If under-inflation is determined to be a significant source of failure for all tires, outlawing retreads won't solve this problem. It would merely shift the incidence of tire failures to non-retreaded tires.

### Outline of Approach

The body of this report is divided into several sections. Section II. provides an overview of highway debris collection in Arizona and in the Phoenix metropolitan area. These data are provided in order to estimate the magnitude of the perceived problem. Tire industry statistics are also provided in this section to provide a background of the national tire market, including sales by type of tire, overall trends in the industry, and the impact of the retread segment on tire sales. These sales data are also used in the final section of this report as a baseline estimate of the quantities of debris that might be found on the highways.

Section III. of this report contains information relevant to assessing debris in terms of responsibility or causation. The first part of this section outlines in detail some of the most common causes of tire failure. The second part identifies several industry studies that have been undertaken to assess the distribution of tire debris among different vehicle classes, retread and original tires, and various causal factors. Numerical results from two TMC studies are reported in greater detail, giving a baseline with which the metro Phoenix sample can be compared. This section also provides accident statistics for

Maricopa County and Arizona, measuring the relative risk of accidents caused by roadway debris and tire defects relative to accidents as a whole. Based on these results, an assessment of tire debris as a safety hazard is included in this section.

The sample of tire debris in metropolitan Phoenix collected for this report is the focus of Section IV. This section begins with an overview of the sampling methodology used, along with its limitations. An overview of the methods used to identify tire fragments is followed by reporting of the metro Phoenix tire debris distribution, including relative frequencies, causal factors and differences between the Phoenix sample and previous industry studies.

Section V. contains conclusions that may be drawn from the data presented in previous sections. Particular attention is paid to assessing over- and under-representation of different tire types in the Phoenix and TMC samples. These assessments are made using tire sales data, estimated share of travel and vehicle configuration statistics. The most frequent causes of tire failure, and the implications of these causes are also discussed. Finally, potential strategies for addressing some of these concerns are discussed.

Several appendices are also included with this report. Appendix A provides brief descriptions of new tire and retread tire manufacturing processes, as well as definitions and locations of the key elements of a radial tire, intended to serve as a glossary of terms used elsewhere in this report. Appendix B provides details for each tire identifiable fragment collected in the metro Phoenix sample, as well as contact information for the tire engineers that provided technical assistance for tire sampling and identification.

## **II. Scope of Arizona Debris Collection and Tire Market Segments**

### **Metropolitan Phoenix and Arizona Tire Debris Statistics**

According to an estimate provided by the Phoenix Maintenance District (Lopez, 1999), ADOT maintenance personnel from the various metropolitan Phoenix yards collected 68,420 tons of debris in 1998. On average, maintenance workers collected 1,316 tons of debris weekly on metro Phoenix state system highways. ADOT personnel at the Durango maintenance yard estimate that the current pick-up on state highways in the Phoenix maintenance district amounts to some 363.2 tons of debris daily. The majority of debris pick-up in metropolitan Phoenix is performed by private contractors that are not required to report quantities of different types of debris collected from Phoenix-area highways. Although some valley landfills charge a separate fee for rubber debris, others do not. The various means of debris collection and reporting make it difficult to estimate the amount of rubber collected on highways in the Phoenix area.

### **ADOT Maintenance Procedures (Metro Phoenix)**

Highway debris creates a burden on highway agencies, in terms of labor, storage and disposal costs. In the metropolitan Phoenix area, most of the debris pick-up on the state highway system is contracted out to private service providers. ADOT currently utilizes two contractors for daily debris pick-up and sweeping of state highways in metro Phoenix. The first, Sun Valley, is responsible for pick-up of large debris, including whole tires and most shreds. Sun Valley utilizes vehicles with an automated debris-capture system, similar to machines used for cotton milling.

Sweeping duties on metro Phoenix state highways are contracted to USA Waste Management, which is responsible for daily sweeping of median and shoulder areas of the roadways. Both contractors operate on a Saturday to Thursday schedule, with Saturdays designated for debris pick-up on Interstate 10 and Highway 202. The contractors handle all aspects of waste removal and disposal, hauling debris to local landfills on a regular basis. The ADOT Phoenix Maintenance District is billed monthly by Sun Valley for fees at local landfills (Campos, 1999).

The extent of the Phoenix-area highway system precludes daily collection of debris from all roadways by contract maintenance workers. Therefore, a significant portion (approximately 30%) of metro Phoenix debris collection is also performed by ADOT Maintenance personnel, usually between or following regularly scheduled duties. The amount of debris collected by ADOT employees varies by the season, public requests and other scheduled duties. Generally, debris pick-up is performed from once or twice weekly (as reported for the East Metro maintenance yard) to virtually daily (as reported for the Durango maintenance yard) (Josefowicz, 1999 and Lopez, 1999).

State highway segments in metropolitan Phoenix are serviced by the four ADOT maintenance yards depending on location. Table 1 lists the highways served by each of the four ADOT maintenance yards in metropolitan Phoenix.

**Table 1: Highways Served by ADOT Maintenance Yards in Metro Phoenix**

Maintenance Yard	ADOT Org	Highways Served
Agua Fria	7871	Interstate 10, US 60 and State Routes (SR) 101 and 303 west of Interstate 17; SR 85
Durango	7875	Interstate 17 from 16 <sup>th</sup> Street to New River; SR 74; US 60 east of I-17; Interstate 10 from the I-17 interchange to 16 <sup>th</sup> St.
East Metro	7873	SR 51, SR 143, SR 153 and SR 347; Interstate 10 east of 16 <sup>th</sup> St.; SR 202 from Interstate 10 to Priest Drive
Mesa	7874	SR 87, SR 88 and SR 587; SR 101 in the east valley; SR 202 east of Priest Drive; US 60 east of the I-10 interchange

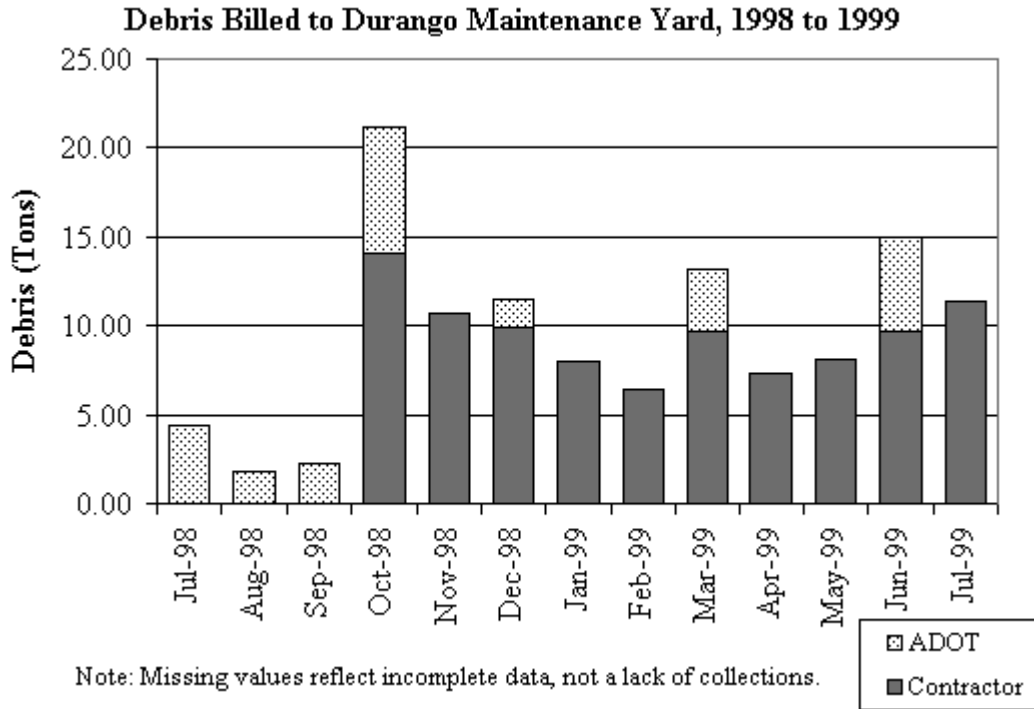
ADOT maintenance yards have storage areas for debris collected, with separate storage for tires and tire shreds at most yards. Debris is stored at maintenance yards until the quantity collected becomes great enough to warrant the expense of hauling it to a landfill. Tires are separated at most yards because many local landfills charge a weight-based fee for disposal of tire rubber. The separated tire debris at ADOT maintenance yards was used for the sampling of tire debris discussed in Section IV of this report.

#### Metropolitan Phoenix Debris Collection

The figure below illustrates reported amounts of road debris collected by ADOT maintenance personnel and Sun Valley Litter Removal contractors. The amounts include only rubber debris for which a fee was charged at local landfills. Therefore, it may be assumed that the figure understates the total amount of debris collected on metropolitan Phoenix highways. The reasons for this assumptions are twofold. First, some local landfills do not charge an additional fee for the disposal of tire scraps and other rubber debris. The billed amounts thus reflect only the debris that were required to be separated by ADOT or the contractor for disposal. Second, local landfills do not charge a fee for whole tires. Complete tires carry a residual value and are therefore recycled. Again, this is only the case at facilities that require rubber to be separated. In most other instances, rubber debris is discarded with other refuse and is not accounted for.

The monthly billed amount of debris collected by Sun Valley waste removal workers from October 1998 to July 1999 varied from approximately 6.4 tons in February to 14.1 tons in October. Billings tended to be higher in the summer and fall and lower in the winter and spring. The amount of rubber refuse billed to Sun Valley and to ADOT maintenance by local landfills was highest in October 1998.

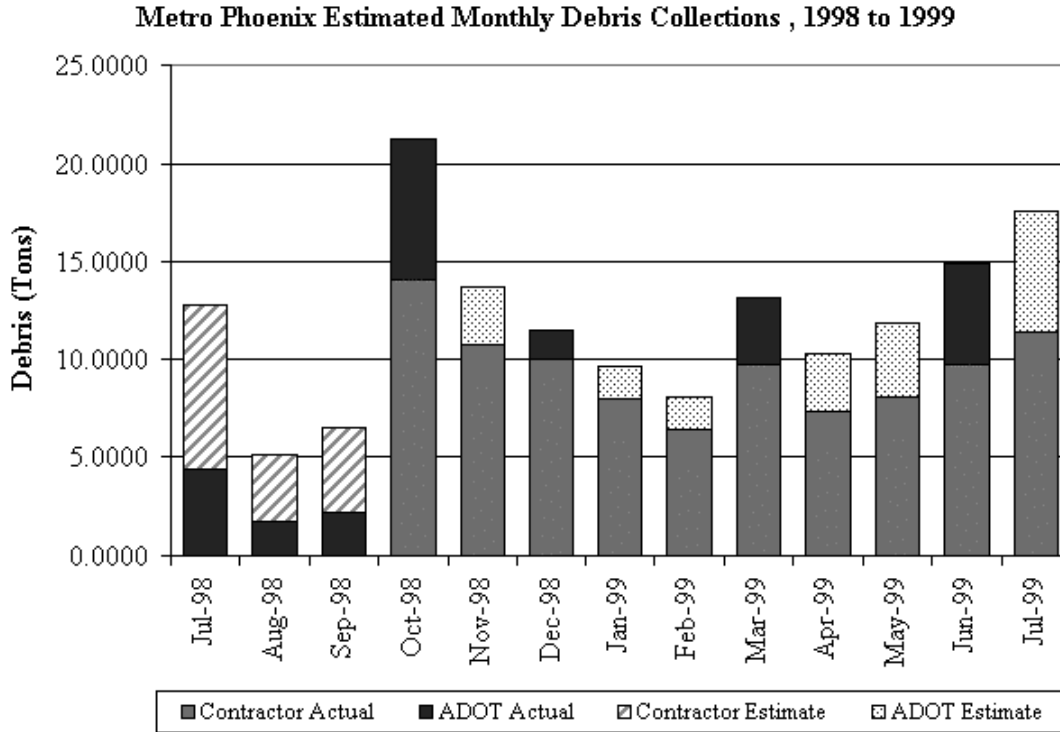
**Figure 1:**



Because the available records of actual rubber debris collections made in the metropolitan Phoenix area are incomplete, an effort has been made to estimate monthly collections based on annualized rates of change in the data that were available. These estimates are illustrated in Figure 2. The data in Figure 2 are intended only as an illustration of the seasonality of rubber debris collections, and not as a report of tire debris quantities in metro Phoenix. In no instance has the actual data shown in Figure 1 above been altered. Instead, Figure 2 simply "fills in the blanks" of missing data using the change in actual data as a baseline.

The seasonal pattern of debris quantities remains the same in the Figure 2 estimates, although the added values tend to smooth the monthly differences and decrease seasonal variation. October remains the month with the greatest quantity of debris collected in the period measured, followed by June and July. Given the actual quantities of rubber debris collected by contractors in June, July and October, it is unlikely that actual collections by contractors in August and September of 1998 were as low as the estimate reported in Figure 2. These months aside, a visible seasonal pattern can be discerned, with estimated collections falling from November to February and rising again in March.

**Figure 2:**



Statewide Debris Collection

Maintenance districts around the state report varying levels of tire debris, depending on the quantity and types of traffic in each district. Table 2 presents weekly estimates of tire debris collected by various ADOT maintenance districts in 1998, as reported by district managers in December, 1998.<sup>3</sup> The state districts reporting average an estimated 25.3 tons of tire debris collected on a weekly basis year-round. A large amount of variation exists among districts surveyed, with virtually no debris reported on a weekly basis in the Globe district and up to 20 tons per week collected during summer months in the Kingman and Yuma districts.

Overall, estimated summer collections of tire debris were 30 percent higher than estimated collections in winter months. In the aggregate, the reporting districts estimated that 28.7 tons of tire materials were collected each week during the summer months. The estimated quantity of tire debris collected in winter months fell to 22.0 tons. Estimates for Holbrook and Yuma had the greatest relative variations, with summer collections of tire debris exceeding winter collections by 225 percent and 100 percent respectively in these districts. Estimates for the Yuma district also exhibited the most variation in absolute terms, with 10 tons of tire debris collected weekly in the winter months and 20

<sup>3</sup> Debris pick-up estimates were reported by ADOT districts to Central Maintenance. Initial totals for Holbrook and Prescott did not include all sources and have been revised upward based on estimates received after this information was forwarded to Central Maintenance.

tons collected weekly during summer months. While these figures represent "best-guess" estimates made by ADOT maintenance supervisors, it is evident from these estimates that seasonal fluctuations in temperature and traffic play a role in the amount of tire debris encountered on state highways.

**Table 2: Estimated Weekly Collection of Tire Materials by ADOT Maintenance District, 1998**

ADOT District	Tons of Tire Materials Collected per Week <sup>3</sup>		
	Summer	Winter	Average
Flagstaff	2.5	2.5	2.5
Globe	0.0	0.0	0.0
Holbrook <sup>1</sup>	1.3	0.4	0.8
Kingman	20.0	15.0	17.5
Phoenix	3.3	3.3	3.3
Prescott <sup>1</sup>	1.5	0.8	1.2
Safford <sup>2</sup>	n/a	n/a	n/a
Tucson <sup>2</sup>	n/a	n/a	n/a
Yuma	20.0	10.0	15.0
<b>Totals</b>	<b>28.7</b>	<b>22.0</b>	<b>25.3</b>

Notes: 1. Prescott and Holbrook totals were revised upward based on estimates reported by district managers at a later date. 2. Data were not available from Safford and Tucson districts. 3. Includes ADOT personnel, Adopt A Highway and prisoner collections.

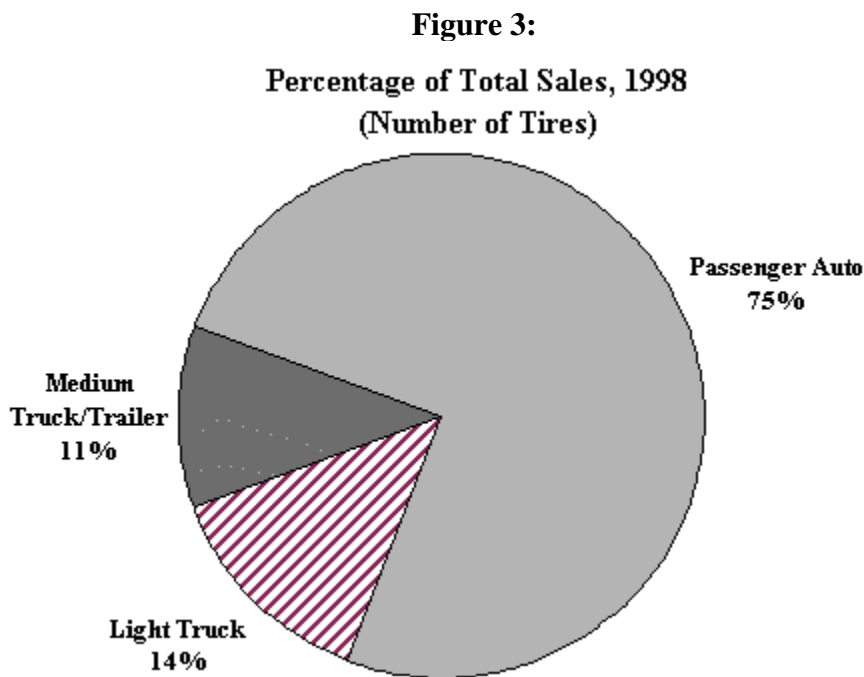
While metro Phoenix collections of tire debris estimated by ADOT maintenance personnel fall in the lower range of weekly collections statewide, these estimates are likely to be low based on the amount of contract clean-up performed in the Phoenix area and different sorting requirements imposed by local landfills. Contracts for sweeping and litter removal on metropolitan Phoenix roadways currently total \$1.04 million, roughly 6 percent of the budget for the Phoenix Maintenance District. Assuming that the cost per ton of rubber debris collection in metro Phoenix is constant for state and contract personnel, a reasonable estimate of the rubber debris collected by contractors on a weekly basis in metro Phoenix is an additional 16.5 tons.<sup>4</sup> The degree to which these tires and tire fragments impact highway safety and the distribution of fragments by vehicle type are discussed in Section III of this report.

<sup>4</sup> This estimate was made based on the Phoenix District budget allocation for in-house debris removal and the reported estimate of tire rubber collections made by metro Phoenix ADOT personnel. This figure does not represent a verifiable quantity of debris collected by metro Phoenix contractors and is intended for illustrative purposes only.



## Tire Sales by Vehicle Type and Market Segment

Passenger automobile and light truck tires make up the vast majority of all automotive tires sold annually in the U.S. According to the International Tire and Rubber Association (1999), passenger car tires comprised 75 percent of the tire market in 1998 and 76 percent in 1997. Light truck tires (i.e. tires specifically manufactures for pick-up trucks, vans and sport utility vehicles) comprised 14 percent of the tire market in 1998 and 13 percent in 1997. For both years, tire sales to these vehicle types made up nearly 90 percent of tires sold.<sup>5</sup> Medium truck tires, which are manufactured for single unit trucks, buses and combination truck tractors and trailers, made up the remaining 11 percent of tires sold in 1997 and 1998. Figure 3 shows the total number of tires sold by user segment in 1998.



