Final Technical Report

for

Task Order No. 4

(DTRS57-97-C-00051)

Blowout Resistant Tire Study for Commercial Highway Vehicles

UMTRI-2000-28

Z. Bareket
D. F. Blower
C. MacAdam

The University of Michigan
Transportation Research Institute

August 31, 2000

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 809 172		

4. Title and Subtitle Blowout Resistant Tire Study for Commercial Highway Vehicles	5. Report Date August 31, 2000
	6. Performing Organization Code
7. Author(s) Z. Bareket, D.F. Blower, and C. MacAdam	8. Performing Organization Report No. UMTRI-2000-28
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road, Ann Arbor, Michigan 48109	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTRS57-97-C-00051
12. Sponsoring Agency Name and Address USDOT / RSPA / Volpe Center 55 Broadway, Kendall Square, DTS-852 Cambridge, MA 02142-1093	13. Type of Report and Period Covered Final 9/9/99 - 5/31/00
	14. Sponsoring Agency Code

15. Supplementary Notes

Technical Contacts: J. Guglielmi, DTS-74, (Volpe Center), J. Britell (DOT), J. Scott (DOT).

16. Abstract

A report of findings for Task Order No. 4 entitled "Blowout Resistant Tire Study for Commercial Vehicles," under the Accident Data Analysis Support project (DTRS57-97-C-00051). The report is organized by the following principal sections: (1) Overview, (2) Crash Data Analysis of Truck Tire Blowouts, (3) Information Review of Truck Tire Blowouts, (4) Blowout Resistant Tire Developments and Related Industry Contacts, and (5) Summary Observations.

Section 1 provides a short summary of the report and its organization. Section 2 contains analyses conducted by the UMTRI Center for National Truck Statistics that address findings regarding the crash record relating to heavy truck tire blowouts. Observations from the crash data analysis note the very small percentage of fatal crashes associated with tire failures overall and the even smaller involvement of tire blowouts in fatal crashes when the blowout occurs at a rearward location on the truck (non-steering axle cases). Crashes related to road debris (of which tire debris represents some unknown portion) are also addressed briefly in Section 2. A key observation from the crash data analysis is the significant linkage between fatalities involving truck tire blowouts and front tire (steering axle) involvement. A strong relationship between type of crash and left- versus right-side front axle blowouts is also noted. Left front blowouts are more frequently associated with multiple vehicle fatal crashes, whereas right front blowouts are more frequently associated with single-vehicle crashes (presumably involving greater chances of truck driver fatalities). These observations are consistent with general expectations that left front blowouts produce a leftward path disturbance to the truck (potentially into oncoming or adjacent traffic), while right front blowouts produce rightward disturbances to the truck which are more likely to involve road departure crashes.

Section 3 contains results and associated discussion of the literature review conducted by the UMTRI Engineering Research Division. In addition to a discussion of certain key studies of truck tire blowouts conducted previously by various agencies in the literature review, more current developments within the tire industry were pursued though industry contacts (as reported in Section 4) and through inquiries of current patent databases to supplement the technical literature review.

Section 4 identifies various technologies relevant to blowout resistant tires as well as associated industry contacts.

Lastly, Section 5 provides a summary of the key observations from each of these areas.

17. Key Words	18. Distribution Statement
truck, tire, blowout, failure, blowout-resistant, tire technology, crash analysis, crash data, commercial vehicle, safety	This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	50	

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1. Overview

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The report is organized by the following principal sections: (1) Overview, (2) Crash Data Analysis of Truck Tire Blowouts, (3) Information Review of Truck Tire Blowouts, (4) Blowout Resistant Tire Developments and Related Industry Contacts, and (5) Summary Observations.

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Lastly, Section 5 provides a summary of the key observations from each of these areas.

All bracketed [ ] numbers within the text refer to the reference list near the end of the report.

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2. Crash Data Analysis of Truck Tire Blowouts

This section of the report describes the crash data analysis of heavy truck tire blowouts conducted by the UMTRI Center for National Truck Statistics.

Available crash data files were surveyed for information on the incidence of truck tire blowout in crashes. The primary emphasis in the crash data analysis was on truck tire blowout as a direct crash causal factor. Note that blowouts that did not lead to loss of control and a crash will be missed. For this analysis, crash files surveyed included the Trucks Involved in Fatal Accidents (TIFA) file, which is based on the Fatality Analysis Reporting System (FARS); the nationally representative sample of police-reported crashes in the General Estimates System (GES) file; and state files from Michigan, North Carolina, Texas, and Washington. In general, tire blowout is not directly identified in most crash data files. At best, most data files indicate only whether a tire "defect" existed. Tire defects can include under-inflation, over-inflation, or insufficient tread, as well as an actual blowout. However, copies of the original police reports are available for the TIFA file, and all cases coded with tire defects over a three year period were reviewed to identify tire blowouts. In addition, the GES file includes a crash event variable which identifies tire blowout as a precipitating event. Both the manual case review of fatal tire defect crashes and the analysis of the GES data provided realistic estimates of the incidence of truck tire blowouts in crashes. Results from the analysis of each crash file are discussed separately below.

A secondary effect of truck tire blowout is the debris from the disintegrating tire left behind on the roadway. Even if the blowout did not immediately lead to a crash, a secondary effect could be subsequent crashes caused by either striking or attempting to avoid striking the debris. Once again, no available crash files identify events at the required level of detail, but both FARS and GES include information on crashes related to avoiding objects in the road. Counts of such crashes provide an upper limit to the proportion of crashes related to truck tire and other types of roadway debris.

Truck tire blowouts in FARS (Fatality Analysis Reporting System) and TIFA (Trucks Involved in Fatal Accidents)

The FARS file compiles data on all crashes involving a fatality. The University of Michigan Transportation Research Institute's (UMTRI) TIFA program subsets fatal truck involvements from the FARS file and provides an improved identification of medium and heavy trucks involved in a fatal crash. As part of the process of building the TIFA file, police reports are collected on every crash involving a medium or heavy truck in the United States. The TIFA file consists of all variables from the FARS crash, vehicle, and person files, along with supplemental TIFA variables providing a detailed description of the truck.

Tire blowouts are not identified directly in either the FARS variables describing the crash or vehicle, or the TIFA variables. However, a multiple-response variable included among the FARS variables identifies "vehicle-related factors," which essentially record vehicle defects present. The defects may or may not have contributed to the crash. Up to two vehicle defects may be recorded. One code available is for "tires." The "tire" code simply reports that a tire defect was present. Worn tires and any other tire defect is included here, in addition to tire blowouts.

Table 2-1 tabulates the defects reported on all trucks involved in a fatal crash between 1995 and 1997. There were 14,768 total trucks involved in a fatal crash over that period. Of these, 129 or 0.87 percent of all trucks were reported with a tire defect.[1] Tire problems are the second leading defect noted. The most common vehicle defect was brake problems with 377 cases over the three years, 2.55 percent of all trucks involved in a fatal crash. Over 91 percent of the trucks were reported with no defects. It is likely that the number of defects is underestimated, since the reporting police officer is usually not trained to identify vehicle problems. Probably only the more obvious vehicle problems are recorded. However, a tire blowout likely falls into the category of vehicle defects that would typically be recorded.

Table 2-1. Vehicle defects reported (TIFA 1995-1997)

	N	%
none	13,496	91.39
tires	129	0.87
brake system	377	2.55
steering	22	0.15
suspension	22	0.15
power train	11	0.07
exhaust system	1	0.01
headlights	11	0.07
signals	9	0.06
other lights	41	0.28
horn	4	0.03
mirrors	2	0.01
wipers	2	0.01
body, doors, other	6	0.04
trailer hitch	26	0.18
wheels	14	0.09
other	61	0.41
hit and run	153	1.04
pushed by pedestrian	1	0.01
unknown	467	3.16
total trucks	14,768	100.00

Police reports on all truck involvements are available as part of the TIFA program. Review of these reports, including the narrative, diagram, and any other information on the report, provides further information on the nature of the tire defect. Police reports on all cases in which a truck was coded with a tire defect for 1995 to 1997

[1] Note that since up to two defects can be reported for each vehicle, the sum of the defects can be greater than the number of trucks. The total number reported in the table is the total of trucks involved in a fatal crash over the period, not the total of defects. Accordingly, the percentage calculation is the percentage of trucks with a given defect.

were reviewed in an attempt to determine the incidence of tire blowout and to assess the results of the blowout. This amounted to 129 police-reported cases from 1995 to 1997.

As indicated in Table 2-2, only 52 (40.31 percent) of the 129 tire defect cases included a blowout. Wheel separation was noted in 12 cases, though these cases should not have been recorded as a tire defect because there is a "wheel" code available that should have been used. "Bald" or "slick" tires constituted the tire defect in 45 cases. In eight cases, no tire-related problems were evident from the police report, either from the narrative, diagram, or any code for vehicle defect or crash event. In these cases, "tire defect" may have been coded in error. In the remaining 12 cases, there was no indication of a tire problem, nor any positive indication that there were no tire problems.

Table 2-2. Review of FARS/TIFA cases with tire defects noted (TIFA 1995-1997)

problem	N	%
blowout	52	40.31
wheel separation	12	9.30
tread depth	45	34.88
no tire problems	8	6.20
unknown	12	9.30
total	129	100.00

Thus, of the 14,768 trucks involved in a fatal crash, 1995-1997, 52 (0.35 percent) suffered a blowout as an event in the crash. In most cases, the blowout precipitated the crash, but in some, the blowout was incidental or even occurred significantly prior to the crash. The rate of truck tire blowouts in fatal truck crash involvements is 0.094 per *billion* miles, compared to an overall fatal truck crash involvement rate of 26.736 per *billion* miles. These rates are calculated using truck travel estimates from the Federal Highway Administration's *Highway Statistics* for 1995 through 1997.