Source: International Tire and Rubber Association, 1999

The tire market is made up of three distinct segments, shown in Figure 4. "Original equipment" (OE) tires are those that come on new vehicles sold at auto dealerships. Sales in this segment rely on automobile manufacturer orders and the volume of new vehicles sold. Original equipment tires made up 22 percent of tires sold in 1998 and 1997.

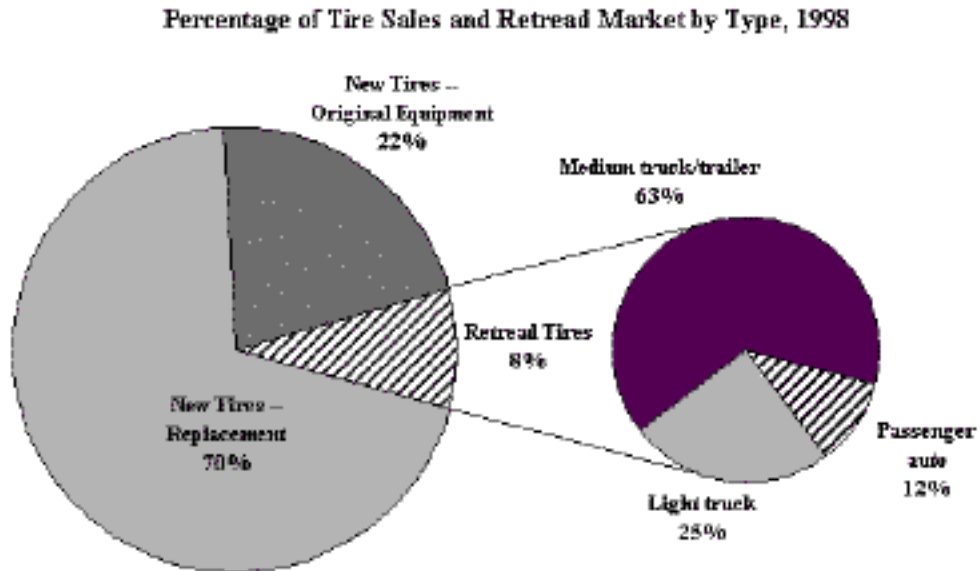
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<sup>5</sup> Note that these figures do not represent the total number of tires sold for use on "light trucks" as defined above. Roughly 7 percent of passenger automobile replacement tires are P-metric tires used on light trucks. Similarly, passenger auto (P-metric) tires made up an average of 25 percent of original equipment tires on light trucks in 1997 and 1998 (ITRA, 1999). Therefore, as a user class, light trucks represent a greater percentage of tire sales than indicated in the chart.

"New replacement" (NR) tires are manufactured as replacements or upgrades to original equipment tires as the OE tires wear out. Most of the sales in this segment are conducted between automobile owners and retailers specializing in tire sales. The replacement tire market represents the largest segment of tire sales in the U.S., with nearly 70 percent of all units sold.

The final segment tracked by the International Tire and Rubber Association is the retread tire market. Retreaded tires are manufactured by applying a new tread layer to a used tire casing (see Tire Analysis, Appendix A). Tires manufactured as retreads made up 8.5 percent of the number of tires sold in 1998, a slight decline from 8.9 percent in 1997. In contrast to the OE and NR segments, the majority of retread tires are manufactured for commercial use on medium trucks and tractor-trailer combinations. While medium truck tires comprised 6 percent of NR tire sales and 8 percent of OE sales, medium truck tires represented 63 percent of retread tire sales in 1998. The number of retreads sold in the passenger automobile and light truck markets has fallen by more than 70 percent since 1969, and is expected to continue to decline. Therefore, it is expected that the role of larger commercial trucks in the retread tire market will continue to grow.

**Figure 4:**

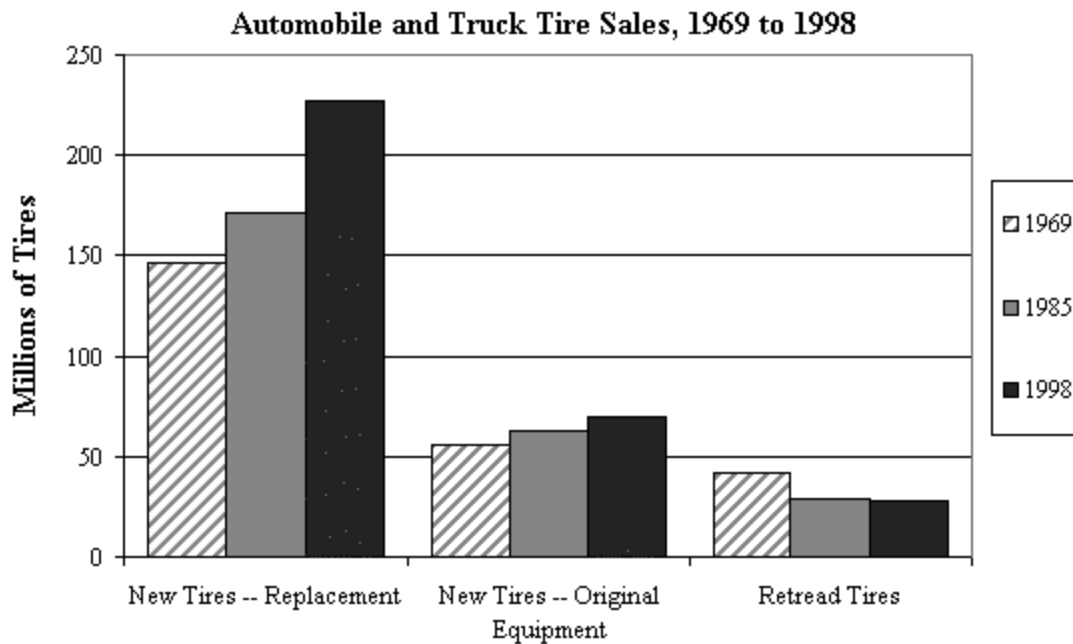


Source: International Tire and Rubber Association, American Tire Retreaders Association, Bendag Corporation

Tire sales for each segment by number of units are shown for 1969, 1985 and 1998 in Figure 5. Annual new replacement tire sales increased by over 55 percent from 1969 to 1998, from 147 million units to 227 million units. Original equipment tire sales totaled 70 million units in 1998, an increase of 26 percent over the 56 million units sold in 1969. Retread tire sales have declined 34 percent since 1969, with virtually all of the losses accruing to the passenger auto segment. Of the 42 million retreads sold in 1969, 32.6 million were passenger auto tires. By 1998, 27.5 million retreads were sold, of which

only 2.9 million were passenger auto tires, a decline of more than 91 percent in the passenger auto segment.<sup>6</sup> In contrast, annual sales of retread tires for medium trucks and truck trailers increased by 142 percent over the same period, from roughly 7.3 million tires in 1969 to 17.7 million in 1998. The ITRA projects continued declines in overall retread sales, which are forecast to fall another 0.7 percent in 1999. Sales of passenger auto retreads are expected to decline by another 13.8 percent in 1999, and light truck retread sales are expected to fall 1.4 percent. Growth is projected to occur in the medium truck and trailer retread segment, with an increase of 1.7 percent (300,000 units) in 1999.

**Figure 5**



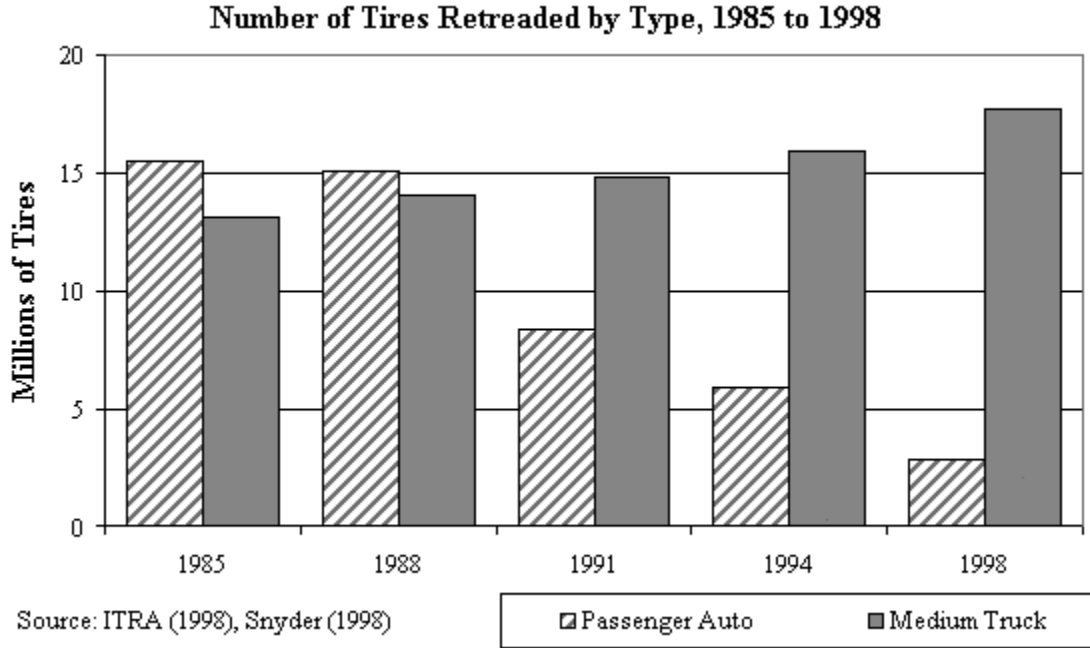
Source: RMA (1974), ITRA (1998), Snyder (1998)

Greater detail of annual sales in the retread tire segment is provided in Figure 6. The most notable change occurs in sales of retreads for passenger automobiles. The rising popularity of more durable radial tires, consumer skepticism over the safety of retreads, and the falling cost of new tires have all contributed to the steady decline of retread sales to the passenger auto segment. In contrast, sales of retread tires to the medium truck segment (including semi trailers) have made up an increasing share of the retread tire market. As indicated above, this steady divergence between passenger auto and medium truck retreads is expected to continue. While retreading of light truck tires has remained relatively constant at roughly 7 million tires over the past several years, the influence of

<sup>6</sup> Retread tire sales figures for 1969 are available for "Passenger Auto" and "Truck and Bus" categories. It is plausible that part or all of the 1969 sales of retreads for pick-up trucks are included in the "Passenger Auto" category. In this case, the overall decline should take into account the number of "Light Truck" retreads in 1998 (6.9 million). In this case the decline in annual sales of "Passenger Auto" retreads is 70 percent between 1969 and 1998.

the medium truck market is expected to play the most important role in the retread tire industry in the coming years.

**Figure 6**



### Applicability of Tire Sales Data

Tire sales data can provide a useful reference for estimating the frequency of tires that might be found on the highway. However, different types of vehicles have different travel patterns, both in terms of distance traveled and type of roadway most frequently used, as well as different tire configurations. Therefore, tire sales data provide an incomplete source for estimating the share of tire debris according to vehicle *type*. For example, using tire sales data to compare the expected share of tire debris between passenger cars and large trucks would fail to account for the greater number of tires generally found on large trucks, as well as the longer distances that these vehicles tend to travel in a given year.

However, tire sales data do provide a legitimate means for comparing expected and observed frequencies of debris for a *specific* vehicle type. The most useful application of this method is for comparing the distributions of medium truck and trailer tire debris. An analysis of this latter sort has been included in the Conclusions section of this report (Section V), comparing the expected and observed distributions of new and retread truck tires for the TMC and Phoenix metro debris samples. An attempt has also been made to compare distributions among different vehicle types using a combination of vehicle miles traveled and average number of tires per vehicle.

### **III. Types and Causes of Tire Debris and Relative Safety Risks**

#### **Primary Causes of Tire Failure**

According to several different studies, punctures and improper inflation techniques are most frequently mentioned as the leading causes of tire failure (Laubie, *et. al.*, 1999 and *Public Works*, 1989). Because the various causes of tire failure are often interrelated, it is often difficult to ascribe causation to any one particular phenomenon. For example, over-inflated tires are more susceptible to shock induced by contact with other objects in the roadway. This in turn makes over-inflated tires likely to suffer higher rates of puncture. While the puncture may be the most visible source of failure, the puncture was more likely to occur based on the initial characteristic of over-inflation. Various causes of tire failure are discussed in greater detail below.

#### Punctures

Punctures were identified as a primary cause of tire failure in tire debris analyses conducted by The Maintenance Council of the American Trucking Association (1999). To a large extent, punctures are an unavoidable problem that affect both original and retreaded tires (Galligan, 1999). However, other tire problems and maintenance issues (e.g. over-inflation) can increase the likelihood of puncture substantially. While many punctures can not be prevented, regular tire inspections and routine maintenance can lessen the impact of this hazard.

#### Under-inflation

Under-inflation has been identified as the most common tire condition (Laubie, *et. al.*, 1999), due to the tendency of all tires to lose air over a period of time. Under-inflation creates excess tire drag, increasing friction between the tire and the road surface. This generates greater amounts of heat, which speeds tread wear and weakens tire components, thereby decreasing the usable life of the tire and rendering it prone to failure (Bearth, 1999).

An under-inflated tire can cause other problems as well. The amount of air in each tire affects weight distribution between the wheels. An underinflated tire in a dual position doesn't carry its full share of the load. This in turn, affects chassis loading, traction, steering, alignment and braking. It may also cause noticeable steering pull when driving or braking (*Public Works*, 1989). Mismatched weight distribution can create excessive loads on weight-bearing tires, increasing heat and wear due to friction.

#### Over-inflation

Excess air pressure causes tires to become rigid, thus reducing the tires' capacity for absorption of sudden shocks encountered on the road. This makes over-inflated tires more susceptible to tears, punctures and body breaks induced by sudden contact with imperfections and debris in the roadway.

### Excessive loading

Truck tire sidewalls are stamped with a tire load capacity that indicates the maximum load that can be safely supported by the tire. The casing strength of a tire is expressed as a "ply rating" or a "load range," both of which refer to a tire's ability to hold air pressure and volume under various loads. Exceeding the load capacity of a tire can increase tread wear, reduce sidewall resilience, and decrease fuel economy (Bearth, 1999). The risk of tire failure is increased substantially by the first two variables.

### Driver error

Driver error encompasses many variables, including the elements of improper maintenance (e.g. inflation and loading errors) discussed at greater length above. Additional causes of tire failure attributable to driver error include poor maneuvering and operating practices. A common example is the tendency to allow tires to roll over curbs when cornering at narrow or congested intersections.

The damage to tires and wheels from dragging over a curb is often experienced instantly, with rims dented or tires blown out. But in many cases tires fail later from belt separation or air loss as a result of curb impact. In a two-hour survey of truck driver behavior at a congested intersection, 20 percent of drivers with trailers of 40 feet or longer either hit the curb or drove over it (Bozorth, 1998).

### Axle alignment and other vehicle conditions

Improper axle alignment can have a severe impact on tire life, handling and fuel economy. Potential sources of alignment error can occur in the toe, camber and "toe-out-on-turns" settings, as well as wheel tracking. Toe alignment refers to the degree to which steering-axle tires are parallel. Excessive "toe-in" (i.e. the fronts of steering-axle wheels are closer together than the backs) causes increased wear on the outside shoulders of tires, while too much "toe-out" (backs of tires closer together than fronts) creates excessive wear on the inside shoulder of the tire (*Public Works*, 1989).

Camber alignment refers to the angle that the wheel tilts from the vertical plane. Positive camber is an outward tilt of the wheel, while negative camber is an inward tilt. Both conditions can create rapid shoulder wear in tires. "Toe-out-on-turns" refers to the difference in the arcs that steering wheels make in a turn. The difference keeps inside tires from rubbing around a turn. Improper alignment causes excess rub wear of the inside tire. Proper wheel tracking keeps the rear wheels on a parallel line with the front wheels when driven straight ahead. If rear wheels are out of track, the vehicle will have a tendency to pull to one side, inhibiting driver control and increasing wear on tires and suspension (*Public Works*, 1989).

Mismatched tires on the dual wheels common on truck trailers can have a variety of detrimental effects. When one tire is larger than the other, it will carry most of the load, which can overload the tire and create a safety hazard. The smaller tire will wear

irregularly and more quickly, as it lacks proper contact with the road. Finally, if mismatched tires rub against each other while in motion, the resulting damage to sidewalls can increase the likelihood of a blow-out.

### Weather conditions

All tires are subject to heat generated as a product of friction between the tire and the roadway. Heat softens and weakens the rubber compounds used in manufacturing the tire, rendering it more susceptible to damage. The problem is compounded by under-inflation as discussed above. Heat poses an additional challenge on roadways in hot climates such as Arizona, in which the road surface can reach higher temperatures that compound the risk of tire failure. Maintenance personnel from the Arizona Department of Transportation report greater collections of tire debris from roadways in the summer months, particularly in central and southern desert climates where excessive heat can cause the rubber compounds in tires to wear more quickly.

Changes in the ambient air temperature also create fluctuations in tire air pressure, making the maintenance of recommended pressures more difficult. Air pressure in a tire goes up or down about one pound for every 10 degrees of temperature change (Deierlein, 1996). Most tire inflation pressures are specified for an ambient temperature of 70 degrees; so to be 100 percent accurate drivers should compensate for temperature when checking tire pressure.

### Industry trends

Certain trends in the trucking industry have been identified as possible contributors to tire failure. In an effort to improve the hauling capacity and efficiency of tractor trailer combinations, some carriers have begun using longer trailers and smaller wheels. While the increased capacity of longer trailers is obvious, the benefits that accrue to users of smaller wheels are derived from the carrier's ability to maintain the same trailer height while lowering the floor, thereby increasing trailer volume. While both of these practices make a carrier more efficient by increasing load volume, each poses a potential detriment to tire maintenance.

Longer trailer lengths are conducive to the curb damage discussed in "Driver error" above. Quite simply, a longer trailer is more difficult to maneuver in congested areas, and its wheels are thus more likely to come into contact with the curb. The most commonly produced (70 percent) trailer length has increased from 40 feet to 53 feet, and trailer axles have also increasingly been set to wider spacing (Bozorth, 1998). These trends have led to increased risks of trailer tire damage in congested areas.

Smaller wheels require more rotations to travel at the same speed as larger wheels. The added number of rotations means that the smaller wheel must spin more quickly, increasing the amount of heat and friction to which the tire is exposed (Lang, 1999).

## **Previous Tire Debris Studies**

In recent years, tire debris has been identified as a mounting problem on highways nationwide. A number of studies have been conducted in an attempt to ascertain the nature of the problem. In most cases, representatives of The Maintenance Council (TMC) have been called upon to provide technical expertise. TMC representatives from Bridgestone/Firestone were also relied upon for the technical aspects of this report. While the continuing presence of industry representatives might be construed as detrimental to the objectivity of these results, an independent analysis of the data collected does not appear to corroborate any type of bias on the part of TMC researchers. Several recent debris studies are discussed in greater detail in the following section.

### Virginia State Police Study

The Virginia legislature recently mandated (Joint House Resolution 545) a study of retread tires on Virginia highways to determine if there was a need for specific state standards for retread tires. The study was approved based on the assumption that existing tire standards for commercial vehicles failed to address potential hazards assumed to be attributable to retread tires. The legislative study was to be conducted by the Safety Division of the Virginia State Police, headed by Captain W. Steven Flaherty.

In an effort to estimate the magnitude of tire debris on Virginia roadways, state personnel spent three weeks collecting tire rubber from 658 miles of Virginia highways. Approximately 46,000 pounds of debris were collected in this three week period. As a second part of the study, the Virginia State Police researchers enlisted the assistance of tire industry experts to take a representative debris sample to be analyzed by type of tire and cause of failure. One pick-up truck load of debris was collected from a 36 mile stretch of Virginia interstate. As in the case of the TMC studies (see below), the primary causes of tire failure were maintenance related (e.g. nail punctures and belt separations). Medium truck tires made up the majority of debris collected, and retreads comprised roughly 65 percent of truck tire debris collected. According to Captain Flaherty, the Safety Division will likely recommend an initiative to increase awareness of maintenance problems, particularly among truckers. No legislation targeting retread tires is likely to be recommended as a part of the Virginia study.<sup>7</sup>

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<sup>7</sup> The tire analysis conducted for the Virginia study was done with the assistance of TMC researchers. The final version of the Virginia report will be available in early January, 2000 pending legislative approval. For more information, contact Captain Flaherty, Safety Division Commander, by telephone at 804-378-3472 or email at [safetyvsp@va.visi.net](mailto:safetyvsp@va.visi.net).



## TMC Studies, 1995 and 1998

The Maintenance Council (TMC) of the American Trucking Association conducted two samples of tire debris at various sites around the country to identify the probable causes of tire failure and tire debris on the road. The first sample was done in 1995, and the second was performed in late 1998. In most cases, state DOT employees collected debris from predetermined highway segments. The debris was then brought to a centralized location for analysis by TMC engineers. The results of the 1998 study were presented by Dave Laubie of Bridgestone/Firestone at an industry conference in March 1999.

In both the 1995 and 1998 studies, samples collected in and around Tucson, Arizona comprised the largest amount of debris sampled at a particular site. The average sample size for a given site was 132 fragments in 1995 and 169 fragments in 1998. However, both averages are positively skewed by the very large samples taken in Tucson. Median site sample sizes were 96 fragments in 1995 and 91 fragments in 1998. The number of fragments sampled were more evenly distributed geographically in 1995, with the largest sample region (Southwest: Arizona, Texas and Nevada) representing 39.9 percent of fragments collected. The 1998 fragments collected had a much higher concentration in the Southwest, with the same three states accounting for 61.8 percent of the total sample. The locations sampled and number of tires and tire fragments inspected at each location are shown in the table below.

**Table 3: TMC Tire Debris Sample Size  
by Location, 1995 and 1998**

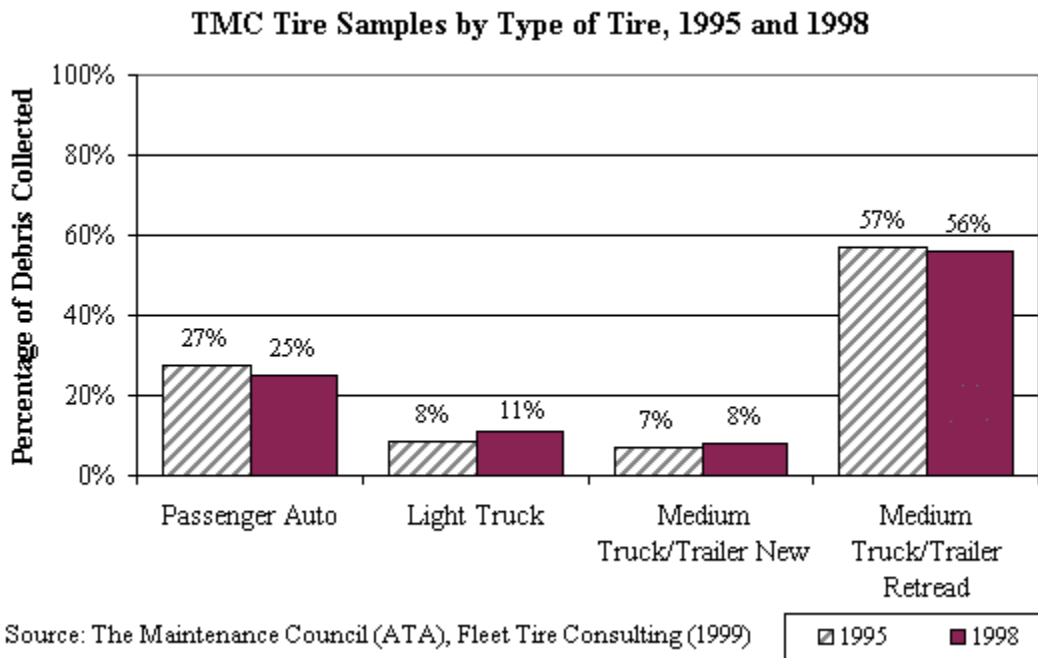
Location	Number of Tires and Tire Fragments	
	1995	1998
Kenley, NC	33	41
Columbia, SC (Truckstop)	27	45
Various, OH (Turnpike)	96	46
Mobile, AL	118	68
Raleigh, NC (TA)	99	71
Pendleton, OR	347	90
Columbia, SC (DOT)	110	91
Raleigh, NC (DOT)	67	105
Milltown, NJ (NJ Turnpike)	37	137
Crosswicks, NJ (NJ Turnpike)	100	147
Las Vegas, NV	68	261
Dallas, TX	87	385
Tucson, AZ	531	713
<b>Totals</b>	<b>1,720</b>	<b>2,200</b>

Source: *Tire Debris Prevention Efforts, 1999*

The proportion of tires collected by type of vehicle in the two TMC studies are shown in Figure 7. Fragments of passenger automobile tires made up 27 percent of the 1995 sample and 25 percent of the fragments collected in 1998. The decline in relative frequency of passenger automobile tire fragments was offset by an increased percentage of light truck tire fragments. Tire debris attributed to light trucks increased from 8 percent of debris collected in 1995 to 11 percent of the debris sample in 1998. This proportional increase is likely an indication of the increasing popularity of pick-up trucks and sport utility vehicles during this period.

The percentage of debris that came from medium truck and trailer tires remained constant in the two samples, representing 64 percent of debris collected in both years. New (OE and replacement) truck tires comprised 8 percent of the sample collected in 1998, up slightly from 7 percent in 1995. The proportion of retreaded medium truck and trailer tires declined slightly, from 57 percent in 1995 to 56 percent in 1998. However, as indicated in the graph, retread tires made up the majority of all tire debris collected in both years sampled.

**Figure 7:**



New and retread medium truck tires collected in both TMC samples were further analyzed in terms of probable cause of failure. Sample fragments were grouped according to several categories of tire failure. Further discussion of causes and symptoms of different types of tire failure can be found in Section IV, page 34. The TMC categories reported in 1995 and 1998 were as follows:

- Belt separations: This category included all fragments for which the primary cause of failure was determined to be the unraveling or separation of tire belting

materials. The most frequent cause of this type of failure is under-inflation. Tire fragments with undecided causes of failure, but exhibiting the symptoms of belt separation, were included in this category.

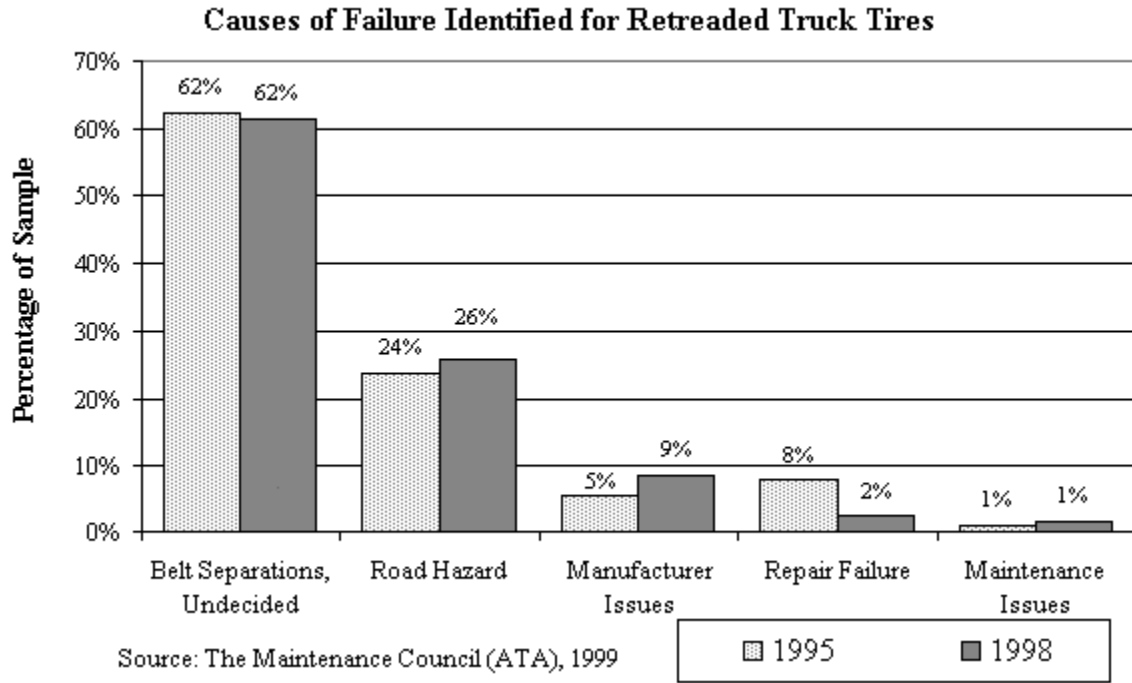
- Road hazard: Fragments classified in this category exhibited signs of stress or breakage imposed by road conditions. These included punctures and tears due to nails and other debris, as well as shocks by such hazards as potholes. Many "road hazard" tire injuries are exacerbated by over-inflation, which renders a tire more susceptible to shock-induced damage.
- Manufacturer issues: This category applied to tire defects due to poor manufacturing processes or lack of appropriate quality controls. For example, failure to properly apply adhesives during retreading can make a tread more likely to separate from the tire casing.
- Repair failure: The "repair failure" category included all tire failures primarily caused by inappropriate or shoddy repairs, as well as repairs for which the original problem was misdiagnosed.
- Maintenance issues: Maintenance issues comprised a variety of conditions, all of which could be attributed to improper attention on the part of equipment operators or fleet maintenance. Examples of this type of problem include running tires on insufficient tread depth, poor axle alignment or uneven wear due to mismatching of tires.

The following charts show the primary causes of failure identified for retread tires (Figure 8) and new tires (Figure 9) in the 1995 and 1998 TMC samples. In both retread and new truck tires sampled, belt separations, typically due to excessive flexing caused by under-inflation, were the cause of the majority of truck and trailer tire failures. Belt separations comprised 62 percent of retread truck tire failures in 1995 and 1998. For new tires, the share of failures attributed to belt separations decreased from 54 percent in 1995 to 49 percent in 1998. The percentage of retread failures due to road hazards increased from 24 percent in the 1995 sample to 26 percent in 1998. A greater percentage of new tire failures was determined to be caused by road hazards. These also increased from 1995 to 1998, from 29 percent to 32 percent of new truck tires sampled.

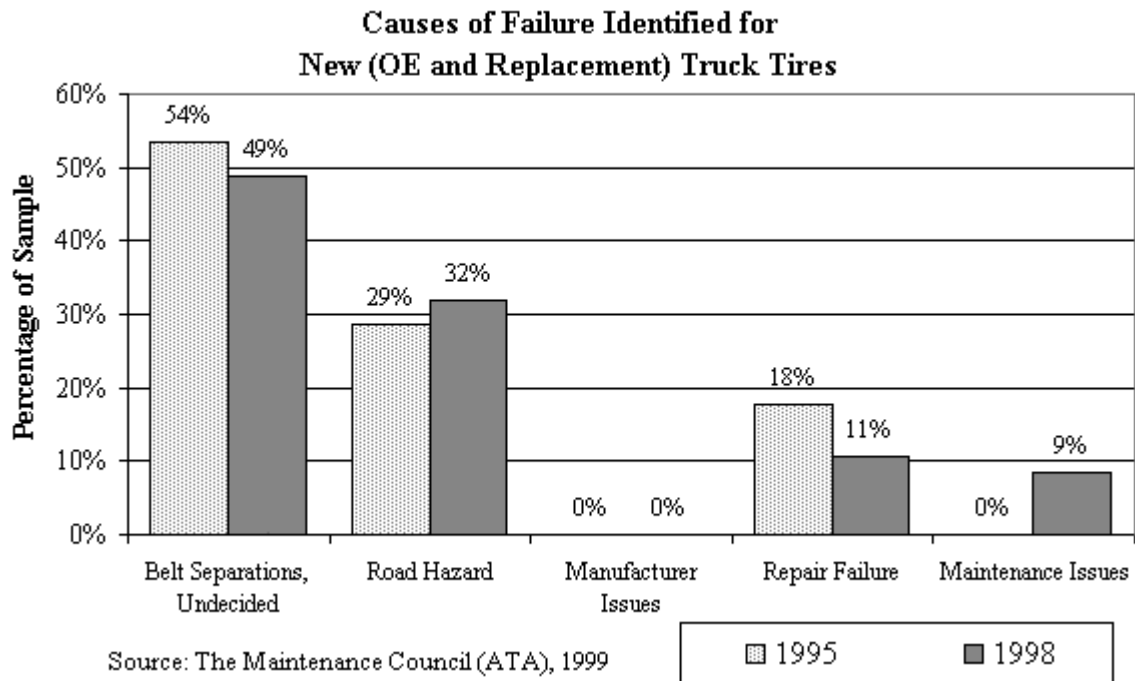
Greater disparities exist in the percentages of tire failure reported for retreads and new tires in the remaining categories. Tire failures due to "manufacturer issues" made up 5 percent of the retread sample in 1995 and 9 percent of the retreads collected in 1998. In contrast, there were no new tire failures identified by TMC in this category in either year. However, repair failures were observed in greater percentages for new tires. Whereas "repair failure" was identified as the cause of 8 percent of retread failures in 1995 and 2 percent of retread failures in 1998, repair failures made up 18 percent and 11 percent of new tire failures in 1995 and 1998 respectively. Finally, "maintenance issues"

represented 1 percent of retread failures in both years sampled, but increased from no observances (0 percent) for new tires in 1995 to 9 percent of new tire failures in 1998.

**Figure 8:**



**Figure 9:**



An analysis of the TMC data presented above leads to several conclusions. First, retreaded truck tires do appear to be over-represented in the sample, comprising more than half of *all* tire debris collected in both years sampled, and averaging 88 percent of truck tire debris collected. While industry representatives are quick to assert that retread failures are not the result of problems specific to retreading as a practice (Bozorth, 1998 and Fisher, 1999), the distribution of tire debris suggests that retreads are more susceptible to failure regardless of the cause.

Furthermore, not only do retreads appear to be over-represented in terms of the distribution of tires, but they are also more likely to have failed due to manufacturer defects. Whether the result of defective materials, improper tread application, or failure to properly inspect the casing prior to retreading, retread truck tires had failure rates due to manufacturer error of 5 percent and 9 percent in 1995 and 1998 respectively. In contrast, no manufacturer defects were observed in the new truck tires sampled in either year.

However, repair failure rates were greater for new truck tires. The greater relative frequency of repair failures in new tires makes sense, given the fact that retread tires must undergo an inspection prior to retreading. This inspection process includes the identification of repairs that might render a tire unsuitable for retreading. In other words, for the most part retread casings in the samples must have been repaired properly up to the point at which they were retreaded.

In the case of both retread and new truck tires, there appears to be a positive trend toward more reliable repairs between 1995 and 1998. However, failures of increasing frequency appear in the "Road hazard" and "Maintenance" categories. While tire debris in particular is often mentioned as a growing problem on the nation's highways, the increased frequency of failures due to road hazards indicates that other debris is impeding traffic flow as well.<sup>8</sup> In addition to the mounting concerns that debris in general appears to pose for tire failure, the TMC data suggest that routine tire maintenance has been increasingly neglected among drivers of all vehicle types. Considering that issues such as under-inflation, balancing and small punctures are the source of most tire failures measured, an increase in tire neglect will exacerbate the tire debris problem considerably.

The results of the TMC studies are compared with tire debris collected in metropolitan Phoenix in Section IV of this report. It should be noted that responsibility for tire debris is not solely a function of the number of vehicles of a given type or the amount of tire sales in a certain class. Variables such as the distribution of traffic in a sample area, prominent vehicle configurations (i.e. axle and tire counts) *within* a class, and the amount of travel measured for different types of vehicles all play a role in making a "reasonable" assessment of the primary sources of tire debris and any disproportionate representation among vehicles or types of tire. These issues are discussed in Section V.

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<sup>8</sup> In light of its inherent flexibility, tire debris generally does not cause the sort of impact-induced failures attributed to road hazards. Therefore, it may be assumed that other sources of (more rigid) debris pose a growing problem as well.

## Traffic Accident Data Analysis

The Arizona Department of Public Safety does not specifically track accidents caused by tire debris on state highways. An effort has been made to approximate the risk to motorists that tire debris can potentially cause by examining accidents caused by any non-fixed object in the roadway. "Non-fixed" objects include, but are not limited to tire shreds, whole tires, other automotive parts, hay bales, boxes and containers, and rocks.<sup>9</sup> Causation was assumed to be the "First Harmful Event" (FHE) recorded by the officer at the scene. Accidents recorded on Arizona state highways from 1991 to 1999 were analyzed, comparing Maricopa County to the state as a whole. A similar assessment was made of the impacts of tire defects (e.g. punctures, excessive tread wear) on accident frequency, utilizing state and county accident counts by "Vehicle Condition Status" for 1991 to 1998.

### Accidents due to roadway debris

Roadway debris does not appear to be a significant causal factor for traffic accidents on state highways for the time period examined. In Maricopa County and in the state as a whole, accidents attributed to non-fixed objects in the roadway represented less than one-tenth of one percent of the total accidents for nearly every period. The average proportion of total accidents statewide that were attributable to roadway debris from 1991 to 1998 was 0.07 percent. The average for Maricopa County was even lower, 0.02 percent. In other words, roadway debris was classified as the cause of only one in every 5,000 traffic accidents on state system highways in Maricopa County from 1991 to 1998.