Fatal truck tire blowout crashes are more likely to be single-vehicle crashes, versus that of the overall record that includes all fatal truck crashes. Direct review of the police reports for the above 52 blowout crashes indicate that 23 (44.23 percent) were single vehicle crashes and 29 (55.77 percent) involved two or more vehicles. This compares with 17.06 percent of all fatal truck involvements from 1995 to 1997 were single vehicle crashes, while 82.94 percent involved two or more vehicles.

As part of the review, the location of the blowout by axle and axle end was recorded, as well as whether vehicle control was maintained. Table 2-3 reports the results of this analysis. Most of the blown tires were on the front axle – 35 of the 52 tire blowouts. This probably reflects the fact that the crash data is restricted to fatal crashes. Steering axle blowouts typically lead to loss of control which may in turn cause a crash. On the front axle there were 22 blowouts on the left (62.86 percent of front axle blowouts), about twice as often as on the right, with 13 (37.14 percent). The preponderance of left side blowout may also reflect the severity bias of the crash file. A blowout to the left front tire typically leads to loss-of-control (LOC) to the left, which directs the truck into the oncoming traffic stream or adjacent traffic. Right-side blowouts usually lead to LOC to the right and a single-vehicle crash, with a lower probability of a fatality in the crash.

Twelve of the tire blowouts occurred either on drive axles or trailer axles. The blowout location could not be determined in five cases. Given that the truck lost control in known ways in three of the five cases, one to the right and two to the left, most likely one of them was a right front tire and two were left front.

Table 2-3. Blowout location (TIFA 1995-1997)

location	N	%
front left	22	42.31
front right	13	25.00
drive left	3	5.77
drive right	1	1.92
trailer left	1	1.92
trailer right	3	5.77
trailer, unknown	4	7.69
unknown	5	9.62
total	52	100.0

Table 2-4 tabulates the result of the tire blowouts by the location of the tire. There is a strong and intelligible pattern. When the blowout occurred on a steering axle, the truck lost control in almost every case.

Table 2-4. Reaction of the truck to tire blowout by location of tire blowout (TIFA 1995-1997)

	tire blowout location									
reaction of the	front left		front right		drive/trailer		unknown		total	
truck	N	%	N	%	N	%	N	%	N	%
LOC[2] left	21	95.5	2	15.4	1	8.3	2	40.0	26	50.0
LOC right	1	4.5	10	76.9	2	16.7	1	20.0	14	26.9
LOC, unknown	0	0.0	0	0.0	0	0.0	1	20.0	1	1.9
same speed	0	0.0	0	0.0	3	25.0	0	0.0	3	5.8
slower	0	0.0	0	0.0	4	33.3	0	0.0	4	7.7
stopped	0	0.0	1	7.7	2	16.7	1	20.0	4	7.7
total	22	100.0	13	100.0	12	100.0	5	100.0	52	100.0

The single instance where control was not lost occurred on a city street. The truck was parked and repairs were being attempted when an approaching passenger vehicle lost control and struck the rear of the truck. In every other case where a steering axle tire failed, the driver lost control of his truck. When the left front tire blew, the truck typically veered to the left, most often into oncoming traffic. When the right front tire blew, the truck typically lost control to the right. Control was typically maintained after blowouts on drive or trailer axles. In three of the 12 cases, the truck continued at the same speed. In four cases, the truck slowed down after the blowout, but proceeded under control. In one case, the truck had stopped to repair the blowout at the time of the crash. In three cases of

[2] Loss Of Control

drive or trailer axle blowouts, the truck did go out of control. In one case, the driver over-corrected following the blowout and left the roadway. In another, a tractor-semitrailer with a propane tanker was negotiating a high speed curve when an outside trailer axle tire blew. This caused the outside tire to lose its bead and deflate. Cargo shift pulled the combination over. In the final case, a right rear tire on a three-axle dump truck blew, causing the vehicle to veer to the right.

In general, the fatal truck crashes precipitated by a blowout, as reported in Table 2-4, can be divided into the following three scenarios:

1. <u>If the front left tire blows</u>, the truck loses control to the left, veers into oncoming or adjacent traffic, and either rolls immediately or after a collision with another vehicle. These crashes are primarily multiple vehicle crashes, with 15 of the 22 involving two or more vehicles.

2. <u>If the right front tire blows</u>, the truck loses control to the right, veers off the road and either rolls, collides with roadside structures, or both. These are typically single-vehicle crashes. Ten of 13 right front tire blowouts were single-vehicle crashes.

3. <u>If a drive or trailer axle blows</u>, the truck typically, though not always, remains under control. [Note: In some cases the crash is entirely unrelated to the flat tire. For example, in one case the truck was rear-ended by an alcohol-impaired driver. The truck driver said he was driving normally and was on his way to get the flat repaired, remarking that "one tire being flat did not slow the truck down that much."]

In 11 of the 52 cases (21.15 percent), the tire blowout did not immediately result in a crash. This is based on the observation that in these cases the truck did not lose control, but either proceeded at the same speed, or at a slower speed while still maintaining control, or was stopped and effecting repairs at the time of the crash. Eliminating these cases from the blowout group leaves 41 involvements (0.28 percent of all fatal truck crash involvements) in three years where truck tire blowout apparently was the immediate cause of the crash.

None of the cases had any information on why the flat occurred.

The Dunlap study [11] reported that 4 to 5 percent of truck crash involvements on the Ohio, Indiana, and Pennsylvania turnpikes were caused by tire failure. This percentage is significantly higher than the 0.8 percent tire-failure proportion of crash involvements he found in the Bureau of Motor Carrier Safety (BMCS) — now the Federal Motor Carrier Safety Administration — data [12], or the 0.35 percent proportion of fatal truck involvements reported here. Dunlap did not explore the reasons for the higher rates he found on the turnpikes. One explanation could be that turnpikes are high-speed roads, with the higher speeds causing heat buildup on under-inflated tires and subsequent failure.

The TIFA data do not support the high turnpike rates found by Dunlap. Turnpikes as such are not identifiable in TIFA, but interstate highways are an appropriate surrogate for turnpike roads. From 1995 through 1997, only 0.61 percent of fatal truck involvements on interstates were related to truck tire blowout. This percentage is far lower than the 4 to 5 percent reported in Dunlap on comparable roads. However, the proportion on interstates, while very low, is still higher than the 0.35 percentage blowouts form of all fatal truck involvements. In fact, 40.38 percent of fatal truck involvements related to tire blowout occurred on an interstate highway, compared with 23.41 percent of all fatal truck involvements. This is consistent with the heat buildup causal mechanism, though there is not enough information in the data to go any further.

Truck tire blowouts in GES

The General Estimates System (GES) file is a nationally representative sample of police reported crashes. All data are coded from the police reports. No supplemental data are used in coding the data. The original police reports are not available for review.

The GES includes a variable to record vehicle defects similar to that in the FARS file. However, a review of TIFA cases showed that, at least for fatal crashes, only about 40 percent of recorded tire problems are blowouts. It is impossible to conduct a review of police reports similar to that done with the TIFA cases, so the tire-defects variable is not a useful way to estimate tire blowouts in the GES file. However, the GES includes another variable to record the precipitating event in the crash, and one of the codes is for control loss due to a tire blowout. Note that blowouts that did not lead to loss of control and a crash will be missed, but this precipitating-event variable is probably a good surrogate for blowout-related crashes.

Table 2-5 summarizes blowout-related crash involvements for trucks and nontruck vehicles. Loss of control due to tire blowout represents only about a quarter of a percent of trucks involved in police-reportable crashes. For nontruck vehicles, which are overwhelmingly passenger vehicles, only 0.12 percent had a blowout as the precipitating event in the crash. The 0.25 percent of all truck involvements due to tire blowout is comparable to the 0.35 percent found for fatal truck crash involvements.

Table 2-5. Blowouts in truck and non-truck crash involvements. (GES 1995-1997)

crash	truck		nontruck	
event	N	%	N	%
blowout	2,807	0.25	41,515	0.12
other	1,109,379	99.75	35,120,000	99.88
total	1,112,186	100.00	35,161,515	100.00

Three years of data are combined to improve confidence in the estimates. The estimated total number of truck blowout crash involvements over three years implies an estimate of about 936 truck tire blowout involvements per year nationally. Since GES is a sample file, there is an associated sampling error to the estimates. An approximate 95 percent confidence interval for the estimated 936 annual truck tire blowout crash involvements would range from 483 to 1,389. The rate of tire blowouts in all crashes, estimated from the GES data, is 1.695 blowout-related truck crashes per *billion* miles of truck travel, compared with an overall truck crash rate of 671.16 truck crash involvements per *billion* miles of travel.

Most crashes resulting from truck tire blowouts were single-vehicle crashes, involving only the truck. In fact, almost 88 percent of truck tire blowout crashes were single vehicle, while only 19.71 percent of other truck crashes were single vehicle. See Table 2-6.

Table 2-6. Number of vehicles involved for truck blowout and other truck crashes. (GES 1995-1997)

vehicles involved	blowout N	blowout %	other N	other %
single vehicle	2,469	87.97	218,650	19.71
multiple vehicle	338	12.03	890,729	80.29
total	2,807	100.00	1,109,379	100.00

Just as in the TIFA data, analysis of the GES data indicates that crashes due to truck tire blowout are more likely on interstate roads. Although the Dunlap study cited above indicated that 4 to 5 percent of truck crashes on turnpikes are due to tire blowout, in the GES data, only 0.63 percent of crashes on interstates were due to tire blowout. Still, that percentage is considerably higher than the 0.25 percentage of crashes on all road types. In the GES data, fully 50.13 percent of truck crash involvements due to tire blowout occurred on interstate roads, compared to 19.96 percent of all truck crash involvements. Heat buildup is a possible explanation.

In general, it does not appear that truck tire blowouts lead to crashes that are more serious than other truck crashes. In the GES data, overall tire blowout crashes are less serious than other truck crash involvements. Table 2-7 shows the distribution of crash severity as measured by the most serious injury in the crash. The distributions are shown for tire blowout and non-blowout truck crashes.

Table 2-7. Crash severity[3] for truck-tire blowout and other truck crash involvements. (GES 1995-1997)

	blowout N	blowout %	other N	other %
no injury	2,231	79.49	802,349	72.32
possible injury	178	6.36	117,387	10.58
nonincapacitating injury	279	9.94	83,890	7.56
incapacitating injury	106	3.76	50,634	4.56
fatal injury	5	0.19	9,039	0.81
injury, unknown severity	0	0.00	4,797	0.43
unknown	7	0.26	41,282	3.72
total	2,807	100.00	1,109,378	100.00

Only GES data are used in the table. Since GES is a sample file, the estimate of fatal involvements does not match the estimate from TIFA. The GES estimate for fatal tire blowouts is based on a very small number of cases and is not statistically reliable. Moreover, estimates from TIFA and GES are not directly comparable because of subtle differences between the two files in the definition of a "blowout" crash. In the set of crashes identified in GES, the blowout precipitated the crash, while TIFA-identified

[3] As indicated on the "Traffic Crash Report" (KABCO code). Definitions for the various injuries can be found in "Manual on Classification of Motor Vehicle Traffic Accidents", ANSI D16.1-1970, National Safety Council, Chicago, Illinois, May, 1970.

crashes includes all blowouts, whether the blowout directly led to the crash or not. However, the overall GES distribution of crash severity in tire blowout involvements is probably about right. Tire blowout crashes are no worse than other truck crash involvements, and possibly somewhat less severe.

Fatalities and injuries in truck tire blowout crashes

Another approach to characterizing the size of the truck tire blowout problem in safety terms is to consider fatalities and injuries resulting from tire blowout crashes. Table 2-8 provides counts of trucks and fatalities for 1995 through 1997. All fatal truck involvements are shown along with truck tire blowout involvements to show the relative magnitude of the problem. Overall, 14,768 trucks were involved in a fatal crash between 1995 and 1997. These fatal involvements accounted for 16,101 deaths. Of the fatal involvements, 52 included a truck tire blowout as part of the crash. These 52 tire blowout involvements resulted in 62 total fatalities over the three years. Truck tire blowouts are only 0.35 percent of all fatal truck involvements. The 62 fatalities amount to 0.39 percent of all the truck-involved fatalities during the period. In other words, 99.61 percent of the fatalities occurred in crashes in which truck tire blowout was not involved.

Table 2-8. Trucks and fatalities for all fatal crashes and truck tire blowout fatal crashes. (TIFA 1995-1997)

	all truck fatal involvements		truck tire blowouts	
year	trucks	fatalities	trucks	fatalities
1995	4,631	5,091	20	24
1996	5,007	5,395	15	19
1997	5,130	5,615	17	19
total	14,768	16,101	52	62

The only data base available that permits national estimates of injuries due to crashes involving truck tire blowouts is the GES file. Because of the small sample sizes and consequent sampling errors discussed above, showing estimates for each of the data years is not useful. However, over the three years, 1995 through 1997, an estimated 357,000 (±46,000) persons suffered an injury in a truck crash. Of these, an estimated 663, or 0.19 percent, occurred in a crash precipitated by a truck tire blowout. The 95 percent confidence interval for injury totals over the three years ranges from 20 to 1306 (large variance due to limited sample size).

State data analysis

State files of all police-reported crashes from North Carolina, Texas, Michigan, and Washington were reviewed for any information they might contain on tire-blowouts in truck crashes.

North Carolina, Texas, and Michigan record tire "defects" in a vehicle-condition variable. Tire defects can include a number of problems other than just flats or punctures. None of the states specifically identifies blowouts in the crash data. To identify blowouts, it would be necessary to review the original police report. The review of TIFA cases reported above showed that only about 40 percent of reported tire defects were blowouts. The TIFA file is restricted to fatal crashes, but there is no reason that the blowout proportion of tire defects would be any greater in nonfatal crashes. It may even be lower. Since tire blowouts are only about 40 percent of tire defects in the TIFA file, it was judged not worthwhile to pursue the small number of tire defect cases any further. Any analysis of this data would be an analysis of crash involvements that primarily did not include a blowout. In any case, the rate of tire defects reported in the three state files is only about 0.4 to 0.5 percent of all truck crash involvements. This is very close to the proportion of tire defects in fatal truck involvements, 0.52 percent also reported in the analysis of TIFA cases.

The State of Washington crash file includes "tire puncture" as a category in a "vehicle defect/condition" variable. Truck crash involvements from the most recent three years of Washington data available (1994-1996[4]) were combined into a file for analysis. The combined file of 21,153 truck involvements over three years includes only 62 truck tire blowouts. Thus, only 0.29 percent of truck crash involvements for 1994-1996 in Washington state included a tire blowout. This percentage is similar to the 0.35 percentage for fatal crashes reported in the analysis of TIFA data. It is also very close to the estimate of 0.25 percent of truck involvements from the GES file.

Table 2-9 shows the proportion of single- and multi-vehicle involvements in the Washington data. As in the case of the GES data reported in table 2-6 above, tire blowouts are predominantly single-vehicle crashes. However, the GES file estimated that almost 88 percent of tire blowouts result in single-vehicle crashes, while only about 65 percent of tire blowouts in the Washington data occurred in single-vehicle crashes.

Table 2-9. Number of vehicles involved for truck blowout involvements and other truck involvements. (Washington 1994-1996)

	blowout		other	
crash type	N	%	N	%
single vehicle	40	64.52	3,228	15.26
multi-vehicle	22	35.48	17,925	84.74
total	62	100.00	21,153	100.00

This is not a serious discrepancy. The coding in GES is for the event that directly led to the crash, while in the Washington data, it is recorded as part of a multiple-response variable characterizing vehicle condition. It is likely that some fraction of the blowouts do not themselves cause a crash. The review of fatal crashes reported above showed that tire blowouts on non-steering axles generally do not seriously affect vehicle handling. Moreover, some of the punctures recorded in the Washington data may even be the result of the collision.

[4] The State of Washington changed its data collection system for the 1997 accident year. As a result, the state has been unable to provide crash data files for 1997 or subsequent years to outside users.

In the Washington data, Table 2-10, tire-blowout related crashes appear to be somewhat more severe, compared with other truck crash involvements, with somewhat higher percentages of nonincapacitating, incapacitating, and fatal injuries. However, it should be kept in mind that there are only 62 tire puncture cases in three years of the Washington file, so a change of one or two cases can easily explain the differences noted.

Table 2-10. Crash severity for truck-tire blowout and other truck crashes. (Washington 1994-1996)

	blowout crashes		other crashes	
crash severity	N	%	N	%
no injury	36	58.06	13,977	66.08
possible injury	9	14.52	3,697	17.48
nonincapacitating injury	11	17.74	2,331	11.02
incapacitating injury	3	4.84	670	3.17
fatal injury	3	4.84	189	0.89
unknown	0	0.00	289	1.37
total	62	100.00	21,153	100.00

Crashes related to truck tire debris

A secondary effect of truck tire blowouts is the debris left on the roadway by blowouts. While a blowout can cause a truck to lose control, leading to a crash, the debris left from a blowout may cause crashes later on, if light vehicles either strike the debris or lose control while trying to avoid the material. Existing crash data files were surveyed for any light they could shed on crashes related to running over or dodging tire debris from truck tire blowouts. Note that in these crashes, the truck has long since departed the area, so these are crashes where it is likely that no truck was involved as a contact vehicle.

FARS, GES, and files from the states of Michigan, North Carolina, Texas, and Washington were examined for any meaningful information on crashes related to truck tire debris. Not surprisingly, no file directly codes any information that identifies debris from truck tires (which can include retreads), much less tire debris directly associated with truck tire blowout events. However, FARS identifies crashes in which the driver swerved to avoid debris in the road. GES includes a code for crashes caused by an object in the road.

In FARS, the pertinent variable is a multiple response variable used to record "driver-related factors." These factors include any driver action that may have contributed to the crash. One of the codes is "avoiding or swerving due to debris or objects in the road." The type of debris or object in the road is not identified. It includes any non-fixed object in the road: tire debris, mufflers, fallen trees, lost cargo, etc. However, since tire debris is included in the code, the number of such cases can serve as an upper limit to the incidence of tire debris crashes. In three years of FARS (1995-1997), 181 cases were identified where a driver swerved to avoid debris. This amounts to 0.16 percent of the 111,853 fatal involvements over those three years.

In the GES file, the relevant variable records crashes precipitated by an object in the road. Where the FARS variable implies that the object contributed to the crash, but did not necessarily lead immediately to the crash, the GES variable is used to identify the immediate "cause" of the crash. Three years of data were examined to identify crashes related to objects in the road, 1995 through 1997. In those three years of police-reportable crashes, an estimated 0.53 percent of traffic crashes were caused by an object in the road. The estimate is for all police-reportable crashes, not just fatal crashes. Moreover, crashes related to all types of objects in the road are included, not just those caused by tire debris. Any type of object, from an errant soccer ball to a fallen tree, is included. So the estimate of 0.53 percent is the maximum proportion of traffic crashes related to truck tire debris. The true proportion (if only those crashes caused by tire debris were included) is likely to be much lower.

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3. Information Review of Truck Tire Blowouts

This section of the report includes a summary of information found in library resources (journal and article databases, online information services, research reports) and industry contacts (professionals and officials who are involved with tire manufacturing, maintenance, and management).

Literature Review

There has been very little crash analysis with respect to truck tire blowouts. The National Transportation Safety Board (NTSB) has investigated six truck crashes since 1972 involving "tire failure," but these crashes do not provide a comprehensive picture. The crashes investigated by the NTSB encompass a variety of causal mechanisms. The following list summarizes the causes of the six NTSB-investigated tire-failure crashes (some of these are addressed later in more detail.)