An average of 66,179 traffic accidents were reported annually on state highways in Maricopa County between 1991 and 1998. Of these, an average of 14 were directly caused by a non-fixed object in the roadway. Statewide, accidents reported on state highways averaged 105,362 annually, with only 79 caused by roadway debris. As shown in Figure 10, the rate of statewide traffic accidents caused by road debris is substantially higher than the rate in Maricopa County, varying from twice as high in 1997 (0.04 percent versus 0.02 percent) to roughly five times as high in 1992 (0.10 percent versus 0.02 percent). While the proportion of total accidents caused by debris remains small in every case, the reasons for these large relative differences between Maricopa County and the state remain unclear. Some possible explanations include the following:

- Traffic congestion: The number of vehicles on a stretch of roadway at a given time is much greater in Maricopa County. The proximity of so many vehicles in a largely urbanized area would likely increase the proportion of accidents caused by collisions between vehicles, which would reduce the incidence of other types of accidents accordingly.
- Roadway dimensions: Highways in urbanized areas provide drivers with more lanes and typically wider roadways. All other conditions being equal, this creates

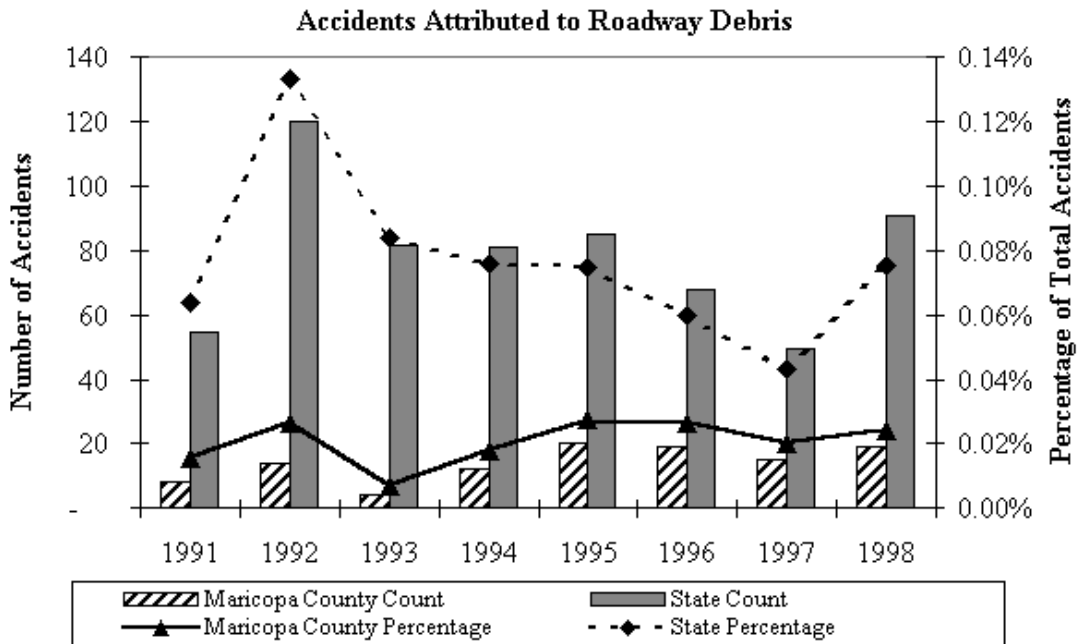
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<sup>9</sup> Note that these data do not include animals in the roadway. Accidents caused by animals are recorded separately.

more opportunity to avoid obstacles in the road. The two-lane, undivided highways found in many parts of the state provide far fewer opportunities for evasive maneuvers.

- **Frequency of maintenance:** The dense urban freeway system in Maricopa County is cleared of debris by maintenance contractors and street cleaners on a regular basis (see page 4). In contrast, the sprawling network of mostly rural roads across the state is not cleared of debris as frequently or as thoroughly, given the high cost of such maintenance and the sheer size of the state highway system.
- **Type of Traffic:** Data collected by the Maintenance Council (TMC) of the American Trucking Association (see page 18) indicates that the majority of tire debris is produced by commercial trucks. Given that these vehicles are also likely to carry larger objects that could fall from trailers on to the road, it is quite possible that the amount and type of debris on the roadway is influenced by the type of traffic in the immediate area. Truck traffic makes up a greater proportion of total traffic on rural routes than urban routes in Arizona.

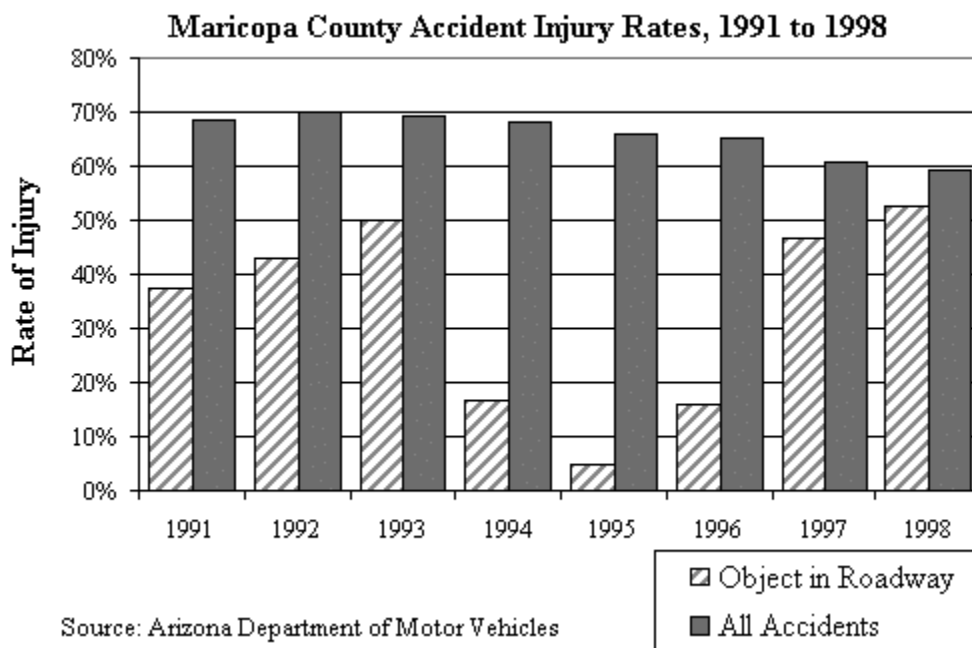
**Figure 10:**



Highway debris is not only a very small contributor to the number of accidents reported in Arizona, but also less likely to cause the most harmful accidents. In general, this observance is true of both injury accidents and fatalities in Maricopa County and statewide. The charts on the following pages show rates of injury and fatality for debris-related accidents. Note that in all cases, only accidents reported to the authorities could be measured. While it is highly unlikely that accidents involving injuries or fatalities would go unreported, the total number of accidents may be somewhat understated.

As shown in Figure 11, rates of injury for Maricopa County accidents caused by road debris fell below the injury rates for all Maricopa County accidents in every year measured. While the rate of injury for all Maricopa County accidents has shown a general decline since 1991, with the injury rate reported falling from 70 percent of accidents in 1991 to about 60 percent in 1998, the percentage of debris-related accidents that resulted in injuries has shown considerably greater variation.<sup>10</sup> After climbing from 1991 to 1993, injury rates for debris-caused accidents fell sharply and remained below 20 percent through 1996. However, the rate of injury for debris-caused accidents has shown a marked increase in Maricopa County in the last two years measured, nearly reaching the injury rate reported for all Maricopa County accidents in 1998.

**Figure 11:**

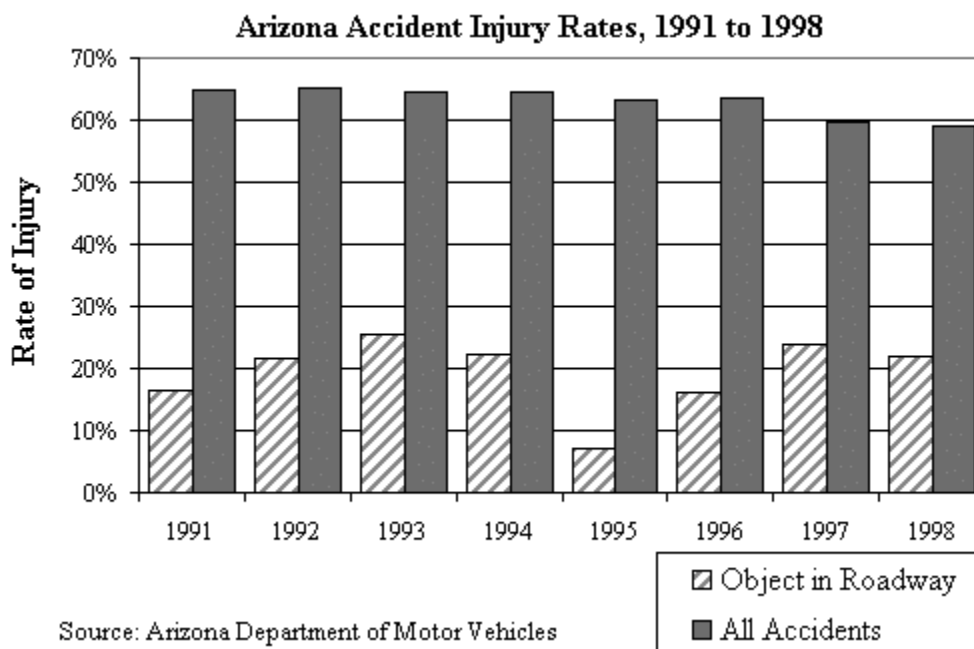


Rates of injury for all accidents reported statewide show a similar pattern as those measured in Maricopa County, with a 65 percent injury rate in 1991 declining to roughly 60 percent by 1998. In the case of debris-related accidents statewide, a similar pattern of injury rates is also observed, with rising rates of debris-caused injuries from 1991 to 1993, a marked decline for the following three years, and a return to greater injury rates in 1997 and 1998. However, statewide injury rates for debris-caused accidents are generally lower than the corresponding rates of injury observed in Maricopa County. The highest rate of injury measured for debris-caused accidents statewide was approximately 25 percent in 1993, significantly lower than the injury rates of 50 percent or more measured for several years of debris-caused accidents in Maricopa County.

<sup>10</sup> It is likely that much of the variation in injury rates observed for accidents caused by road debris is the result of the relatively small number of these accidents reported.



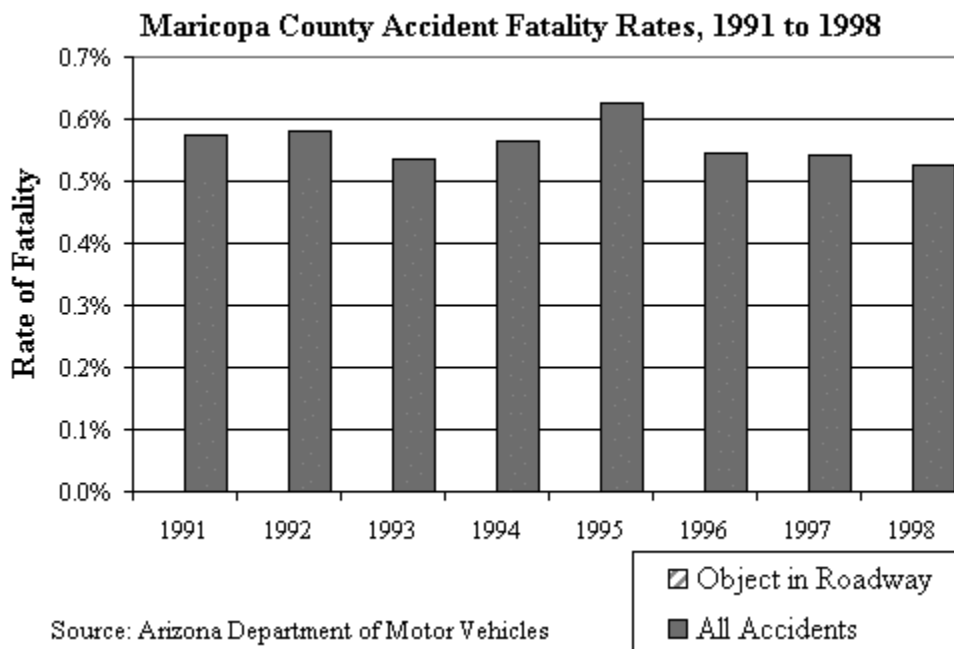
Figure 12:



Highway debris generally poses a greater risk of causing injurious accidents in Maricopa County than statewide. In four of the eight full years measured (1991 to 1998), the relative risk of injury in Maricopa County accidents caused by highway debris was roughly double the risk statewide. On average, the relative risk of injury in debris-caused accidents in Maricopa County was 55 percent greater than statewide. In comparison, Maricopa County was only 3 percent more dangerous than the state as a whole when all types of traffic accidents were considered.

An assessment of relative risk based on the number of injuries sustained in accidents is subject to considerable variation. Injuries can range from minor cuts and bruises to major, life-threatening traumas requiring extensive hospital care. As a more robust alternative measure, the rate of fatality for debris-caused accidents and all automobile accidents in Maricopa County and the state has been prepared. Figure 13 shows the fatality rates of Maricopa County automobile accidents from 1991 to 1998. Fatalities generally ranged from 0.5 to 0.6 percent of all Maricopa County accidents reported during this period, with a slightly higher rate measured in 1995. In comparison, there were *no* fatalities reported for Maricopa County accidents attributed to roadway debris between 1991 and 1998.

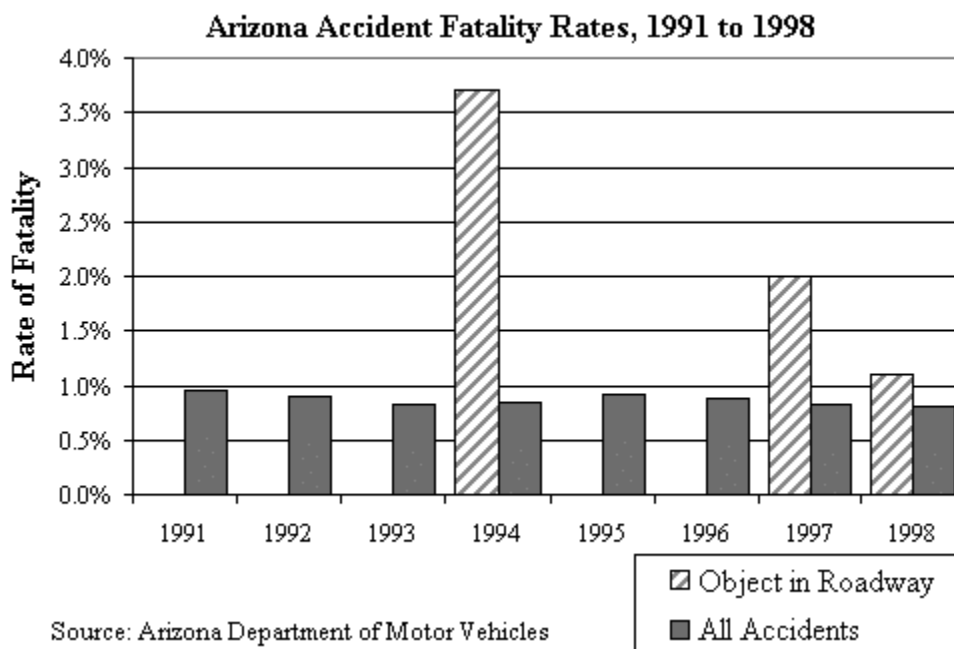
**Figure 13:**



The fatality rate for all Arizona accidents between 1991 and 1998, shown in Figure 14, remained relatively constant at just under 1.0 percent, with the highest percentages reported in 1991 and 1995. Statewide, accidents caused by roadway debris exhibited a wide range of fluctuation in years with measurable occurrences. While there were no fatalities reported statewide for debris-caused accidents in most years measured, when fatalities due to debris did occur, their rates of incidence were generally higher than the overall fatality rate. The highest debris-caused accident fatality rate was approximately 3.7 percent, measured in 1994. Fatal accidents caused by debris were also recorded in 1997 and 1998, with fatality rates in these years of 2.0 percent and 1.2 percent respectively.

Whereas no fatalities in Maricopa County were attributable to debris-caused accidents over the period measured, the fatality rate for Arizona accidents caused by debris was as high as 3.7 percent in 1994. Despite the occasional spikes in state fatality rates shown in the chart below, the high fatality rates (relative to the all accidents case) measured in 1994, 1997 and 1998 do not indicate high *frequencies* of death in debris-caused accidents for those years. A total of 5 fatalities were the result of debris-related accidents over the entire period from 1991 to 1998. The occasional high rates of fatality are as much a factor of the small total number of debris-caused accidents. For example, the 3.7 percent fatality rate measured in 1994 corresponds to a total of three deaths reported. The spikes in Arizona fatality rates for debris-caused accidents represent not only a very small portion of total accident fatalities, but also appear to be anomalistic in terms of overall accident patterns.

Figure 14:



An assessment of traffic accidents reported on state system highways indicates that, as the cause of less than one-tenth of one-percent of the accidents, roadway debris is not a significant safety hazard. While tire and other debris may be of concern as eyesores and environmental problems, debris in general does not pose a substantial risk for drivers in Maricopa County or across the state. However, should efforts be made to reduce the amount of tire debris on Arizona roadways, the relative frequency of accidents and magnitude of risk posed by debris can serve as useful guidelines for targeted cleanup efforts. Specifically, the proportion of traffic accidents caused by roadway debris across the state is much greater than the proportion reported in Maricopa County. However, accidents caused by debris tend to be more injurious in Maricopa County than statewide, posing a greater relative risk to highway users.

The relative importance of these variables might be of use in determining the most appropriate target(s) for debris cleanup efforts. It should also be noted that some degree of convergence has occurred between the state and Maricopa County proportions of total accidents attributable to road debris. The state proportion has generally declined since 1991, with the notable exceptions of 1992 and 1998. In contrast, the role of debris in accident causation has increased slightly in Maricopa County since 1991.