1. In a 1971 crash, the crash was precipitated by a flat on a passenger car, which was being repaired on the side of the road. Traffic backed up and a truck hit the queue. There was no blowout on the truck [25].
2. A crash occurring in 1973 was caused by an undetected nail puncture to a front tire of a tractor-semitrailer causing a slow leak. Under-inflation of the tire caused heat build-up which in turn led to failure of the tire side wall [17].
3. A 1980 crash involving a truck and a school bus was caused by a badly worn steering axle tire of a tractor, which had some tread separation. The tire finally blew, causing loss of control of the truck [18].
4. In a 1983 crash, an undetected nail puncture in the left front tire of a school bus caused a slow leak, which in turn resulted in side wall heat buildup and subsequent blowout [26].
5. In another 1983 crash, a truck was struck by another vehicle. The impact ruptured a tire. The blowout was after impact; it did not cause the crash [19].
6. In a 1985 crash involving a propane truck, the left front steering axle tire suffered tread separation and the driver lost control. The tire probably deteriorated over an extended period of time. Previous vibration had been noted, tires were found to be out of round and were balanced only with difficulty, yet the operator continued to use them. Eventually, the tread separated and the tire failed [27].

Excessive wear that may cause tread separation, and low inflation pressure due to slow leaks from undetected nail punctures, were the predominant factors among these cases. But the cases themselves are essentially anecdotal and therefore provide no insight into the magnitude of the truck tire blowout problem or, despite the depth of investigation, the primary factors associated with tire failure.

A 1972 report from the Bureau of Motor Carrier Safety (BMCS) [12] concluded that tire failures were the second leading cause of mechanical defect-related crashes at that time, accounting for 1,186 tire-related crashes from 1968 to 1970. Front tires accounted for two-thirds of the tire failures. Right front tires failed more often than left, possibly due to damage from hitting curbs. Other possible explanations for this asymmetry include the crown of the road shifting the truck load to the right, or that a left front tire failure may <u>less</u> often lead to a crash since the driver has more time to get the vehicle under control (with lighter load on the tire, the steering response to failure will be less abrupt.) The proportion of all truck involvements caused by tire failure was not addressed.

In 1977, the relationship between front-axle load of truck tractors and the safe operation of such vehicles was addressed in a report to Congress [1]. The study was initiated following an increase in allowable gross weight, authorized by the Federal-Aid Highway Amendments of 1974 for the interstate system. The new limit of 80,000 lbs. would result in a load distribution on the tractor's axles such that 34,000 lbs. could be placed on each of the tandem drive axles, while the front axle could carry a maximum load of 12,000 lbs. The report focused primarily on the following four aspects of front-axle loading: (1) steering effort, (2) directional stability, (3) vibrations and ride, and (4) safety issues due to the potential of a front tire failure.

The report [1] provides historical background to the federal involvement in highways since 1802 and describes legislative efforts regarding weight limitations at the federal level between 1956 and 1976. Single-axle load limits that were discussed as part of the legislation were up to 20,000 lbs. Labor representatives recommended that a load restriction of 10,000 lbs. be placed on the front axle to reduce steering effort and increase safety in the event of a tire blowout. Manufacturers, on the other hand, recommended that no specific load cap be imposed, rather, that the design rating of the tires and suspension components be used.

Results of another study [2], conducted in 1977, evaluated front-tire failure. From the limited literature available, it was concluded that front-tire failure was not a major causal factor — less than 2% of truck crashes. At the same time, however, it was found that such crashes have the highest fatality rate and property damage costs of all truck crashes. Additional meaningful findings were: (1) failed tires had significantly less tread depth, (2) "significant increase in gross vehicle weight exists for trucks with front tire failures compared with other accident involved tires," and (3) tires failed primarily because of manufacturing defects. The analysis also finds that "non-significant differences exist between failures of left and right tires on the steering axle." Between 1969 and 1975, there were a total of 298,338 truck crashes, of which 2,290 were front-tire crashes (about 0.8%). These crashes resulted in 133 fatalities and in more than $21,000,000 property damage.

A similar analysis that was performed in the United Kingdom [3-6] attributed a much higher proportion (3% – 12%) of truck crashes to tire failures. However, those numbers are regarded with skepticism, as studies by Baker and McIlraith [7-10] showed that tire-failures are often alluded to incorrectly as the cause of the crash.

The report to Congress [1] also describes tests and simulations that focused on investigating the effect of front axle loading on steering effort, directional stability, and ride vibrations. The report describes past and current (for 1976) efforts to establish, legislate, and enforce axle load limits. To gauge the existing state of affairs, statistical data were used to present and analyze the extent and frequency of steering axle loading. Recognizing the variety of applications and suspension configurations, alternatives to setting some specific axle-load limits are then discussed.

The conclusions of this steering axle study report by the Bureau of Motor Carrier Safety (BMCS) [1] regarding safety issues associated with front-tire failure, include: (1) overloading of tires and/or suspensions beyond the manufacturer's recommended limits is unsafe and may cause a crash; (2) "front tire failure accidents are usually more severe since steering control of the vehicle may be lost"; (3) crashes caused by front tire failure are rare, and usually result in single-vehicle crashes; (4) in 1974, a small percentage of commercial vehicles have a front-axle load of 10,000 lbs., and a much smaller percentage had front-axle loads over 12,000 lbs.; (5) "data are not presently available that justify limiting the load on front axles to 10,000 pounds." The 1977 BMCS report also concludes with a recommendation **not** to pass federal legislation that specifies a front-axle load limit, "but the tire loading requirements of the Federal Motor Carrier Safety Regulations should be a requirement for all commercial motor vehicles, whether in interstate or intrastate commerce."

Findings from another study [11] in 1974 conducted by HSRI (Highway Safety Research Institute — now known as UMTRI), were extensively used in the report to congress [1]. These findings provided similar statistical results as noted above. Data sources included (1) the BMCS crash reports, (2) crash records from two large carriers, (3) three years of crash data from the State of Texas, and (4) crash data from the states of Indiana, Ohio, and Pennsylvania turnpikes.

Dunlap's report [11] is the most comprehensive crash analysis on truck tire blowout in the last thirty years. About 4 to 5 percent of all truck crash involvements were linked to tire failure. Dunlap did not address the discrepancy between the rate of involvement derived from the BMCS data and the much higher rates from the turnpike data. In general, Dunlap found that truck crashes resulting from tire failure were predominantly single-vehicle crashes, involving neither injury nor death.

Literature, interviews, and crash databases were used in HSRI's report [11] to analyze the extent of a truck tire blowout occurrences, and to asses the character and frequency of the resulting crashes. One of the main findings in this study was that "in general, truck crashes resulting from tire failure were found to be so rare as to make only a minor contribution to the total body of accident statistics." And also "...because such accidents are almost always single-vehicle involvements, the traveling public is not greatly endangered by the occasional accident resulting from the failure of a truck tire." This study also amplified the finding of [1] that, for the most part, tire-failure crashes are single-vehicle crashes. However, regarding fatalities, the report to congress study [1] found that "these accidents have the highest fatality," while the HSRI study [11] was less clear, noting that "the fatality rate ... is greater ... in the State of Texas and on the Indiana Turnpike, but less ... on the Ohio and Pennsylvania Turnpikes."

Regarding the left/right failure rate of front-axle tire blowouts, the HSRI study [11] differs from the Biotechnology report [2] insofar as observing somewhat more right-side tire failures, versus a more even left/right distribution cited in [2].

Another important aspect of tire failures that was addressed in the HSRI study regarded the failure of retreaded tires. Based on BMCS data [12-16], the study states that "it is evident that the majority of tires which fail in tire-failure accidents are tires with original grooves." The explanation given is that since retreaded tires are typically not mounted on steering axles, and since most tire-failure crashes are due to a failed front tire, that "if a tire fails and causes an accident, it will typically be a front tire with original grooves."

Of those factors cited in [11] as potential reasons for tire failure, maintenance practice seems to be most significant. Though the study recognizes that "worn tread is <u>not</u> a major cause of front-tire failure," it also includes results from BMCS roadside-inspection reports that "4% of the inspected tractor-trailer units had front axles which were potentially overloaded. ... as much as 60% of the front tires were under–inflated."

Findings from the literature, mostly point out that maintenance is the main cause for highway truck tire blowouts. This view is also shared rather widely by the tire and trucking industry (see feedback from industry contacts in Section 4). Crash reports by the NTSB also support this observation. A crash report [17] from October 1973, describes a crash where the front-left tire (tubed) of a tractor-semitrailer blew out on the New Jersey Turnpike, causing the truck to veer to the left through the guardrail and into the oncoming traffic where it collided with a passenger car and a Greyhound bus. The two occupants of the passenger car, the bus driver and six passengers were killed. The NTSB concluded that the tire blowout was caused by a sidewall failure due to under-inflation. The state of under-inflation was the result of a slow air leak caused by a nail.

Another NTSB crash report [18] from April 1980, describes a crash where the front-left tire (tubed) of a truck-tractor blew out on a rural two-lane California highway. As a result the tractor swerved to the left, crossed the centerline, and collided head-on with a schoolbus. The bus driver and three students were killed. The NTSB concluded that the tire blowout was caused by inadequate maintenance by the trucking company. The deterioration of the tire was gradual, and should have been detected during inspection. California Highway Patrol Inspectors were also interviewed since the vehicle was inspected 6 days before the crash without detecting the unsafe tire.

In an April 1983 NTSB investigation, the front-left tire of a tractor car-carrier semitrailer travelling on a rural two-lane New-York highway hit a towed farming device and blew out [19]. As a result, the tractor swerved to the left, crossed the centerline, and collided head-on with a bus. The bus driver and four passengers were killed. The NTSB concluded that the tire blowout was caused by a reason unrelated to the truck's operation and maintenance. However, the loss of control was attributed to the front tire blowout.

Reference [20] is a 1964 collection of papers focused on cost issues that are related to commercial truck tires. The parts of this collection that pertain to tire failure are those that discuss retreading and tire life as affected by faulty maintenance and operations. It should be noted that when these articles were written, bias-ply, tubed tires dominated the market. At that time, the usage of tubeless radials have not yet reached a significant level with commercial fleets. The benefits of retreads are noted and measured in terms of dollars/mile (from new until the tire is scrapped). Regarding failures of retreaded tires "most part of the blame is generally placed on either poor inspection of the retread candidates or poor shop practices." However the article goes on to indicate that "our experience has shown that in tires with a sound carcass retreaded in a first-class facility, there will be very few premature failures." Interestingly, the article states that even though tubeless tires are more likely to "slowout rather than blowout," (slowly leak) they have a higher potential to become inferior retreads. When a tubeless tire is punctured in such manner that a slow leak develops, the initial air pressure can penetrate the plies in the carcass, causing earlier separation and other oxygen-induced deterioration.

To date, the 1975 report by Dynamic Science [22] is the only documented effort that was found which performed a side-by-side evaluation of commercially-available devices for minimizing the effect (not the occurrence) of tire blowout. The report summarizes work done by Ultrasystems, Inc., under contract with the BMCS (Bureau of Motor Carrier Safety). In addition to the testing of devices, the work encompassed investigating the magnitude of the front-tire failure problem, and testing of baseline tire failure for later comparison. Core assessment of the magnitude of the problem is similar to those determined in [1] and [11] and is based on related data sources.

The Dynamic Science report [22] also describes the dynamics associated with directional control of truck tractors, including steering and suspension geometry. A simplified analysis showed that if the truck is on a straight course, a tire failure will translate into a manageable addition of 20 lbs. of force and 12 degrees turn of the steering wheel. If the tire fails on a curve, the lateral load transfer compounds the problem, and it may cause up to 60 lbs. additional steering effort, and a 200 degree steering wheel turn. An exploded sidewall may also result in a brief impulse of up to approximately 150 lbs. This situation was determined to be very rare.

Road tests of tire blowouts by Dynamic Science while travelling in a straight line at 50 mph with a loaded five-axle tractor-semi supported their simplified analysis noted above and indicated about 23 ft-lbs of required driver steering wheel torque to trim the vehicle in straight-line recovery. Peak values of steering wheel torque were in the vicinity of 60 ft-lbs; peak steering wheel angles were about 180 degrees. Road tests also noted that within 6 seconds of the driver-initiated blowout, the tractor-trailer combination had traversed about 2.3 ft (average) off its course. (For unprepared drivers, the truck is likely to travel further into the adjacent lane.)

Twelve "counter-measure" devices were evaluated by Dynamic Science in [22]. Ten devices were external to the wheel assembly and were aimed at reducing the post-blowout loss of control (rather than preventing the sudden and complete deflation of the tire). Four devices were spring-loading mechanisms which clamp onto the axle. A typical design (by "Steer Safe") is shown in Figure 1.

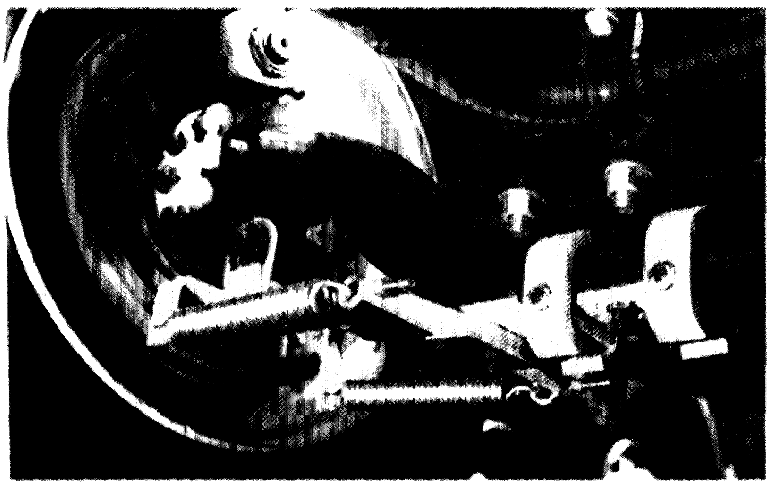

Figure 1. Steer Safe

Three other devices were similar in principle, but employed hydraulic shock absorbers instead of springs. Two were axle designs ("Center Point," and "Centerline") that eliminate the offset between the kingpin and the rim's centerline, thus reducing the leverage of the increased drag force from the deflated tire acting to steer the truck. Another device was an air-actuated power assist (like a bolt-on version of power steering).

The last two devices were individual designs which involved the tire/rim assembly: a (then) newly-developed tire (Cantilever), whose width and structure characteristics were such that reduced the likelihood of the sidewalls buckling and collapsing under the rim, and a "Safety Roller" insert, with a design similar to the "RunFlat" by Hutchinson (see Figure 2).

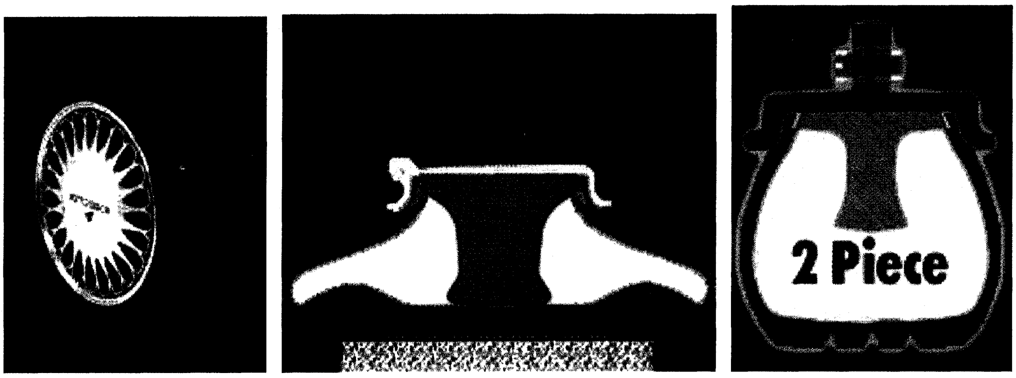

Figure 2. Hutchinson's RunFlat

Table 3-1 shows test results of the various devices evaluated by Dynamic Science [22] relative to the baseline test condition (shown in the first row of the table).

Table 3-1. Test Results Relative to Baseline Test.

Device	Mean Steering Wheel Torque (ft-lb)	Mean Tie Rod force (lb)	Peak Displacement Within 6 seconds (ft)
Baseline	***23.0***	***563***	***2.2***
Safety Rollers	10.4	199	1.4
Center Point	16.5	392	0.4
Cantilever tire	14.0	333	5.8
Centerline	11.0	475	1.0
Power-assist steer	11.5	510	2.7
Shure Guide springs	23.3	275	Unknown
Steer Line shocks	26.0	388	3.8
Cure Ride shocks	22.0	671	1.4
HECO shocks	27.0	798	1.3
Steer Safe springs	26.0	605	5.4
Positrol springs	26.5	550	2.4
Steering Stabilizer springs	24.5	475	4.9

The first table column lists the device variation, followed by three columns of test measurements showing: 1) mean steering wheel torque following blowout, 2) corresponding mean tire-rod force, and 3) the maximum lateral deviation of the vehicle within 6 seconds of the blowout.

A simulation study of the directional behavior of a truck-tractor combination following a front-left tire blowout was also examined in a 1979 SAE paper entitled "The effect of vehicle design on post blowout controllability" [21] by Bernard and Shapley. Their analysis used both linear and nonlinear simulation models. The models assume that following a tire blowout, a large amount of drag force is created accompanied by no side force. The assumed post-blowout normalized drag force coefficient for the blown tire was 0.3. The two main findings of this study were: (1) "the steer angle required to maintain a straight trajectory after a front wheel blowout is inversely proportional to wheelbase," and (2) "decreasing wheelbase and increasing compliance in the steering system serve to increase the severity of the post-blowout problem." An example simulation result showed that when the front tire of a baseline tractor with a 140 inch wheelbase blows out, the transient response required at the steering wheel (to maintain a straight trajectory) has a peak value of 180 degrees, and a steady state value of about 50 degrees.

To illustrate these observations further, Appendix A of this report includes results of computer analyses for left vs. right truck tire blowout scenarios using an existing UMTRI computer model. The simulation analysis helps to provide additional technical insight into the likely vehicle responses produced by front tire blowouts on heavy vehicles. The simulation results tend to support many of the observations reported in the technical literature and the crash statistics that cite the importance of front tire (steering axle) blowouts and the likelihood of ensuing path disturbances to the truck.

Federal Motor Carrier Safety Regulations, Rules and Notices

Some people in the tire and trucking industry as well as the public, though not necessarily the majority, view retreaded tires as a pitfall to safety, and as a significant contributing factor to tire failures — from premature disintegration as "road gators," up to blowout-related crashes. Based on data in the literature as summarized above, this notion does not seem to be strongly validated. In addition, information from industry surveys and interviews (see Section 4), further weakens that notion. Against that backdrop, a pertinent question is: What does the law say regarding limits of use of reconditioned tires (retreaded, recapped, or regrooved)?

Early regulatory efforts which led to current rules are presented in [23]. It is one in a series of suggested regulations composed by the members of the Truck and Bus Tire Committee of the Federal Vehicle Equipment Safety Commission in 1973. It is not clear what the final outcome of this regulation was or what form it eventually took, but it appears very similar in form and content to the current Federal Motor Carrier Safety Regulation (FMCSR) issued by USDOT [24]. Section 6.1 of document [23] states what shall be considered unsafe in regards to tire installations on the front axle of power units (trucks, tractors, etc.). Item (e) specifies as unsafe (for front-axle installation):

> *Any tire which has been retreaded, recapped, or regrooved, except that they are permissible when used on vehicles in intra-city (city and suburban) service or on vehicles 10,000 pounds gross vehicle weight or less.*

This definition of unsafe tire installation could not be found in the current FMCSR rules. However, a less strict version of such prohibition does appear in Appendix G to subchapter B of the regulation (see discussion below). At the same time, a limitation on installing retreaded tires on the front axle of buses is included in section 393.75 of the FMCSR, but it is not part of this VESC-9 regulation [23].