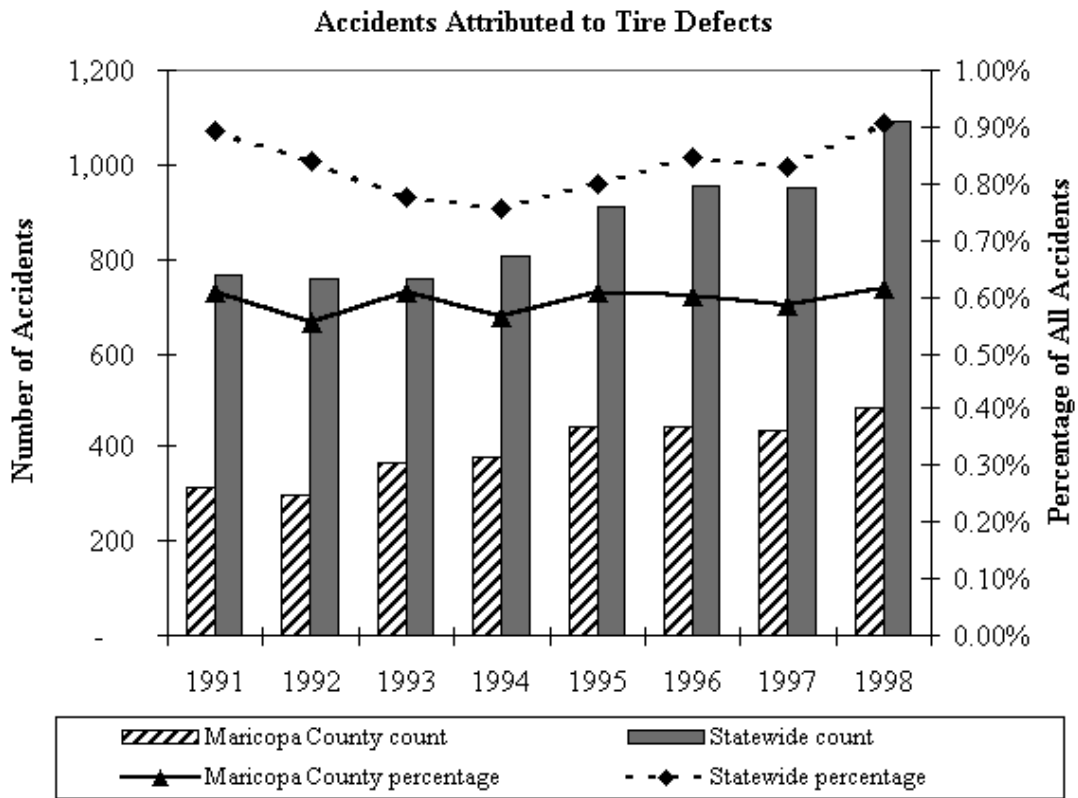
The general impact of highway debris on traffic accidents in Arizona serves as a useful proxy for the potential impact that increased amounts of tire debris could have on traffic safety. A more specific analysis has also been prepared to demonstrate the frequency of traffic accidents that were related to tire defects on the vehicles involved. As previously noted, the most common causes of tire failure identified in tire debris samples taken by

TMC were punctures and under-inflation (see page 19), factors that not only contribute to the amount of debris on the roadway, but also represent an operating hazard for drivers.

Accidents due to tire defects

On average, tire defects were causal factors in approximately 400 accidents per year in Maricopa County from 1991 to 1998. Statewide, traffic accidents involving vehicles with tire defects averaged 875 annually over the same period. As in the case of accidents attributed to highway debris, the percentage of accidents for which tire defects were reported has historically been quite small. The Maricopa County percentage of total accidents is lower than the state percentage, averaging 0.6 percent and 0.8 percent respectively. The percentage of Maricopa County accidents attributed to tire defects remained relatively constant from 1991 to 1998. The statewide percentage has exhibited more fluctuation, declining steadily from 1991 to 1994 and then increasing in a similar manner.

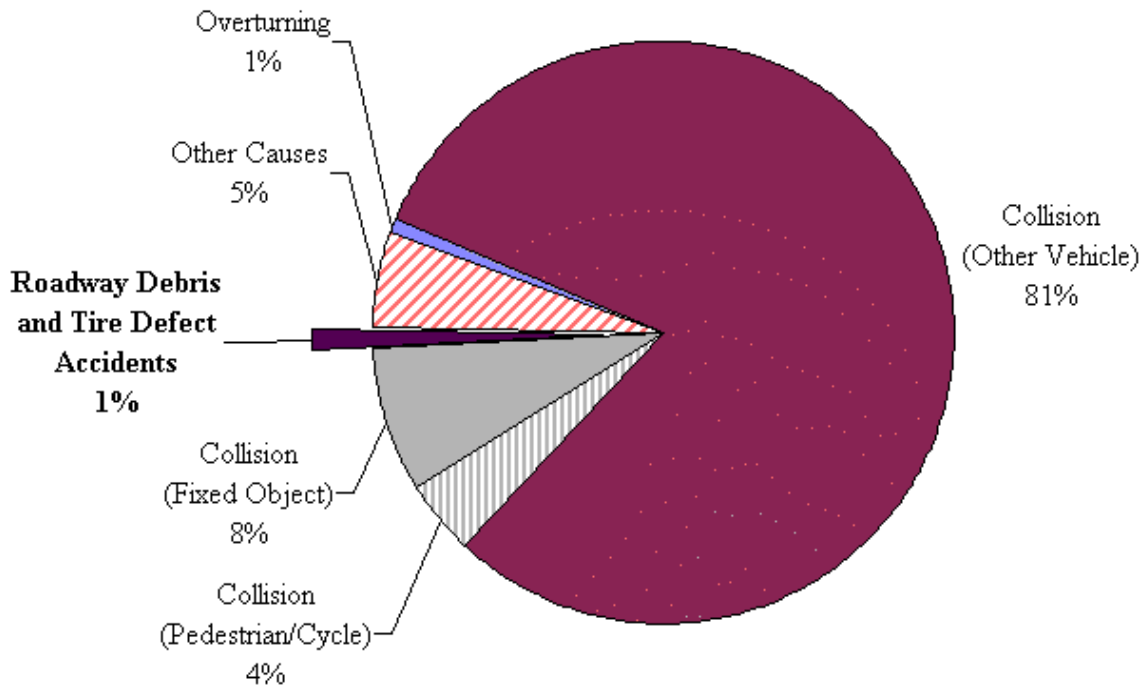
**Figure 15:**



The total number of accidents related to tire defects has grown nearly every year in both the statewide and Maricopa County cases. However, these growth patterns are representative of broader growth trends in traffic as the Arizona population continues to increase. Overall, as in the case of accidents caused by roadway debris, tire defects appear to have a negligible impact on the frequency of traffic accidents at both the

Maricopa County and state levels. The minimal influence of accidents due to both tire defects and roadway debris relative to other causes of traffic accidents in Arizona is shown in Figure 16. Even assuming that tire defect accidents are completely unrelated to debris-caused accidents,<sup>11</sup> both categories combined account for only 1 percent of Arizona traffic accidents reported from 1991 to 1998. In comparison, collisions with other vehicles comprised 81 percent of accidents reported over this period, and collisions with fixed objects such as median barriers and trees made up 8 percent of accidents reported.

**Figure 16: Average Share of Arizona Traffic Accidents by Cause, 1991 to 1998**



Accident rates, injuries and fatalities due to road debris and tire defects in both Maricopa County and Arizona are generally lower than rates reported at the national level. An estimated 250,000 accidents resulting from under-inflated tires occurred in 1996, representing 3.6 percent of traffic accidents reported (Deierlein, 1996). Collisions with unclassified debris (including tire debris) represented 0.4 percent of all accidents reported nationally in 1996. National fatality and injury rates for accidents caused by unclassified roadway debris in 1996 were 0.7 percent and 0.3 percent respectively (NHTSA, 1996). Despite a slightly larger share of accidents nationwide, highway debris and tire defects do not appear to pose a significant safety risk at the national level either.

<sup>11</sup> This scenario is unlikely, as debris in the roadway is more apt to induce such tire defects as punctures and tears. However, roadway debris and tire defects have been aggregated in Figure 17 simply to illustrate the small impact that *both* of these causes have on the total number of Arizona traffic accidents.

## IV. Metropolitan Phoenix Tire Samples

Tire samples were taken from ADOT maintenance yards in the Phoenix metropolitan area. Whole tires and tire fragments sampled were identified in terms of type of tire (e.g. passenger automobile, light truck, or medium truck), new or retread tire, and probable cause of failure. In all cases, the primary focus of this research was to determine whether any particular type of tire or cause of failure was disproportionately represented among tire debris found on state highways in the Phoenix area.

### Sampling Methods

All tire debris is separated from other road debris at ADOT's Central (Durango), Mesa and East Valley (Tempe) maintenance yards. The Agua Fria maintenance yard separates whole tires only. While the debris collected by ADOT personnel and stored at these yards does not comprise the majority of debris collected on metropolitan Phoenix state highways, the broad coverage of the ADOT maintenance districts and regular collection of roadside debris suggests that tire remnants stored at ADOT maintenance yards provide a representative sample of tire debris generated in metropolitan Phoenix.

Debris samples were collected from all four maintenance yards in September, 1999. Because the frequency of trips to local landfills for disposal of debris varies by yard, the "age" of each debris sample varied considerably. For example, the Durango yard sample consisted of debris that had been collected no more than two weeks prior to sampling, whereas the debris sample collected at the East Valley yard had been accumulated over approximately six or seven months. While the relative "age" of debris sampled from each yard was not expected to influence the distribution of fragments by vehicle type, the "younger" fragments were expected to show a higher incidence of failure related to heat stress (e.g. belt separations).<sup>12</sup>

Whole tires and fragments were sampled using a front loader whenever possible in order to eliminate selectivity from the collection process. In the case of large debris piles, random sections were selected based on a coin-flip or the roll of a die and subsequently sampled by loader. This methodology was used as described for the Mesa and East Valley maintenance yards. Because the Durango yard was sampled shortly after a landfill run, a limited collection of debris had been accumulated in the following two week period. For this reason, the Durango debris was taken in its entirety, requiring no sample selection.

The Agua Fria yard presented a problem in that tire fragments had not been separated from general road debris. While whole tires at the Agua Fria facility were collected via front loader, sample fragments were collected from the general debris by hand. All fragments visible on the surface of the debris pile were collected when possible.

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<sup>12</sup> This assumption was based on the influence of ambient air temperature during the summer months. However, it is by no means certain that tire fragments collected recently also failed recently; given the length of state highways in each territory and the limited amount of time that can be dedicated to scheduled debris pick-up, some non-hazardous fragments can remain at the side of the road for extended periods.

However, in many cases, fragments were out of reach or could not be dislodged by hand. The collection of debris at the Agua Fria yard can not therefore be considered a random sample. While the results of the Agua Fria sample have been compared to the other samples in metro Phoenix to determine their similarity to randomly collected fragments<sup>13</sup>, samples taken in the future should request separation of debris as it is collected at the Agua Fria yard for a specified period of time.

### **Limitations of this Sample Method**

In addition to the problems posed by the distribution of debris at the Agua Fria yard, the samples collected for this study are subject to a number of limitations. The data collected were stratified based on the desire to collect from all four yards, which is believed to comprise a representative sample of road conditions valleywide. However, a conscious effort was also made to collect samples of both whole tires and tire fragments at the yards that separated these types of debris (Durango, Agua Fria and Mesa). For the Agua Fria and Mesa yards, these sub-level samples by type can not be aggregated to determine the percentages of whole tires versus fragments because both types of debris were collected based on volume rather than quantity.<sup>14</sup> Therefore, any assessment of the proportional distributions of whole tires and fragments can only be made from the Durango sample (which represents a two-week collection period *in its entirety*) and the Tempe sample (in which fragments and whole tires had not been separated prior to collection).

Secondly, the collection of debris solely from ADOT maintenance yards may skew the distribution of tire debris to some extent. This observation is based on the fact that only a small fraction of ADOT maintenance personnel-hours are spent on scheduled debris collection. Unlike the debris collected by contractors with regular debris-removal schedules, some of the pieces collected by ADOT maintenance workers are removed from the roadways due to complaints or requests from other sources. It seems logical to assume that larger pieces of debris (such as truck tire fragments) are more likely to pose a hazard to motorists or are simply more likely to be noticed. Thus, it follows that these larger fragments are more likely to be called in for unscheduled removal and therefore more likely to appear in the samples taken from maintenance yards than in the entire population of metro Phoenix roadway debris.

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<sup>13</sup> Other factors such as local road conditions and the distribution of traffic can also play a role in sample distribution by type and cause of failure. Even in the case of high similarity between the Agua Fria sample and the other metro area samples, a definitive conclusion regarding the applicability of the Agua Fria sample can not be made.

<sup>14</sup> Yards that separated whole tires from fragments tended to have far greater quantities of fragments than whole tires. However, whole tires have a greater volume of displacement (i.e. take up more space). Both yards were sampled by filling a one-ton pick-up with debris twice; the first time with whole tires and the second with tire fragments. This procedure was followed regardless of the apparent frequency of debris in the separated piles. Despite the generally small quantities of whole tires at each yard, an entire pick-up load was required for whole tires due to the amount of space required to transport them. Thus a greater percentage of the total whole tire count at each yard was collected relative to the percentage of fragments. This procedure was followed regardless of the apparent frequency of debris in the separated piles.

## Tire Identification Methods

The following sections provide a brief overview of the means of identifying types of tires and primary cause(s) of failure. A discussion of tire manufacturing and the essential components of a radial tire is included in Appendix A of this report. Appendix B provides additional detail on the most common reasons for tire failure, including such variables as weather conditions and trends in the automobile and trucking industries.

This section is not a definitive discussion of the methods for identifying types of tires and causes of failure, but rather an introduction to the practice. The actual identification of metropolitan Phoenix tire debris was conducted by tire industry professionals. The information below serves only as a guideline to the various factors that make up an accurate tire analysis.

### Identifying Types of Tires

The identification of tires by type can be further subdivided into two separate processes: identification by type of vehicle and identification of retread versus original tires.

- Vehicle type: Identification of tire fragments by vehicle type is generally reliant on variables such as tread width, wheel diameter, and tread pattern. Previous studies have divided tire samples into three segments: passenger auto (PS), light truck (LT) and medium/heavy truck (TB) tires. In the interest of comparability, the same approach was undertaken for this study. Large truck tires are generally the easiest to classify, given the larger wheels, wider tires and distinctive tread patterns common to many of these vehicles. For example, the rib pattern that often suggests truck trailer usage is distinct from most passenger auto and light truck tread patterns.

In some cases, the type of tire does not necessarily reflect the type of vehicle. This is especially the case for passenger autos and light trucks, for which some degree of tire interchangeability exists. While wheel diameters tend to be larger for light trucks (e.g. 15 inches to 17 inches) than for passenger autos (e.g. 13 inches to 17 inches), some amount of overlap occurs. Tread patterns and width provide a more definitive classification, though particularly in the case of the former, a high degree of familiarity with various brands and configurations is required.

- New versus retreaded tires: A common assumption among motorists is that the truck tire fragments found on highways are the result of retread tire failure. However, it can not simply be assumed that tread and ply wire fragments found on the road are retread fragments, nor that these fragments are due to defects in the retreading process. Identification of retread versus original truck tires involves several inspection techniques, depending on the expertise of the inspector. Retreads commonly exhibit a visible layer in the tire sidewall, a slight groove or protrusion where the new tread rubber was applied. However, many truck tires have similar sidewall grooves that are not necessarily distinguishable to the lay observer. Larger retread companies (e.g. Bandag, Oliver) stamp their tread rubber with a corporate



logo or other identification, providing a more reliable means of identifying retread tires. Finally, because retreaders often offer application-specific tread patterns, a skilled examiner can usually identify more common retread tires through tread pattern analysis.

### Identifying Primary Causes of Tire Failure

The most frequent distinct causes of tire failure and their respective means of identification are listed below. Note that these categories are aggregates of more specific causes of failure. The variety of specific causes identified in the metro Phoenix tire sample can be found by individual listing in Appendix B (page 57), along with additional detail of the specific causes that were included in each aggregate category.

- Under-inflation (belt separation): Tire failure due to belt separation is generally an indication of under-inflation. Tires run at lower pressures are more susceptible to heat and friction stress. Belt separations commonly result in shredded tire fragments, as the whole tire can not be held together for long once the casing has separated. Tread rubber fragments will still be attached to pieces of the tire casing, which can be identified by the loose wires projecting from the fragment. These wires are part of the casing of radial tires, and become exposed as the belts separate and fragments are torn from the tire. Retreaded tires will show the same pattern of damage, with casing materials and wires protruding from the fragment.
- Road hazard: Tire failure due to punctures or tears is usually the simplest to identify. Tires damaged in such a way will exhibit holes in the affected area. However, it should be noted that susceptibility to debris-induced stress is magnified by over-inflation, another common maintenance problem. Generally, tears in the tire surface that were caused by impact with road debris will cut at an angle to the radial plies. For example, whereas tires run under-inflated will separate or split *along* the radial plies, impact-related tears will cut the individual plies. Tread damage and reinforcing ply damage will also exhibit a relatively clean or smooth cut, usually at an angle juxtaposed to the tread or ply configuration.
- Repair failure: Repair failure refers to failure at the site of a previously performed tire repair. For example, improper application of adhesives or patching materials can lead to an unstable patch that separates from the tire casing under stress. Most repairs can be readily identified from whole tires sampled, as the patched are visible inside the tire casing. However, identification of a repair failure on a tire fragment requires the actual fragment that was repaired. Many blow-outs due to punctures and repair failures appear as belt separations when the initially damaged tire remnant is not part of the sample.
- Manufacturer defects: Manufacturer defects refer to errors made in the tire construction process that subsequently induce tire failure. Air bubbles in tire casings and weak adhesive bonds from improper heating of retreaded tires are examples of

these types of defects. Often tires will lose tread materials with little other damage sustained. This is particularly common in the case of retreads. Another "manufacturer" defect unique to retread tires is the failure to properly identify holes or previous repairs prior to retreading. These particular holes will tend to leave an impression in the retread material, and will usually show rust in the belt wires from moisture that was not blocked by an appropriate repair. Except for the specific case of tread separation, many of these defects are also difficult to identify, particularly in the case of blow-outs, in which the defective tire materials may not be included in the sample.

- **Other maintenance:** Maintenance issues such as irregular and excessive tread wear can usually be identified from a tire fragment. In the former case, the tread pattern will exhibit uneven depth or beveled tread lugs on one or both sides or throughout the tread pattern, depending on the type of wear. These types of wear are indicators of mismatched tires, poor alignment or tracking, or overloading. Excessive tread wear is identifiable based on the depth of treads in a section or throughout the tire. Excessive wear generally refers to tread depths of  $\frac{2}{32}$  inch or less. Many tires exhibiting this problem will have been worn through to the belt, a condition often caused by brake lock.

Other symptoms of maintenance-related failure include bead damage and misapplication. The former can be identified by inspection of the bead area for gouges or deformation, which are usually the result of improper tire mounting techniques. Misapplication refers to the mounting of a tire on a rim for which the tire was not intended. Casing deformation and bulges, particularly in the bead and sidewall areas, are indicators of this type of damage. Some tires will also exhibit irregular wear due to misapplication (e.g. grooves with rust on sidewalls from contact with fixed sections of the vehicle were observed on several tires in the Phoenix sample).

## **Metro Phoenix Sample Statistics**

All of the metro Phoenix samples contained tire fragments that were too small to be identified reliably. As a general rule, passenger auto and light truck tire fragments were excluded from the identifiable sample if shorter than 24 inches. Medium/heavy truck tire fragments were excluded if shorter than 48 inches. These minimum measurements were used for two reasons. First, many causes of failure are location-specific, and a longer piece of tread increases the reliability of the failure diagnosis. Second, tires that separate into multiple pieces will generally be found together. Using larger pieces reduces the likelihood of double-counting a particular tire fragment.