It appears that the FMCSR is the latest evolution of the work performed by the Federal Vehicle Equipment Safety Commission, summarized in the VESC regulation.

What is the current ruling? The pertinent Federal Motor Carrier Safety Regulations are found under Part 393, entitled "Parts and Accessories Necessary for Safe Operation." It is stated in subpart G — Miscellaneous Parts and Accessories, section 393.75 ("Tires") that:

> *(d) No bus shall be operated with regrooved, recapped or retreaded tires on the front wheels.*
>
> *(e) No truck or truck tractor shall be operated with regrooved tires on the front wheels which have a load carrying capacity equal to or greater than that of 8.25-20 8 ply rating tires.*

(NOTE: The FHWA is proposing to amend § 393.75(e) in order to make the requirements easier to understand. Section 393.75(e) prohibits the use of regrooved tires which have a load carrying capacity greater than that of 8.25–20 8-ply rating tires, but does not specify the load range rating for this tire. According to the Tire and Rim Association's 1996 Year Book, an 8.25–20 bias ply tire has a maximum load carrying capacity of 2,232 kg (4,920 pounds) at 793 kPa (115 psi) cold inflation pressure. This maximum capacity applies to tires of load range G. Tires with the load range of E and F have maximum load carrying capacities of 1,837 kg (4,050 pounds) and 2,041 kg (4,500 pounds), respectively. The FHWA is proposing to use the 2,232 kg limit under § 393.75.)

Furthermore, interpretation and guidance for these regulations listed on FHWA's website, provide the following question and answer:

> ***Question 3:*** *May a vehicle transport HM*[5] *when equipped with retreaded tires?*
>
> ***Guidance:*** *Yes. The only CMV that may not utilize retreaded tires is a bus, and then only on its front wheels.*

However, Appendix G to subchapter B — "Minimum Periodic Inspection Standards" states that "a vehicle does not pass an inspection if it has one of the following defects or deficiencies," and under the section that addresses tires, the following deficiency is stated:

> *(9) Regrooved tire except motor vehicles used solely in urban or suburban service.*

This suggests that trucks are not allowed to operate on the highways with regrooved front tires, <u>even</u> if the load carrying capacity is less than that which is specified by section 393.75(e) above (the equivalent to 8.25-20 8 ply rating tires). Consequently,

[5] Hazardous Material

the regulations and associated explanations seem to be confusing on the matter of retread usage.

Patent Database Research

Databases of U.S. patents (both domestic and foreign registration) were searched for devices, methods, and systems that are aimed at detecting, correcting, and/or preventing event sequences that can potentially lead to tire blowout. Most of these patented inventions, in one form or another, have already been discussed under the literature review and/or will be described in the context of future applications in the next section that discusses industry contacts. This section provides some specifics of the patent database research and details about pertinent patents not covered in other sections of the report.

During the last two decades, hundreds of patents related to tire safety and maintenance were registered. In many cases, what seems to be the same device, system, or method may have more than one patent registered. The bulk of these patents can be divided into three groups:

(1) recent development – new technology that is either under development or under advanced prototyping tests,

(2) commercially available – products that are available in the market, and

(3) exotic – products that were developed in the past and hold some potential, though their commercial availability is unlikely or limited

The patents described here fall primarily into groups (2) and (3). As one might expect from the nature of the tire industry, new developments are under strict confidentiality limitations.

However, information obtained from industry contacts indicates that the "hot spot" of upcoming tire development lies in what is often referred to as the *Smart Tire*: an integrated circuit that is embedded in the tire will monitor and/or report tire condition (e.g., pressure, temperature, etc.). Practically all the main tire manufacturers are working on such a system, and it has a promising potential for near-future deployment that will significantly reduce the frequency of maintenance-related tire failures (the cited cause of most tire blowouts).

The following list is a representative collection of patented inventions focused on tire safety and maintenance. U.S. patent numbers are cited in parentheses. As noted above, there is often more than one patent that describes similar systems. The last four items represent patents related to the Smart Tire. They date as far back as 1970. However, due to the lack of applicable technology, they were not put into a commercial-application track until recently.

- Dispenser for injecting viscous sealant into tire to protect against blowouts and punctures (5,908,145). The dispenser is filled with viscous sealing fluid which is admitted into the tire via a flexible hose and a pneumatic valve. Its purpose is to protect the tire against subsequent blowouts or punctures.

- Back up tire within tubeless tire (5,885,383). The back up tire is made of semi-elastic material mounted on the rim of the vehicle wheel and serves as a cushion between the rim edges and the tread of the tubeless tire when complete deflation occurs. It prevents the complete collapse of rims onto the outer tire, to avoid loss of control and minimize damage to both tire and rim in the event of a blowout.

- Internal flexible casing (5,840,274). A casing ring formed from rolled flexible laminated plastic sheets with air spaces between them inside the tire. The sheets are rolled into a cylindrical shape and formed into a ring so the opposite ends of the cylinder are adjacent. Its purpose is to help the tire to resists deflation when severely punctured or subject to a blowout.
- Onboard tire inflation system (4,498,515). Air inflation and control system for road vehicle and trailer tires. It has air line from an on-board compressor that is connected via a rotary pipe union to the tire's air valves.
- Security tire (4,305,444). A pneumatic tire and rim combination wherein the tire is captivated about the rim and a chamber is defined between the tire and the rim and a portion of the tire extends into the chamber within the carcass of the tire and serves as an annular support structure upon deflation of air within the tire, so that if it collapses, as by a blowout, a vehicle on which it is installed will continue to be supported by the tire as the interiorly extending annular portion of the tire engages the confronting surface of the rim.
- Tire pressure monitoring system (4,148,008). A wireless tire pressure monitoring system warns a driver of a vehicle of low pressure in one or more of its tires so that the driver may take corrective action before a tire blowout occurs. A pressure transducer, transmitter and antenna are integrally housed and mounted to the tire stem of a tire. When the pressure transducer senses a tire pressure below a pre-selected pressure, the transmitter broadcasts a radio signal that, upon detection by a receiver mounted on the vehicle, warns the driver of abnormally low pressure. In a preferred embodiment, the transmitter is a SAW (surface acoustical wave) device that is periodically interrogated by an RF signal from a transmitter on the vehicle.
- Air pressure control for dual tires (3,760,859). A device for equalizing the pressure in the pneumatic tires of a dual wheel assembly, employs a valve shuttle which has three positions: (a) it isolates pressure in one tire, (b) it equalizes the pressure between the tires, and (c) it isolates pressure in the other tire. A fill valve assembly has an element for holding the valve shuttle in position (b) so that the tire pressures are equalized during filling. Also, the valve shuttle closes by pressure differential in the case of a blowout or puncture of one of the tires, to prevent loss of pressure from the other tire. Furthermore, a pressure relief valve is provided to prevent overpressure in either of the tires.
- A heat detecting tire (a tire heat detecting system, 3,875,558). A coating of a heat sensitive electrically-conductive material set to melt at about 250-300°F over the inner surface of the tire and the bead area of the tire. The coating is done in such a way, that it causes a completion of a circuit through the tire when the tire is heated to excessive operating temperatures. It enables sensing when blowout conditions are approached and provides a warning thereof. Also, means are provided for

detecting under-inflation of a tire and warning the driver to prevent tire destruction from under-inflation.

- Dispensing fluid within a tire (4,130,144). An enclosed container having a divided chamber with an air pressure section and a liquid coolant section separated by a pressure-transmitting wall. When the tire loses air, the liquid is released into the tire cavity to an amount below the normal operating pressure as in the event of a puncture or blowout for cooling and lubrication of the tire.
- A low tire pressure warning system. (3,665,387, 1970 by Goodyear) For any number of wheels of a vehicle, provides dashboard indications of system operation and low pressure conditions while the vehicle is in motion. A pair of coils mounted on each wheel are interconnected under normal conditions by a switch responsive to tire pressure and periodically, due to wheel rotation, quench an oscillator circuit by reversing the normal magnetic field occurring in a second pair of coils in the oscillator. A low pressure condition or inoperativeness of the circuit is recognized by a red lamp indication or absence of any indication. A minimal warning system for a multiple wheeled vehicle are tire pressure switches for truck and passenger car applications.
- An active integrated circuit transponder mounted in or on a vehicle tire (5,483,827). A pressure sensor, a temperature sensor and a tire rotation sensor are mounted on a substrate along with the integrated circuit transponder chip, the power supply, and an antenna. Upon receiving an interrogation signal from a remote source, the transponder activates the sensors to sense tire pressure and temperature and transmits an encoded radio frequency signal to the remote source containing serial, encoded tire identification, tire position on the vehicle, current tire pressure, current tire temperature and accumulated tire revolutions, as well as maximum and/or minimum tire and temperature pressure values encountered over a predetermined time period and other information specific to the tire.
- A method and system for monitoring and measuring the amount of deflection of a pneumatic tire (5,749,984, 1998 by Michelin). A monitoring system in the tire detects tire sidewall deflection by measuring the length of the tire contact patch area relative to the total circumference of the tire. The embedded sensor device generates a signal which varies as it passes through the tire contact patch within the tire on a moving vehicle. The sensor's electrical signals are digitized and counted to determine deflection, tire speed and the number of tire revolutions.
- A method for monitoring various physical conditions of pneumatic tires, including a monitoring device (5,562,787, 1996 by Bridgestone). The invention relates to a method of monitoring tires which uses an active, self-powered programmable electronic device which is installed in or on the interior surface of a pneumatic tire or on a tire rim. This device can be used for monitoring, storing, and telemetering information such as temperature, pressure, tire rotations and/or other operating conditions of a pneumatic tire, along with tire identification information. The device can be activated by externally transmitted radio frequency waves or microwaves and in response, the device compares or transmits information and provides a warning in the event a pre-selected limit is exceeded.

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4. Blowout Resistant Tire Developments and Related Industry Contacts

The surveyed industry views maintenance as the primary cause for tire blowout. Consequently, their attempts to solve the problem are mainly focused on addressing the source. A great deal of effort goes into helping fleets in developing proper maintenance procedures and driver education. In addition, there are technological developments and specific hardware intended to assist in the task of monitoring and maintaining the tires. Potential devices aimed at minimizing the potential for tire blowouts are:

- Central inflation/monitoring system — the most promising and accepted in terms of cost-benefit and applicability.
- Monitoring by "Smart Tire" and computer chip technology — under development.
- Supporting inserts — potentially helpful, currently used only on military and security vehicles.
- Tire filling (e.g., with some rubber substance) — not applicable for highway trucks due to heat.

Information from various entities related to the tire industry and tire usage have been collected via interviews and official publications. These organizations include tire manufacturers, industry organizations, manufacturers of other tire-related products, truck fleets, and the U.S. Army. This section presents summaries of the information obtained from each organization.

Maintenance Council of ATA (American Trucking Associations)

Ms. P. Fisher from the Maintenance Council provided information about a study entitled "Tire and Retreads in the Commercial Truck Market," conducted by Newport Communication in 1998. This study is an outcome of investigated "tire usage, maintenance, specification and purchase for both new tires and retreads." Some of the main findings that pertain to tire usage and maintenance are that:

- Retreads are used by 78% of the fleets.
- Retreads are used on 46% of drive axles.
- Retreads are used on 61% of trailer axles.
- Short-haul (local / regional carriers) fleets hurt most by road hazard damages (17% of failures)
- Short-haul (local / regional carriers) fleets use significantly more retreads than long-haul fleets.
- The bigger the tire the longer its life.
- More than 90% of the fleets perform their own inflation checks.
- 60% outsource tire maintenance.
- 88% maintain tire records.
- Cost per mile: 75% calculate it for new tires, 82% do not calculate it for retreads.
- Retread's life is 67%–78% of a new tire, depending on haul length.

Interim results were presented in March 1999 from an ongoing task force on tire debris prevention (aka "Rubber on the Road" task force). This task force was put together by the Maintenance Council (since 1995), and it is chaired by Ms. Fisher. Findings of the task force were:

- Under-inflation caused about 86% of tire failures.
- There is an increase in maintenance issues.
- Fleet surveys about obstacles to proper tire maintenance, indicate that 58% drivers do not pay attention, 52% drivers do not think tire maintenance in their job, and 32% of drivers lack proper tire maintenance education.
- Only 67% of fleets have written tire maintenance procedures.
- Fleet surveys indicate that only 22% of drivers check pressure before each trip; only 37% use a pressure gauge; 87% of the fleets check pressure every 60 days or less on the tractor and every 90 days or less on the trailer.

Rubber Manufacturers Association (RMA)

RMA has no statistics regarding recent tire-blowout data. Regarding blowout-related devices, RMA supported the information gathered from other sources, that no anti-blowout, or post-blowout stabilizing devices are currently used on heavy commercial trucks. For the most part, the industry is focused on the root of the problem — maintenance.

"Tire Chip," "Smart Tire," etc., — different names for a similar product concept — is under development by most tire companies. It involves the placement of a computer chip in the tire so that it stores information and transmits it. It is not yet ready or available for application in heavy commercial trucks. One of the reasons is technical difficulty in having to survive the multiple life cycles: it has to be part of the carcass of the tire, so that when the tire gets stripped and retreaded or regrooved, the chip would still maintain its functionality. Additional issues that need to be resolved are: (1) the ability to provide simple go/no-go information instead of pressure and temperature values, and (2) bookkeeping issues regarding keeping track of the tires, rotating tire locations, mixing trucks and tractors, etc.

In response to an inquiry regarding means that are viewed by the RMA as supportive for tire preventative maintenance, and which are used by fleets, they point to the central tire inflation system (such as Pressure Systems International by Meritor, Cycloid, and Hutchinson). It monitors and/or maintains proper tire pressure. In principle it senses air losses per axle, or in the case of some more elaborate systems – per side of the axle, and it warns the driver (about an axle or an axle-side, but not an individual tire) if it deems that the pressure loss is abnormal. It also has the capability to automatically correct the problem (only to a limited extent) by inflating the tire.

Concerning retreads on a front axle, the norm in industry practices (though the law might allow a more lenient approach), is to install the newest tires on the front axle for best steering and because of the crucial impact of that location in regards to blowout. As the tire gets old, it is generally moved rearward onto successive axles. There are exceptions to this practice, however, as in the case of trash truck. Because of the abuse that their front axles are subjected to and the multiple retreading they receive, the "freshest" tire is not always mounted on the front axle.

Tire Retread Information Bureau (TRIB)

One of the main focuses of TRIB is to refute the unjust blaming of retreads for tire failures (blowouts and "road gators"). The vast majority of these incidents involve bad maintenance, low pressure, overloading, or other factors that are not related to the fact whether the tire was retreaded or not. By examining samples of tire debris on the road, they show that they contain carcass elements (ply belts) which indicate failure at locations other than the retread area (retreading involves only the rubber in the tread area.)

According to TRIB, disintegration and blowout of tires can almost always be attributed to lacking maintenance: under-inflation, overloading, tire mismatching, etc. Regarding means to avoid that phenomenon (other then proper driver and fleet maintenance procedures), it was indicated that central tire inflation systems hold a promising potential. As it was maintained "[a central tire inflation system] is a system whose time has come – it is only a matter of time before all heavy commercial trucks will have it." This system has a tremendous long-term value as far as safety and tire life."

U.S. Army Tank-Automotive Command (TACOM) / Radian

The U.S. Army uses CTIS (Central Tire Inflation System) to maintain and control pressure. However, these systems are employed only in tactical vehicles, primarily by their mission definition (not in highway commercial-type trucks such as the M915/M916). The system's response is rather slow, and the tires sometimes fail during the transition time because they are under-inflated for the loading and speed conditions (that is, when drivers do not wait to complete inflation when getting on the highway.)

Devices such as Hutchinson's "RunFlat" are used on tactical vehicles, especially Hummers and lighter trucks. They also used bead-locks without the supporting insert ring (also by Hutchinson), to hold the tire beads in their place on the rim, in case of a tire failure.

Most failures come from the sidewall ("zipper" failure.) When the vehicle is used off the road, they must run under-inflated to increase mobility. The added vertical flexibility of the tire stresses the sidewall, and the generated heat causes premature tire failure (especially when a hot, stressed tire gets on the road and start being operated at highway speeds, before cooling down and/or reaching proper inflation pressure.) In addition, impacts with off-road objects (rocks, etc.) magnify the tire-damaging problem, and increase the likelihood of the tire blowing out. Often, ply cords break inside the tire with no outside indication that will provide a warning for an imminent tire failure.

Radian is an engineering services corporation, which provides (among other clients) technical support services to TACOM. They are working in cooperation with TACOM on developing an infrared (IR) -based system to detect defects/potential failures in the tire. The core idea is based on the hypothesis that the heat buildup can be characterized and related to various potential failure modes. Currently they are testing tires to build a knowledge base and to create databases of answers for questions such as:

What do good tires look like to the IR camera? How do certain defects/damages seen on the IR image? The objective is that eventually, by having a truck driven past the IR camera (e.g., when going over the scales in a weighting station), the tire image will provide information that will allow an immediate analysis of the "health status" of the tire and even to predict an imminent failure so that the tire can be prevented from going on the road again.

The following two infrared photographs in Figure 3 illustrate the benefits and the potential of this IR system. The top picture was taken in a laboratory during a research work involving thermal-imaging analysis of tires (US. Army TACOM/TARDEC report "Endurance/Infrared Tire Test," dated 29 March, 1999.) The picture shows the top half of a tire with broken cords which were not apparent externally. The second picture is a frame captured from a video made by Radian Inc. intended to demonstrate the concept of using thermal-imaging video camera to monitor the condition of truck tires as they go by. The direction of motion is from left to right, and clearly the rear dual set is hotter than the front set. However, there are no apparent hot-spots.