Counts of all tires and fragments collected at each location, as well as the number of identifiable pieces by location are shown in the table below. As indicated in the table, roughly half of the pieces collected at each location could be identified according to the measurement criteria. Out of a total of 859 tires and fragments collected, 495 (57.9

percent) could be identified. The greatest success in terms of identification was the Agua Fria sample, for which 89.6 percent of fragments could be identified. However, this result is influenced by the Agua Fria collection methods (page 32). Larger fragments were more visible in the Agua Fria debris, and thus were more likely to be collected.

**Table 4: Sample Size by ADOT Maintenance Yard**

<b>Maintenance Yard</b>	<b>ADOT Org.</b>	<b>Tires Collected</b>	<b>Tires Identified</b>	<b>Estimated Sample Error<sup>1</sup></b>
Agua Fria	7871	134	120	+/- 8.9%
East Metro	7873	267	140	+/- 8.3%
Mesa	7874	211	125	+/- 8.8%
Durango	7875	247	110	+/- 9.3%
<b>Totals</b>		<b>859</b>	<b>495</b>	+/- 4.4%

Note: 1. All errors estimated at 95% confidence level assuming distributions of equal proportion.

Because the actual data are not equally distributed, the estimates above are conservative.

Source: "Sample Size Calculator," Creative Research Systems, 1998.

Identifiable sample sizes ranged from 110 pieces to 140 pieces, with a mean sample size of 124 pieces and a median size of 122.5 pieces. Sample errors are shown in Table 4 for identifiable pieces from each yard, as well as the overall sample. Simply defined, sample error is the difference between the results obtained from a sample and the results that would occur in the entire population. The size of a sample error will vary with the size of a sample and the distribution of values in the sample. In all likelihood, because the distribution of fragments by type and cause is not even, the actual sample error is slightly lower.

Sample errors shown in Table 4 represent the maximum range of error at the 95 percent level of confidence for the samples shown. For example, if the total sample consists of 25 percent light truck tires, it is 95 percent certain that the entire tire debris population is comprised of 20.6 percent to 29.4 percent light truck tires. Sample errors range from +/- 8.3 percent to +/- 9.3 percent for the individual samples and +/- 4.4 percent for the total identifiable sample. Because of the small sample sizes and large sample error margins for individual yards, the most reliable comparisons of tires by type and cause of failure use the aggregated sample results.

## Metro Phoenix Sample Detail

The following section provides summary tables and charts tabulating the Phoenix debris sample according to several variables. When applicable, the data are aggregated according to broad failure category. Specific detail for each observation are provided in Appendix B.

Table 5 presents debris counts according to type of tire for each maintenance yard location. As shown in Table 5, the distribution of fragments by tire type does appear to be influenced by location. The Mesa and Durango yards had lower frequencies of large truck tires and higher frequencies of passenger auto tires than the East Metro and Agua Fria yards. The greater percentages of truck tire fragments in the Agua Fria territory (42 percent) and the East Metro territory (38 percent) are likely due to the influence of Interstate 10 traffic on both of these locations. In all cases, the percentage of tire debris attributable to passenger autos and light trucks is higher than the share for these vehicle types measured in the TMC samples. This is also likely to be a function of location, as the TMC samples were taken outside of major metropolitan areas. In total, passenger auto tires made up 43 percent of the metro Phoenix debris sample. Light truck tires represented 26 percent of the total sample, and medium/heavy truck tires represented 31 percent of debris collected.<sup>15</sup>

**Table 5: Distribution of Fragments by Location and Tire Type**

Maintenance Yard	Passenger Auto		Light Truck		Med/Hvy Truck	
	Count	Percent	Count	Percent	Count	Percent
Agua Fria 7871	41	34%	29	24%	50	42%
Durango 7875	51	46%	37	34%	22	20%
East Metro 7873	49	35%	38	27%	53	38%
Mesa 7874	72	58%	23	18%	30	24%
Totals	213	43%	127	26%	155	31%

The observed distribution of retread tires was closely related to the share of medium/heavy truck tires collected at each sample location. Given that all but one of the retread fragments collected were from medium/heavy trucks, this result was expected. The greatest share of original tires (91 percent) was observed in the Durango sample, which corresponds to the low share of large truck tires collected at this location. The Agua Fria and East Metro samples had the largest shares of truck traffic and correspondingly high percentages of retread tires. However, whereas the Agua Fria sample had the largest percentage of large truck tires, a greater relative frequency of retread tires was measured at the East Metro yard. Overall, original tires represented 78 percent of debris collected and retreads comprised 22 percent.

<sup>15</sup> Note that these percentages refer to counts only, not volume of debris. See Appendix B for measurements of individual tire fragments. Fragment weight was not measured a part of this study.

**Table 6: Distribution of Retread and Original Tires**

Maintenance Yard	Original		Retread <sup>1</sup>	
	Count	Yard Percentage	Count	Yard Percentage
Agua Fria 7871	86	72%	34	28%
Durango 7875	100	91%	10	9%
East Metro 7873	99	71%	41	29%
Mesa 7874	99	79%	26	21%
Totals	384	78%	111	22%

Note: With the exception of 1 passenger auto tire, all retreads were medium/heavy truck. Two complete original med./hvy. truck tires had been retreaded and are counted as retreads in the failure analysis tables and discussion.

Proportional causes of tire failure according to sample location are shown in Table 7. In most cases, noticeable fluctuation does not occur. However, a few exceptions provide grounds for speculation. The relatively high frequency of failures due to "Maintenance issues" observed in the Durango and Agua Fria samples suggest that operator behavior may vary according to region of the valley. Because the distribution of tires by type varies considerably between these two locations, no conclusion can be drawn about this category by vehicle type. However, both of these yards service state highways in the western region of the metropolitan area.

Failures caused by road hazards also tend to increase from east to west across metropolitan Phoenix. Failures due to road hazards comprised 14 percent of tire failures identified in the Mesa sample, which covers the easternmost highways in the metro area. This percentage increased to 27 percent of the westernmost sample (Agua Fria). While debris on the road can vary considerably according to traffic patterns and types of terrain and economic activity in the surrounding area, the pattern of these failures provides some indication of regions that could be potential targets for additional debris removal.<sup>16</sup>

**Table 7: Cause of Failure by Location**

Location	Maint. Issue	Manuf. Issue	Other	Road Hazard	Run Under-Inflated	Total
Agua Fria 7871	7%	9%	2%	27%	56%	100%
Durango 7875	9%	6%	5%	21%	59%	100%
East Metro 7873	3%	15%	3%	18%	61%	100%
Mesa 7874	2%	11%	0%	14%	73%	100%
Totals	5%	11%	2%	20%	62%	100%

<sup>16</sup> Because the sample errors calculated for individual locations are quite high, it is entirely possible that the location-based fluctuations for a given cause of failure shown in Table 7 are not indicative of population trends. However, the possibility raised by the road hazard distributions does warrant future attention. If a more reliable (e.g. larger) sample indicates a similar pattern, added maintenance efforts to remove road hazards in "problem" regions could have a beneficial impact on tire failures in the metro area.

Table 8 presents aggregated causes of failure (see Appendix B) by type of tire. As in the case of the TMC samples discussed in Section III, under-inflation was the most frequently observed cause of failure in every tire category in the metro Phoenix sample, accounting for a total of 309 cases. Failures due to "Road hazards" and "Manufacturer issues" were the next most frequent categories, with 97 and 53 observances respectively.

**Table 8: Cause of Failure by Type of Tire**

Cause of Failure	Passenger Auto	Light Truck	Medium/Heavy Truck			Total (All Tires)
	Total <sup>2</sup>	Total	Original	Retread <sup>3</sup>	Total	
Run under-inflated <sup>1</sup>	127	82	30	70	100	309
Road hazard	43	30	11	13	24	97
Other	8	2	0	1	1	11
Manufacture issue	19	7	0	27	27	53
Maintenance issue	16	6	2	1	3	25
Totals	213	127	43	112	155	495

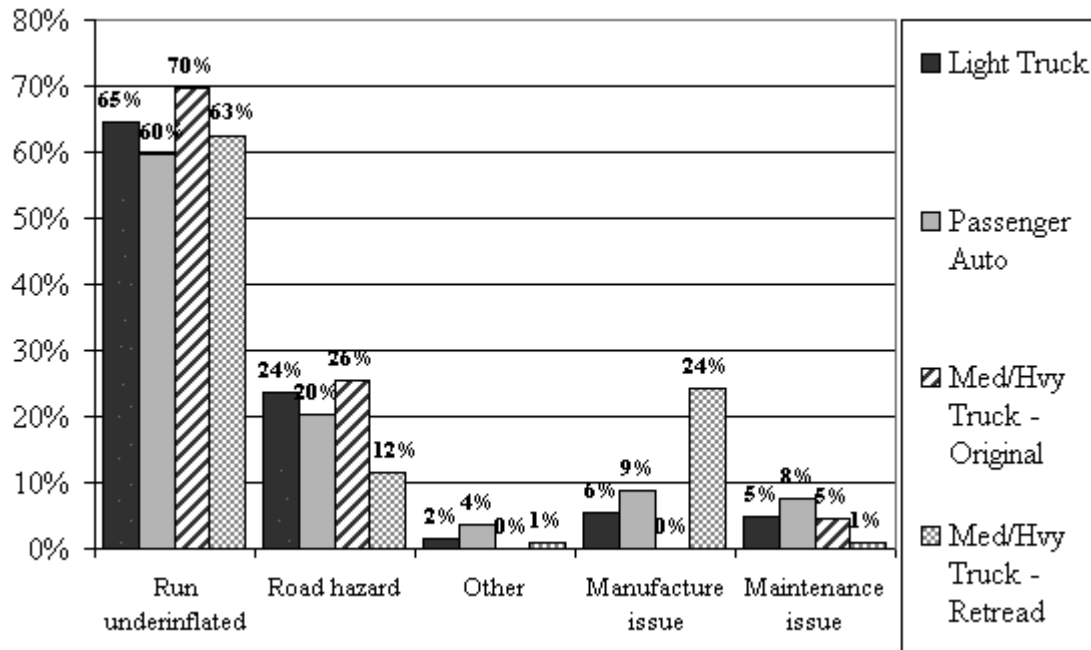
Note: 1. Nail holes and other punctures classified as "Run under-inflated" 2. One passenger auto tire was a retread, with failure caused by running under-inflated. 3. Includes two complete tires.

The percentage distributions of causes of failure by tire type are shown in Figure 17. As indicated in the chart, under-inflation was not only the most common cause of failure, but also the most *consistently* distributed among tire types. Failures caused by running tires under-inflated ranged from 60 percent (passenger autos) to 70 percent (large truck - original) of all failures in each subcategory. Other causes of failure exhibited greater variation. "Road hazards" were the cause of failure for 20 percent to 26 percent of passenger auto, light truck and original medium truck tires, but represented only 12 percent of retread failures. In contrast, "Manufacturer issues" were more highly represented in the sample of retread tires (24 percent) than in any other tire category. Medium/heavy truck retreads had the lowest percentage of failures due to "Maintenance issues" and "Other/unidentified" causes (2 percent combined), while passenger auto tires had the highest percentage of failures (12 percent combined) due to these causes.

"Manufacturer issues" (i.e. defects) occurred in the sample among all types of tires identified. Failures due to these defects occurred most often in medium/heavy truck retreads and passenger autos tires. Failures due to "Manufacturer issues" represented 24 percent of retread failures and 9 percent of passenger auto failures. No failures caused by "Manufacturer issues" were observed for original medium/heavy truck tires.<sup>17</sup> Light truck tires failed due to "Manufacturer issues" in 6 percent of cases sampled. Table 9 presents the distribution of the various causes of failure in the "Manufacturer issues" category by tire type.

<sup>17</sup> Note that due to the small count of original medium/heavy truck tires, the percentage of failure in any category for tires of this type is subject to considerable sample error. The actual percentage of failure due to a particular cause in the original medium/heavy truck tire population could deviate considerably from the sample percentage.

**Figure 17: Cause of Tire Failure by Type of Tire**



A more detailed analysis of "Manufacturer issues" is provided in Table 9. Each of the various causes of failure in the "Manufacturer issues" category are summarized according to percentage of *all* tire failures for a particular tire type. The totals in the bottom row represent the percentage of failures due to "Manufacturer issues" for each tire type. As shown in the table, tread failures due to belt lift/separation and tread lift/separation made up the majority of light truck and passenger auto tire failures due to manufacturer defects. In contrast, bond failures and missed nail holes made up the largest "Manufacturer issues" categories for retread tires.

**Table 9: Manufacturer Issues Detail  
(Percentage of All Tire Failures by Type)**

Manufacturer Issues	Tires by Type			Truck Tire Detail	
	Light Truck	Passenger Auto	Medium/ Heavy Truck	Original	Retread
Bond Failure	0%	0%	6%	0%	9%
Missed Nail Hole	0%	0%	7%	0%	10%
Repair Failure	1%	0%	4%	0%	5%
Tread: Belt Lift/Separation <sup>1</sup>	4%	6%	N/A	N/A	N/A
Tread: Tread Lift/Separation <sup>1</sup>	1%	2%	N/A	N/A	N/A
<b>Total Percentage of Failures:</b>	<b>6%</b>	<b>9%</b>	<b>17%</b>	<b>0%</b>	<b>24%</b>

Note: 1. Tread area failures classified as manufacturer defects for LT and PS tires only. These types of failure are generally an indication of under-inflation in large truck tires (Laubie, 1999).

The percentage of truck tire failures due to poor repairs in the Phoenix sample was lower than the corresponding "Repair failure" rate found for the TMC samples. The greatest difference occurred in original medium/heavy truck tires, for which no repair failures were identified in the Phoenix sample. Repair failures in the TMC samples averaged 15 percent of all new/original medium truck tires failures. While the variability of both sets of results is magnified by small samples of identifiable debris, it appears that most repairs are performed correctly for tires of all types. As indicated in Table 9, the largest problems in the "Manufacturer issues" category appear to be related to the retreading process, either through bond failures or poor inspection prior to retreading.

Average tread depths by type of tire and cause of failure are shown in Table 10. Passenger auto tires sampled had an average tread depth of  $\frac{6}{32}$  inches and light truck tires had a mean tread depth of  $\frac{8}{32}$  inches. Among medium/heavy truck tires sampled, the average tread depths were  $\frac{8}{32}$  inches for original tires and  $\frac{10}{32}$  inches for retreads. Tires with failure caused by "Maintenance issues" had the lowest average tread depth for all tire types, which reflects problems such as excessive wear that are included in this cause of failure category. Medium/heavy truck retreads exhibited greater average tread depths (i.e. failure earlier in tire life) than original tires for all causes of failure.

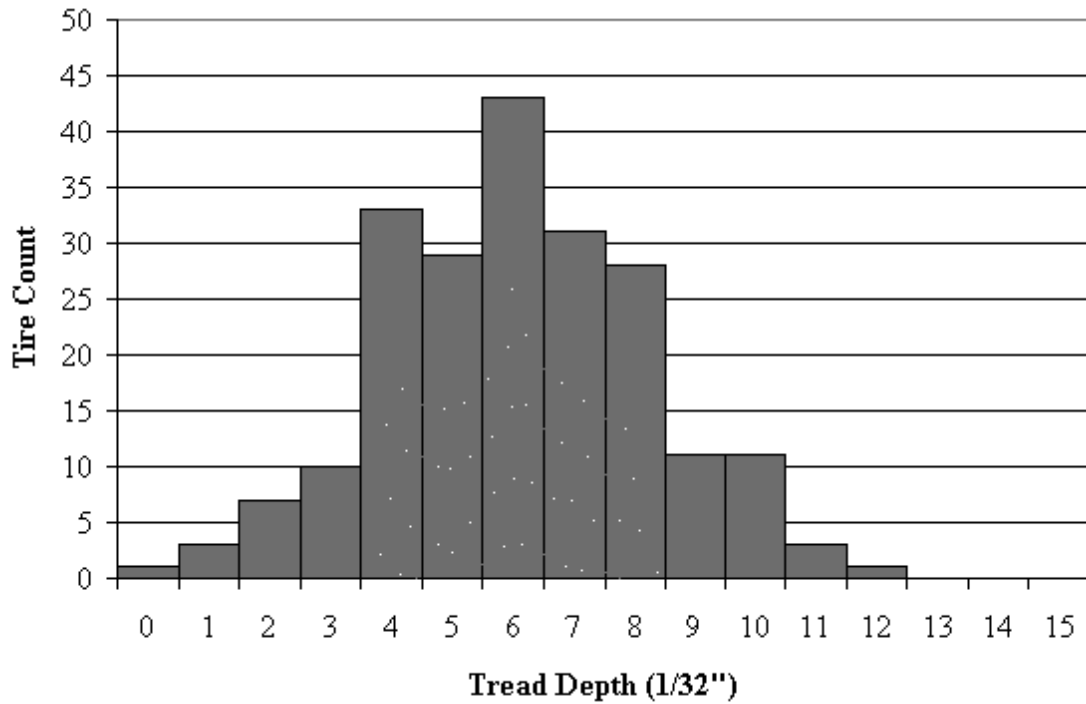
**Table 10: Average Tread Depth by Tire Type and Cause of Failure**

Cause of Failure	Type of Tire				
	Passenger Auto	Light Truck	Medium/Heavy Truck		
			Original	Retread	Total
Maintenance issue	3.3	5.5	3.0	9.0	5.0
Manufacture issue	6.1	5.8	10.5	10.6	10.6
Other	6.1	7.8	N/A	13.0	13.0
Road hazard	6.8	8.0	8.8	9.9	9.4
Run under-inflated	6.1	8.4	8.9	10.3	9.9
<b>Total</b>	6.1	8.0	8.7	10.3	9.9

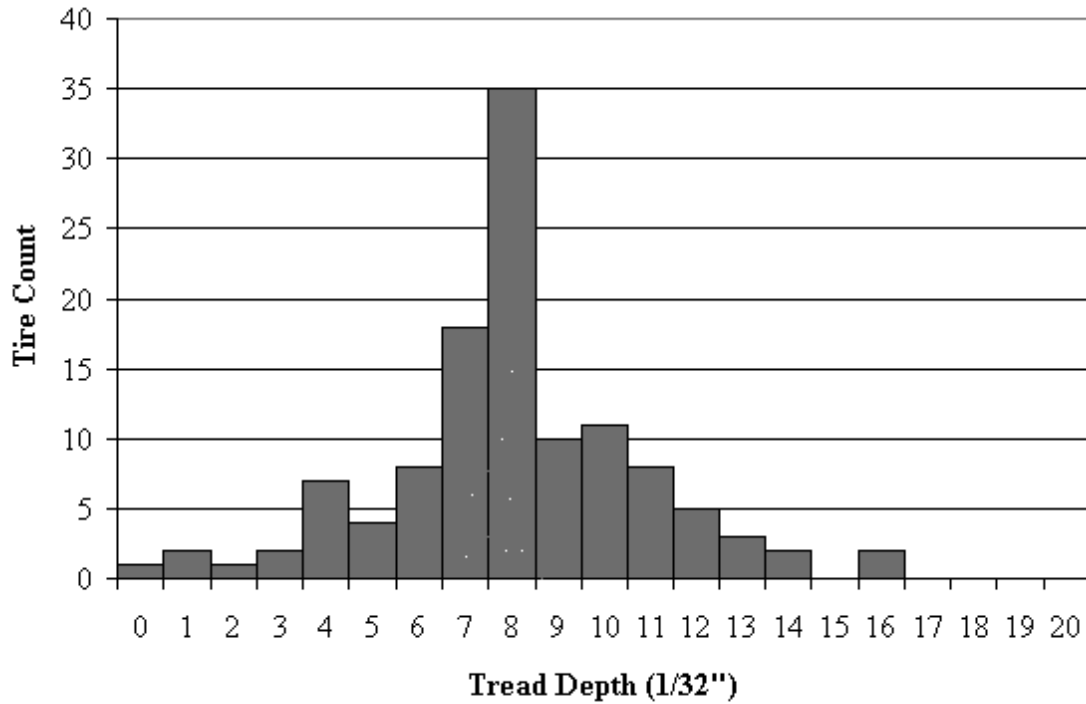
Figures 18 to 21 on the following pages provide frequencies of tread depth by tire type. With the exception of medium/heavy truck original tires, all distributions were basically normal. The distribution of medium/heavy truck retreads exhibits some positive skewness.



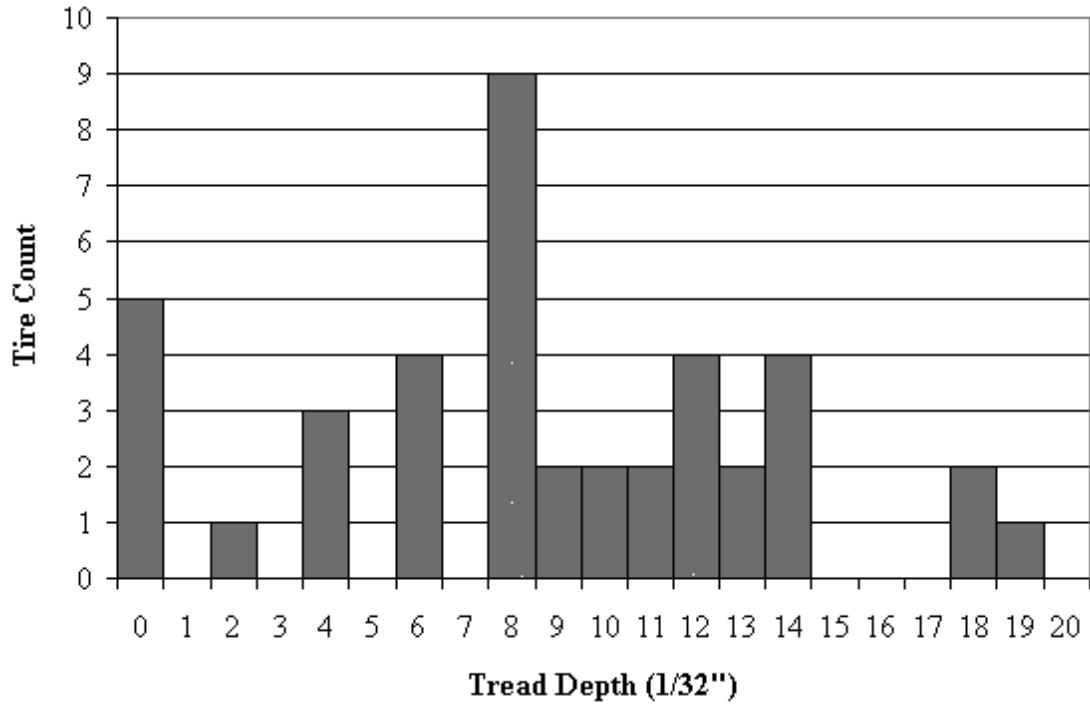
**Figure 18: Distribution of Tread Depth - Passenger Auto Tires**



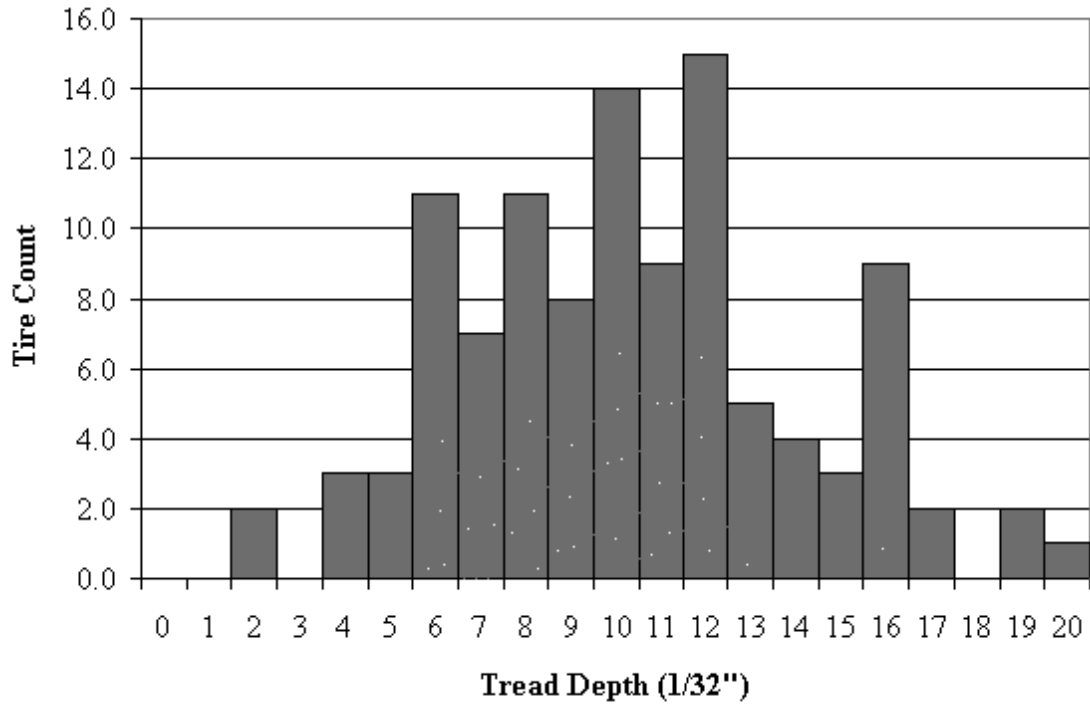
**Figure 19: Distribution of Tread Depth - Light Truck Tires**



**Figure 20: Distribution of Tread Depth - Medium/Heavy Truck Original Tires**



**Figure 21: Distribution of Tread Depth - Medium/Heavy Truck Retread Tires**



## **Metro Phoenix Sample Discussion**

An analysis of the metro Phoenix data illustrates several differences from the results of the 1995 and 1998 TMC studies. First, retreaded truck tires do appear to be over-represented in the sample relative to new truck tires, but the total share of medium/heavy truck tires is lower than the results of the TMC studies. Medium/heavy truck tires made up 31 percent of debris collected in metro Phoenix, compared with an average of 64 percent of debris collected in the TMC studies. This differential is most likely attributable to the differences in traffic composition between the rural areas sampled by TMC and an urbanized area such as Phoenix (Laubie, 1999).

The percentage of metro Phoenix tire failures due to running under-inflated and due to road hazards are similar to the shares of these causes of failure in the TMC samples. Together, these two issues comprised a large majority of failures in both metro Phoenix and TMC samples. However, failures due to "Manufacturer issues" (i.e. defects) are observed in much larger frequencies in the metro Phoenix sample. As measured by TMC, retread truck tires had failure rates due to manufacturer issues of 5 percent and 9 percent in 1995 and 1998 respectively. In contrast, 24 percent of retread truck tire failures in metro Phoenix were due to manufacturer defects.

Retreads were not the only type of tire with "manufacturer issues." Passenger auto tires had a 9 percent failure rate due to defects in the Phoenix sample. Failures due to manufacturer issues were observed in 6 percent of light truck tires. While cause of failure detail for passenger autos and light trucks were not included in the TMC summary, the increased relative frequency of defects in retread truck tires in the Phoenix sample may be cause for concern. Unfortunately, DOT numbers that provide manufacturer identification and date of manufacture are not found on tire shreds. Therefore, it can not be determined whether the high rates of failure due to defects are related to a particular manufacturer or manufacturing period.

As in the case of the TMC data, the results of the metro Phoenix analysis suggest that routine tire maintenance has been increasingly neglected among drivers of all vehicle types. Considering that issues such as under-inflation, lack of proper balancing and small punctures are the source of most tire failures measured, an increase in tire neglect will exacerbate the tire debris problem considerably. The same may be said of debris in the roadway. A steady failure rate of approximately 25 percent in all three samples is caused by road hazards. In fact, it is possible that among types of road debris, tire debris is maligned more due to its visibility rather than any real safety risk. While collection and disposal of tire debris poses a measurable problem for highway maintenance departments, the tire failures due to sudden impact with road hazards examined in metro Phoenix suggest that far more rigid and potentially dangerous debris is a common occurrence on highways.

## V. Assessing the Sources and Impact of Tire Debris

### Discussion and Conclusions

This section is divided into two distinct sections, each of which uses a different methodology to assess responsibility for highway tire debris. The first section estimates the relative share of debris that different vehicle *types* (e.g. passenger cars, medium trucks, etc.) are expected to leave on the highway, based on amount of travel and number of tires per vehicle. This expected contribution is then compared to the shares of debris collected by vehicle type for the TMC and Phoenix samples. The second section uses tire sales data to determine whether retread tires are disproportionately represented in the samples of medium/heavy truck tires.

#### Share of Debris by Vehicle Type

The distribution of tire debris according to type of tire can not be appropriately interpreted without a frame of reference. The proportions calculated for passenger auto, light truck and medium/heavy truck tires should be weighed according to several factors. Vehicles in the three major tire categories identified in the TMC and metro Phoenix samples have different characteristics that could play a role in the proportional share of debris those vehicle types are apt to leave on the highway. Specifically, large trucks tend to have more tires per vehicle and travel greater distances on average. These two factors are considered in the following analysis in an effort to fairly account for differences in the distribution of debris by type of tire.

Table 11 presents an analysis of the TMC data collected in 1995 and 1998. In order to estimate the share of tire debris that might be expected to be left on the road by a particular type of vehicle, a weighted allocation by vehicle miles of travel (VMT) and average number of tires per vehicle was calculated. These adjusted shares of expected debris by tire type were then compared to the actual results of the TMC samples. The following steps were taken to estimate the expected share of debris:

1. Average share of VMT was calculated for each vehicle type (passenger autos, light trucks and medium/heavy trucks) according to federal estimates of travel in 1995. Motorcycles were included with passenger autos and 2-axle, 6-tire single unit (2A6T SU) trucks were included with light trucks.
2. The average number of tires per vehicle was assigned according to *Forecasts for the World Rubber Economy* (Smit, 1984), with several modifications. Passenger auto estimates were adjusted downward from 4.8 to 4.0 tires to account for the addition of motorcycles and the assumption that the spare tire included in Smit would receive little of the actual miles traveled. Light truck estimates were revised upward from 4.8 to 5.0 tires to compensate for the addition of 2A6T trucks. Finally, the estimate for larger trucks was revised upward from 8.0 to 12.0 tires to account for industry trends toward larger vehicles.

3. The average number of tires was multiplied by the VMT estimate for each vehicle type.<sup>18</sup> The result was the weighted adjustment factor for each type of tire.
4. Each weighted adjustment factor was then divided by the sum of the adjustment factors to derive a final estimate of the share of debris by type of tire that could reasonably be expected on the nation's highways.

As shown in Table 11, both passenger autos and light trucks produced far less debris than might be expected based on their estimated shares. In contrast, medium/heavy truck tires were over-represented in the samples taken by TMC. In both 1995 and 1998, debris from truck tires comprised more than three times the estimated share for these vehicles. Passenger auto tires were under-represented in the TMC results by approximately 50 percent. The proportion of light truck tires collected in the TMC samples was less than  $\frac{1}{3}$  of the expected share for these vehicles. The disproportionate representation of medium/heavy truck tires indicates that these vehicles *are* largely to blame for the debris problems experienced on many highways.

**Table 11: Share of Travel versus Share of Debris on U.S. Highways**

Tire Type	Share of Tire Travel on U.S. Highways, 1995				Share of Debris <sup>1</sup>	
	VMT Share	Average Tires <sup>2</sup>	Adj. <sup>3</sup>	Adjusted Share <sup>4</sup>	1995	1998
Passenger Auto	59.8%	4	2.3908	48.4%	27.4%	25.0%
Light Truck <sup>5</sup>	32.6%	5	1.6305	33.0%	8.5%	11.0%
Medium/Heavy Truck	7.6%	12	0.9144	18.5%	64.1%	64.0%

Note: 1) Aggregate shares of debris collected in TMC samples. 2) Average number of tires by vehicle configuration (Smit, 1984). 3) Adjustment made by multiplying share of VMT by number of tires. 4) Adjusted share equals "Adj." by type divided by sum of adjustment values. 5) Includes 2A-6T SU trucks

Source: TMC, 1999 and Federal Highway Administration

A similar analysis was prepared for the metro Phoenix sample, with two modifications. First, the share of VMT by type of vehicle was assigned according to ADOT estimates from 1997. Second, because the Phoenix metropolitan area was region of interest, only shares of urban VMT were assigned. While the share of VMT assigned to medium/heavy trucks was still greater than the national share for these vehicles shown in Table 11, using urban estimates significantly reduced the share of VMT for medium/heavy trucks relative to state totals.

The "comparison ratio" shown in the final column of Table 12 illustrates the degree to which each type of tire is over- or under-represented in the sample according to its

<sup>18</sup> No attempt was made to account for differences in weight among types of vehicle. The implicit assumption was that tires for a given vehicle type are constructed to withstand the amount of load associated with that type of vehicle.

corresponding share of weighted travel. A comparison ratio of 1.00 means that the share of debris collected for that type of tire was exactly the same as its weighted share of travel.

The results shown in Table 12 differ considerably from the assessment of national shares according to the TMC samples. Although passenger autos remain under-represented in the debris sample relative to their share of tire-travel, the case of light trucks changes dramatically. Whereas debris attributable to light trucks was under-represented in the TMC samples by roughly 66 percent, light truck tire debris is over-represented by more than 40 percent in the metro Phoenix sample. The amount of over-representation of medium/heavy truck tires is reduced in the metro Phoenix sample to nearly the same level as that of light truck tires. According to these results, the *quantity* of debris found on metro Phoenix roads is most affected by both light and medium/heavy truck traffic.

**Table 12: Share of Travel versus Share of Debris on Urban Arizona Highways**

Tire Type	Share of Tire Travel on Urban Arizona Highways				Share of Phoenix Debris	Comparison Ratio
	VMT Share <sup>1.</sup>	Average Tires <sup>2.</sup>	Adj. <sup>3.</sup>	Adjusted Share <sup>4.</sup>		
Passenger Auto	60.3%	4	2.4113	47.8%	25.7%	0.54
Light Truck <sup>5.</sup>	30.5%	5	1.5263	30.3%	43.0%	1.42
Medium/Heavy Truck	9.2%	12	1.1031	21.9%	31.3%	1.43

Note: 1) VMT calculated based on ADOT HPMS estimates for 1997. 2) Average number of tires by vehicle configurations. 3) Adjustment made by multiplying share of VMT by number of tires. 4) Adjusted share equals "Adj." by type divided by sum of adjustment values. 5) Includes 2A-6T SU trucks

Sources: ADOT Highway Performance Monitoring System, 1997

Tables 11 and 12 assess the relative "blame" to be assigned different vehicle types for the *quantity* of debris collected on the highways as measured by number of fragments or whole tires. However, given the different sizes of tires, it is reasonable to assume that a differential impact exists among tire fragments in terms of maintenance clean-up efforts and traffic safety. The average truck tire weighs more than twice as much as the average passenger auto tire. Therefore, it seems logical that these fragments would pose more of a maintenance and safety problem. However, the lack of data on accidents directly attributable to tire debris allows nothing more than speculation on the latter hypothesis.

Share of Truck Tire Debris: New and Retread Tires

Evaluation of tire market data provides insight to the types of tire debris that might be attributed to particular subtypes within a class of tire. As an example, Table 13 presents the sales figures for new and retread medium truck and trailer tires in 1995 and 1998, contrasted with the percentage of medium truck tire debris that each tire type represented in the samples taken by TMC in these respective years. The shares of these types of tires in the metro Phoenix sample is also included. Sales of new tires (including both NR and OE) and retread tires were split virtually evenly in the medium truck tire segment in both 1995 and 1998. However, retreads made up a disproportionately large portion of the truck tire debris collected in all three samples.

**Table 13: Medium/Heavy Truck Tire Sales and Share of Debris**

Truck Tire Type	U.S. 1995		U.S. 1998		Phoenix, 1999
	Tires Sold <sup>1</sup>	Percentage of Debris <sup>2</sup>	Tires Sold <sup>1</sup>	Percentage of Debris <sup>2</sup>	Percentage of Debris <sup>3</sup>
New Tires <sup>4</sup>	50%	11%	51%	13%	29%
Retread Tires	50%	89%	49%	87%	71%

Notes: 1) Percentage of truck tire sales as reported in Section II. 2) Medium truck tire debris collected by TMC. 3) Medium truck tire debris collected in metro Phoenix samples. 4) Consists of new replacement (NR) and original equipment (OE) tires.

Source: International Tire and Rubber Association (1999), The Maintenance Council (1999)

Table 13 is based on a limited set of data and is not intended as an indictment of retread tires *per se*. No conclusions can be drawn from this data about the propensity of retreads to fail in a particular manner. It is possible that such variables as tire placement or a propensity to use retreads in more demanding applications could skew particular types of failure toward a particular type of tire. However, because the type of vehicle (medium trucks and truck trailers) was held constant, Table 13 does suggest that retreads do have a greater susceptibility to tire failure *regardless of the cause*. This susceptibility is observed in both TMC samples and in the metro Phoenix sample.

The data shown in Table 12 do indicate trend toward increased reliability on the part of retread tires. The share of retreads has fallen from 89 percent of the 1995 TMC sample to 71 percent of the metro Phoenix sample. Interestingly, this decline in representation has occurred despite *higher* rates of failure due to manufacturer defects. It is plausible that the trucking industry has responded to increased public scrutiny of retread tires, or to its own economic incentive to ensure high maintenance standards. Given the substantial savings that retreads provide to the trucking industry, this latter scenario seems particularly likely.

## Summary of Findings and Options for Reform

The following points provide a summary of the findings in this report. A brief discussion of these findings and potential strategies for further investigation are included below.

- Tire debris poses a challenge for state maintenance districts, particularly in dense urban areas such as metropolitan Phoenix and in rural areas with heavy truck traffic.
- Tire debris and tire defects do not pose a substantial threat to highway safety in Maricopa County or Arizona.
- Both light truck and medium/heavy truck tires comprise a greater share of debris counts in metropolitan Phoenix than is warranted by these vehicles' travel patterns and configurations.
- Retread truck tires are disproportionately represented in the debris counts, making up a greater share of total truck tires than sales data would suggest.
- The most frequently measured causes of tire failure are under-inflation and damage caused by road debris. These two causes of failure represent the vast majority of tire failures regardless of tire type.
- Manufacturer defects are a growing concern, particularly in the case of retread truck tires. Failure rates due to manufacturer defects in the Phoenix sample were more than twice the rates measured in previous studies.

As debris of all sorts increases on state highways, failures caused by debris can also be expected to increase. These added failures can create more debris, adding to the strain on maintenance budgets, which may in turn result in fewer resources available for a given segment and still greater amounts of debris. This cycle is exacerbated by recent trends toward increased speed limits. Studies of tires on several trucking fleets found that after increasing their average operating speeds, 80 percent reported a decrease in tire life and lower durability and 78 percent observed an increase in tire expenses (Galligan, 1999).

Tire under-inflation is largely an economic issue. The value of maintenance is lower than the value of time saved. Stated another way, time saved through reduced maintenance is of greater value than the incremental cost of increased tire wear. While heightened public awareness of the costs of poor tire maintenance might be expected to induce some shift in behavior, it seems likely that drivers left to their own devices will come to realize the added cost of poor maintenance.

Problems associated with retread tires are also an issue of economics. While retreads appear to fail at a greater rate than new tires, the savings that commercial fleets obtain by using retreads appear to outweigh the costs of more frequent tire replacement. An increase in the unreliability of retreads (or any other tire) would increase the cost of that



tire relative to the savings it provides, and it is expected that commercial fleets would adjust their tire procurement strategies accordingly.

It appears likely that many of the causal factors associated with tire debris will work themselves out, as individual drivers and/or commercial trucking fleets realize the potential cost of poor tire maintenance. The trucking industry in particular has the greatest incentive to manage tire expenses, with an estimated 4 percent of a given fleet experiencing tire-related breakdowns each year (Fisher, 1999).

The cost savings that can be realized by trucking fleets properly maintaining tires have led to the development of devices that monitor air pressure and, in some cases re-inflate, truck tires while in operation (Lefort, 1999). Widespread adoption of such devices could be expected to significantly reduce the number of truck tires, both retread and original, that are run under-inflated. Given that under-inflation due to poor maintenance and minor road hazards is the most frequently observed cause of tire failure, air pressure monitoring and re-inflation systems might reduce the amount of truck tire debris on the highways considerably.

Spot checks of commercial carriers are conducted on a recurring basis in the metro area in an effort to identify a variety of violations. However, these checks are time-consuming, and generally involve only a few vehicles at a given time. A recent inspection by the Mesa Police Department and DPS involved only 21 vehicles (Szczepanski, 1999). Of these, five were found to have tire-related problems or violations, usually excessive tread wear or punctures. However, in all cases, vehicles were stopped only if they had visible violations. It seems reasonable to assume that tire problems would occur less frequently on properly maintained vehicles.

Tire debris and roadway debris in general have not been shown to be a significant threat to highway safety. While tire "alligators" are an unsightly addition to the roadscape, risks associated with debris of this sort are almost entirely anecdotal. Similarly, tire problems on vehicles in operation are observed in small proportions of the total number of traffic accidents reported.

Given the relatively low safety risk associated with roadway debris and tire problems, most options for addressing tire debris seem an unnecessary expense. Because the vast majority of tire failures are caused by poor tire maintenance or neglect by individual drivers, the effectiveness of any efforts at debris reduction depends in large measure upon changes in driver behavior. Insofar as tire debris does not pose a significant highway safety risk, legislation aimed at driver behavior (e.g. fines for poor maintenance, etc.) may be politically unpalatable and very difficult to enforce. While tire debris is expected to continue to increase with traffic, improvements in tire design and durability and technological solutions such as pressure management systems suggest that much of the problem is of a temporal nature that does not warrant specific policy action.

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## Interviews

Name	Organization	Date
Craig Cornwell	ADOT Phoenix Maintenance	Jul 24, 1999
Peggy Fisher	Fleet Tire Consulting	Jul 29, 1999
Joe Campos	ADOT Maintenance - Contract Supervisor	Jul 30, 1999
Roy Lopez	ADOT Maintenance - Durango Yard	Aug 2, 1999
Bob Josefowicz	ADOT Maintenance - East Valley Yard	Aug 2, 1999
David Laubie	Bridgestone/Firestone	Aug 10, 1999
Ron Snider	Bridgestone/Firestone	Aug 12, 1999
Captain S. Flaherty	Virginia State Police, Safety Division	Sep 9, 1999
Detective J. Martinez	Mesa Police Department	Oct 6, 1999
Officer J. Szczepanski	Mesa Police Department	Oct 6, 1999
Linda Falada	ADOT Phoenix Maintenance	Oct 21, 1999

The following individuals provided technical expertise for the Phoenix sample analyses:

- David Laubie, Director of Engineering, Bridgestone/Firestone
- Don Nelson, National Technical Service Manager, Bridgestone/Firestone
- Ron Snider, RD Field Engineer, Bridgestone/Firestone
- Ed Rios, Bridgestone/Firestone

## List of Acronyms

ADOT	Arizona Department of Transportation
AHAS	Advocates for Highway and Auto Safety
ATA	American Trucking Association
ATRA	American Tire Retreaders Association
CRASH	Citizens for Reliable and Safe Highways
DPS	Department of Public Safety
FHWA	Federal Highway Administration
ITRA	International Tire and Rubber Association
LT	Abbreviation for light truck tires
MSW	Municipal Solid Wastes
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NR	New replacement tires
OE	Original equipment tires (i.e. tires supplied on new vehicles)
PS	Abbreviation for passenger automobile tires
RMA	Rubber Manufacturers Association
TB	Abbreviation for medium truck and trailer tires
TMC	The Maintenance Council (American Trucking Association)
TRB	Transportation Research Board
TRIB	Tire Retread Information Bureau
VSP	Virginia State Police

## **Appendix A: Tire Analysis**

Virtually all passenger automobile tires, as well as the majority of light truck and medium truck tires on the road today, are radial tires. While bias-ply tires are considered superior for certain uses (e.g. off-road applications), highway usage is dominated by radial tires. As a part of this analysis, a survey of tire failure conditions and means of identifying these conditions was conducted. This appendix provides a brief description of tire manufacturing, a guide to the key components of a radial tire and a basic description of the tire retreading process.

### Radial Tire Manufacturing (Goodyear, 1998)

Tires are manufactured from a variety of raw materials, including chemicals, pigments, cord fabric, bead wire and roughly 30 different kinds of rubber. The process has several steps, beginning with the combination of basic rubbers with oils, carbon black, pigments and other additives which are blended together under extreme heat and pressure to form the basic tire compound. This compound is then cooled and processed into slabs that are milled into strips and processed into various parts of the tire (e.g. sidewalls, treads, etc.). Another type of rubber is used to coat the fabric that makes up the body of the tire.

The bead, a high-tensile steel wire shaped like a hoop, fits against the vehicle's wheel rim. The bead strands are aligned into a ribbon coated with rubber for adhesion, then wound into loops that are then wrapped together to secure them until they are assembled with the rest of the tire. Radial tires are built on one or two tire machines, starting with a double layer of synthetic gum rubber called an innerliner that seals in air and make the tire tubeless. The processed rubber components are used to wrap the bead wires and radial belts. Because radial tires incorporate steel cords, moisture must be strictly controlled in the manufacturing process (West, 1984). The tire building machine pre-shapes radial tires into a form very close to their final dimension to make sure the many components are in proper position before the tire goes into the mold.

Tires get their final shape and tread pattern in the curing press. Hot molds engraved with the appropriate patterns vulcanize and the rubber under high heat and temperatures. Tires are generally cured from 12 to 24 minutes at 300°F, and then removed from the mold for inspection. Tires are inspected both visually and by machine. This phase is especially critical for radial tires. Any irregularity in the belts of radial tires impairs their performance (West, 1984), so proper care must be taken to ensure that the curing process does not distort the tire shape. Tires passing the required inspections are stamped and painted with manufacturer logos and specifications prior to final distribution.

## Key Components of a Radial Tire

In order to understand the various causes of tire failure, some familiarity with the essential elements of a typical tire is also necessary. The figure below illustrates the components of a typical radial tire. A definition of each component, excerpted from the *Radial Tire Conditions Analysis Guide* (TMC, 1994), is provided below.

**Figure 22: Tire Composition Cutaway View**

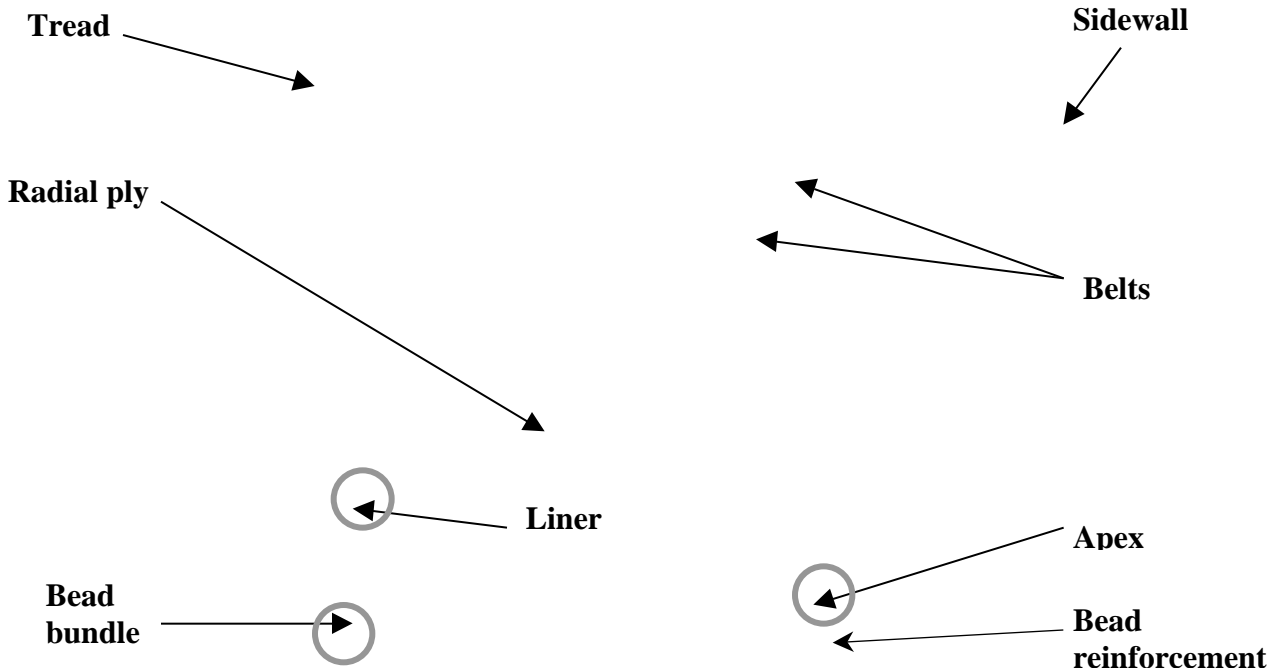


Image source: Goodyear Tire Corporation, 1998

The illustrated elements of a radial tire are described by The Maintenance Council as follows:

- **Tread:** Rubber interface between the tire structure and the road. The primary purpose of this component is to provide traction and wear.
- **Belt:** Belt plies, usually steel, provide added strength to the tire, stabilize the tread, and protect the air chamber from punctures and other hazards.
- **Radial ply:** Together with the belt plies, the radial ply contains the air pressure of the tire. The ply transmits all load, braking and steering forces between the wheel and the tire tread. Whereas bias-ply tires have diagonally-oriented plies, radial plies are arranged horizontally, perpendicular to the tire bead.

- Sidewall: The sidewall rubber is specially compounded to withstand flexing and weathering while providing protection for the radial ply.
- Liner: A layer of rubber in tubeless tires that is compounded to resist air diffusion. The liner in the tubeless tire replaces the inner-tube of the tube-type tire.
- Apex: These are rubber pieces used to fill in the bead and lower sidewall area, providing a smooth transition from the stiff bead area to the flexible sidewall.
- Bead reinforcement: A ply laid over the radial ply turn-up outside of the bead. The bead reinforcement provides added strength and stability in the transition zone between bead and sidewall.
- GG Ring (not pictured): A groove in the sidewall that is used as a reference for seating the bead area on the rim.
- Bead bundle: Made of continuous high-tensile wire, wound to form a high-strength unit, the bead bundle provides an anchoring foundation for the casing, which maintains the required tire diameter on the rim.

## **Tire Retreading**

The following describes the basic processes and procedures used to retread a tire. This information was excerpted from *Fleet Equipment* (October, 1996), as originally provided by the Bandag Corporation. Additional references are cited in the text.

Retreading refers to the application of a new tread package on an old tire casing. There are two basic systems used to retread a tire, mold cure and pre-cure. Concurrent development of these two retreading systems is a matter of industrial organization rather than a specific application for each method. According to industry experts (Laubie, 1999 and Deierlein, 1993), there is no measurable difference in strength or durability between the two methods. However, an estimated 80 percent of tires are retreaded using the pre-cure method.

The initial steps in retreading a tire are the same regardless of which retreading system is used. These common steps are:

- Inspection: Each tire received in a retread plant is subjected to a very rigorous visual inspection. Many retreaders also employ non-invasive technology to inspect tire casings for defects that may not be visible to the eye.

- Buffing: Tires have the old tread mechanically removed on high speed buffers. Modern buffers can be calibrated to remove the proper amount of old rubber while shaping the tire to a specified diameter and profile.

Following the inspection and buffing stages, new tread rubber is applied to the tires. This is where the two retreading systems differ. In the pre-cure system, the tread rubber has already been vulcanized with the new tread design. The buffed tire has a thin layer of cushion gum wrapped around the tread area and the pre-cured tread is then applied. The cushion gum serves to bond the pre-cured tread to the tire. The tire is then placed in a curing chamber and the pre-cured tread adheres to the tire through a vulcanizing process very similar to the vulcanizing process used in new tire construction.

In the mold-cure system, unvulcanized tread rubber is applied to the buffed tire. The tire is then placed into a rigid mold which contains the tread design in the tread area. The mold is heated and the rubber in the tread area vulcanizes and adheres to the tire with the new tread design molded in. Again, this vulcanization process is very similar to the vulcanizing process used in new tire construction.

Both systems require a combination of time, heat and pressure to create the vulcanization of the new rubber to the tread area of the tire. Following the application of the new tread rubber, the retread is subject to a final inspection. Tires are subjected to tests for quality control and durability. Tires that pass a plant's final inspection are trimmed to remove any excess rubber and then painted according to the appropriate manufacturer specifications.

### Retreadability factors

A number of factors contribute to a tire's viability as a retread. Because a retread is essentially a "used" product, the condition of the tire casing is of paramount importance for the strength of the retread. In addition to the influence of age, the condition of the casing is a function of the application in which the tire has performed (e.g. long haul, on/off road, pick up and delivery), the type of equipment on which the tire has been mounted, how well the equipment on which the tire has been mounted has been maintained and how well the tire has been treated while in operation (Deierlein, 1996).

Perhaps the most important element for predicting casing durability is its "heat history." The heat history, that is how much heat a casing has experienced during its life, largely determines whether a tire casing is suitable for retreading. While it is not feasible to track the heat history of every tire, most commercial trucking fleets have the ability to get a macro picture of the heat exposure of tires by making a broad determination of the routes to which tires have been exposed (Birkland, 1994). A new tire in a severe application with poor attention to equipment and tire maintenance may be "old" long before its life should be over and may, in fact, not be retreadable. On the other hand, an older tire that has not been subjected to overloaded or under-inflated conditions and has been on regularly maintained equipment is likely to be retreaded several times (Deierlein, 1996). The appropriate and informed use of proper inspection techniques allows the



retreader to make a determination of the retreadability of a worn casing based on more than just its calendar age.

## Appendix B: Results of the Metropolitan Phoenix Tire Sample

The following pages contain a table of individual records for tires identified in the metropolitan Phoenix sample. The table is organized according to sample location, type of tire, measurements, relevant wear and repair characteristics and cause of failure. Not all fields were identifiable for each tire fragment. Debris was sorted according to a computerized system developed by Bridgestone/Firestone engineers. The following individuals provided technical expertise for the tire identification sessions:

Name	Title	Organization	Contact Information
David Laubie	Director of Engineering	Bridgestone/Firestone	LaubieDavid@bfusa.com
Don Nelson	National Technical Service Manager	Bridgestone/Firestone	NelsonDon@bfusa.com
Ron Snider	RD Field Engineer	Bridgestone/Firestone	SniderRon@bfusa.com
Ed Rios		Bridgestone/Firestone	

The table below shows the broad categories of tire failure found in Section IV of this report, along with the specific causes of failure attributed to each category.

Failure Category	Specific Causes of Failure	
Run under-inflated:	<ul style="list-style-type: none"> <li>• Bead Failure</li> <li>• Heat</li> <li>• I:Run Flat</li> <li>• Nail/Puncture</li> <li>• Runflat/BLB</li> <li>• Runflat/BLC</li> </ul>	<ul style="list-style-type: none"> <li>• SW:Spread/Damage Cord</li> <li>• T:Belt Lift/Sep (TB)</li> <li>• T:Impact Breaks</li> <li>• T:Lug Base Cracking</li> <li>• T:Tread Lift/Sep (TB)</li> </ul>
Manufacture issue:	<ul style="list-style-type: none"> <li>• Bond Failure</li> <li>• Missed Nail Hole</li> <li>• Repair Failure</li> </ul>	<ul style="list-style-type: none"> <li>• T:Belt Lift/Sep (PS and LT)</li> <li>• T:Tread Lift/Sep (PS and LT)</li> </ul>
Maintenance issue:	<ul style="list-style-type: none"> <li>• Brake Lock</li> <li>• Misapplication</li> </ul>	<ul style="list-style-type: none"> <li>• T:Excessive Wear</li> <li>• Worn to Belt</li> </ul>
Road hazard:	<ul style="list-style-type: none"> <li>• Impact</li> <li>• R/H Impact</li> <li>• SW: Cuts/Snags</li> </ul>	<ul style="list-style-type: none"> <li>• SW:Impact Break</li> <li>• T:Road Hazard</li> </ul>
Other:	<ul style="list-style-type: none"> <li>• No Reason Found</li> </ul>	<ul style="list-style-type: none"> <li>• Undecided</li> </ul>

Abbreviations: I (interior), T (tread), SW (sidewall), BLB (belt leaving belt), BLC (belt leaving casing), R/H (road hazard)