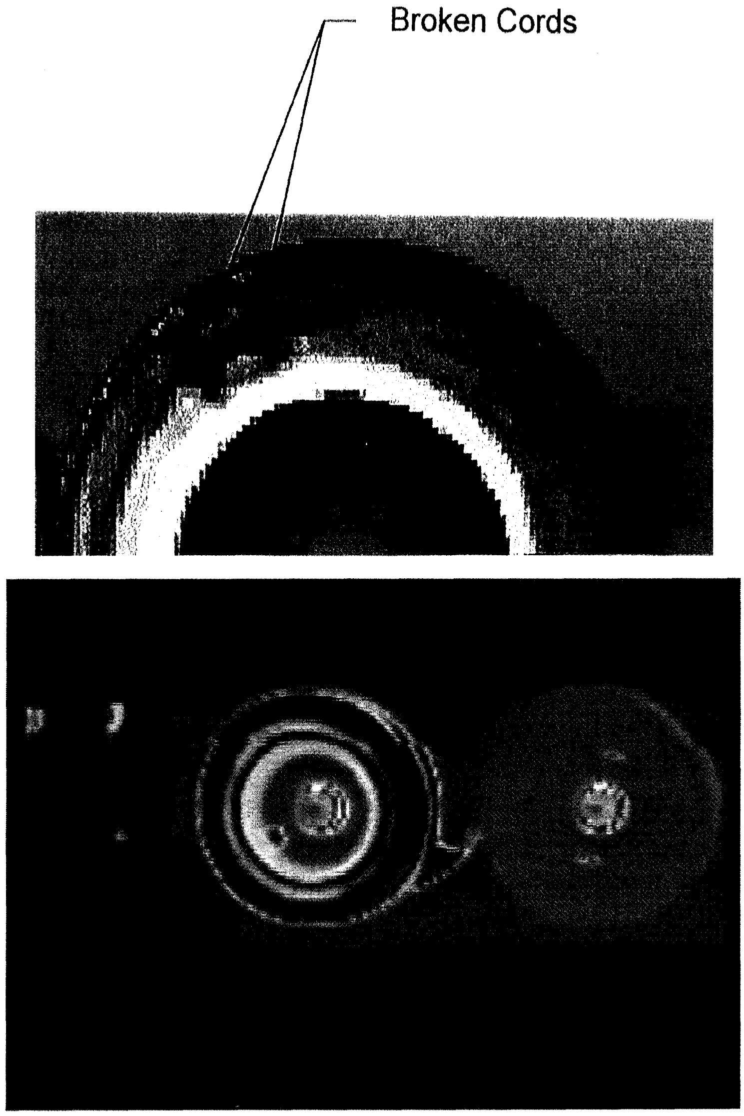

Figure 3. TACOM / Radian Infrared Photographs

Fleets

Inquiries regarding tire-blowout experience of some major trucking fleets indicate that most fleets view blowout prevention as more of a cost issue than a safety issue. In addition, blowout of a front-axle tire followed by the loss of control is considered a very rare event, one that a trained and alert driver could avoid. Proper tire maintenance practices should be applied to all the tires on the rig, regardless of their location. In addition, they affirm RMA's assessment that the norm in industry practices is to install the newest tires on the front axle for best steering and due to the importance of that tire location. The general notion is that "...unless you hit a road hazard, your front tires will not blow."

For the most part, fleets are concerned with the rear tires and the trailer tires. They are almost exclusively installed in a dual configuration. When one tire fails, the driver may not even notice it until the damage is too high. The tire may disintegrate, with its debris impacting upon its dual mate (which is already overloaded, carrying the load of two tires), and possibly causing it to fail as well. This mode of failure may be accompanied by fire. The common method fleets use to combat this issue (in addition to maintenance practices) are systems such as central inflation and pressure/temperature monitors.

Tire Manufacturers

All the tire manufacturers unanimously agree with the assertion that inadequate maintenance — through its various aspects — is the leading cause for tire blowouts. From the findings of the "Rubber on the Road" Task Force (noted earlier), the vast majority of tire failures are due to maintenance issues (90% were under-inflation). As a result, the industry is focused on the source of the problem as the means to prevent it. Specifics that were learned from individual manufacturers are provided below.

Goodyear

The company puts significant efforts into educating drivers and fleets about tire maintenance, including providing them with computer programs to help manage tires and maintenance. Blowout is a maintenance issue. Because of the control-loss ramifications, front tires are usually checked by the drivers, and are considered best-maintained. Therefore they "almost never blow out" (some staff reported that in 20 years of being in the business, front-tire blowouts were largely unheard of). Even when driving over an object, the front tire most often just "flips" it, and the rear tire gets blown. Trailer tires are most abused and most neglected, hence they are the ones that blow out most often (lease trailers, etc.) The industry addresses tire blowouts by education. A driver who is educated about tire maintenance and who pays attention to the tire's condition and air pressure will very likely not have a blowout.

Goodyear developed a blowout-resistant tire which can only be used on passenger cars. Run-Flat (Goodyear's system, not to be confused with Hutchinson's that is described later in this section) is built into the tire (not an insert). It is a sidewall reinforcement that supports the tire and prevents it from collapsing in the case of a flat.

Consequently, when a flat occurs, it may not be noticeable by viewing the tire. Therefore run-flat-equipped cars must also be equipped with a sensor system at each wheel to alert the driver to any loss of pressure. The low-pressure sensor system can be easily installed on any vehicle fitted with Goodyear run-flat tires. For passenger cars, it is designed to be driven with no air pressure for up to 50 miles at 55 mph and still be fully repairable. When evaluated for commercial heavy-truck application, Goodyear found that the sidewall would have to be 9 inches thick to support the vehicle when the air is lost, which is impractical (heat, weight, etc.)

Currently, there are no commercial means to prevent blowouts on trucks or to improve controllability in the case of a front-tire failure.

Michelin

Practically all the tire companies are working on electronic chips in attempts to monitor pressure/heat. There are various applications: extracting detailed information (what is the pressure? What is the temperature?) versus a pass/fail type of information (too hot/pressure too low). There are also data-related variations: data that are transmitted continuously to the cab versus data that are transmitted only as alarms, or data that are not transmitted at all. Rather, readers scan chips periodically at truck stops, etc. Cost will determine the various configurations that will be marketed.

There are challenges in applying this chip: It must be resilient enough to survive the thin tread of a worn tire, and to survive the intense heat of retreading. In addition, the installation must survive the extremely flexible environment of the sidewall.

The opinion of one Michelin engineer is that the number one reason for tire blowout is low pressure. However, it is not only maintenance: road debris which causes a puncture often leads to a blowout. He suggested looking at the statistics of blowouts, its correlation with the availability of funds for road maintenance, and the type of roads the truck travels on. In other words, road cleanup may have a meaningful contribution to tire blowout prevention.

Regarding Goodyear's patented run-flat for trucks: the technology to make something like it is almost here. It will not fully sustain the shape of a properly inflated tire, rather it will prevent the total collapse that results in loss of control (allowing a "limp-home" mode). Commercializing such a tire is mostly a cost issue. Michelin has developed "PAX" (see Figure 4), which is another run-flat device (similar to Hutchinson's). It was shown in trade and auto shows for passenger cars so far, but the concept also can be applied to trucks.

Several after-market pressure monitors may be a possible solution until the chip-in-the-tire technology is commercially available. Examples include SmartTire by a Canadian company, Schereder, Eaton, etc. Central tire inflation pressure systems are a significant step towards reducing blowouts.

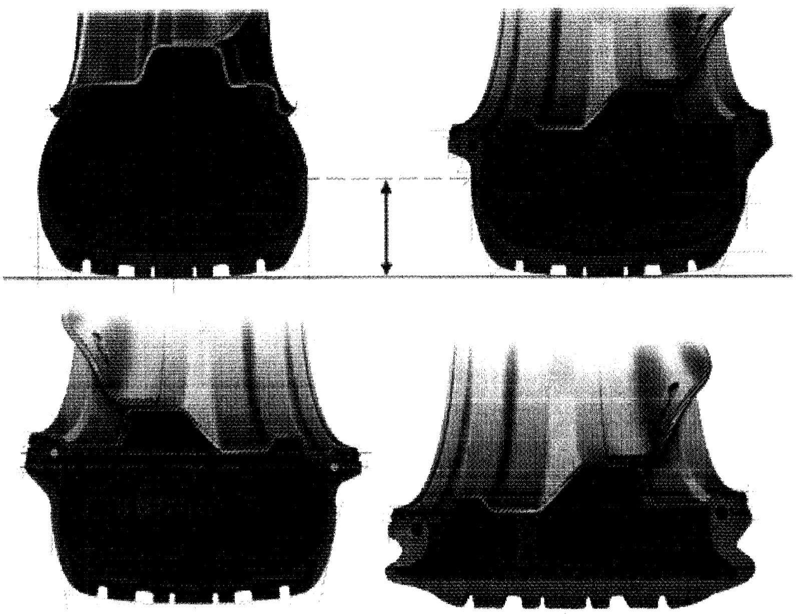

Figure 4. Michelin PAX System

Bridgestone

Bridgestone has reservations about the term "blowout"; they instead refer to this event as instantaneous air loss. The company shares the view of many in the industry that tire blowouts – instantaneous air losses – are caused primarily by inadequate air-pressure maintenance.

All of the main tire manufacturers are developing the microchip technology (one reason details are not currently available). The system can be set to trigger an on-board warning/information to the driver or to use a drive-by system (while entering fuel islands in truck refueling areas, yards of fleets, etc.) that displays the pressure/temperature information externally. This technology will be commercially available and useable in the near future (almost definitely by the end of 2001).

Regarding the control impacts of a front-tire blowout, Bridgestone believes the industry is doing whatever possible to prevent tire blowouts regardless of wheel location. In other words, there is no special effort that focuses on front-axle tire failures.

During workshops that Bridgestone conducts, it demonstrates a fully loaded tractor-trailer at 80,000 lbs. driving over an object that causes the front tire to blow. If the driver employs the correct technique (accelerate), the driver can still maintain the rig within the lane boundaries when a front tire blowout occurs.

Central tire inflation systems are a good idea, and they can serve as a solution to compensate for miscellaneous shortcomings in tire-maintenance practices. They are, however, cost-prohibitive in most cases.

Tire-Related Products

Hutchinson

Hutchinson's insert (see Figure 2) is called RunFlat (not to be confused with Goodyear's). Other than for military vehicles, they are installed in many fire-fighting and rescue trucks. Another major application in the civilian world is monorails. The conditions and motivation are just right for this type of a system: a very smooth running track which allows the insert to be positioned very close to the tire's inside surface, so that the "drop" that occurs during a flat is minimal. At the same time, because of the accurate alignment, too large a drop can cause snags and costly repairs. The cost benefit in this case is deemed justified.

Regarding heavy commercial truck applications, these trucks commonly use a drop-center tubeless wheel design with no "hump" to help set the tire bead against the rim's edge (see Figures 5 and 6). Instead, the surface of the rim is smooth, and even sloped towards the center. Installing RunFlat on such a rim will not be effective, as the tire will slide and "peel" off the wheel. In addition, the RunFlat ring has to be split into two halves to allow installation. Hutchinson makes heavy truck-size wheels that can work with the RunFlat device. They are successfully installed on General Motors heavy truck (commercial-type trucks used by the military) which are operating in Europe.

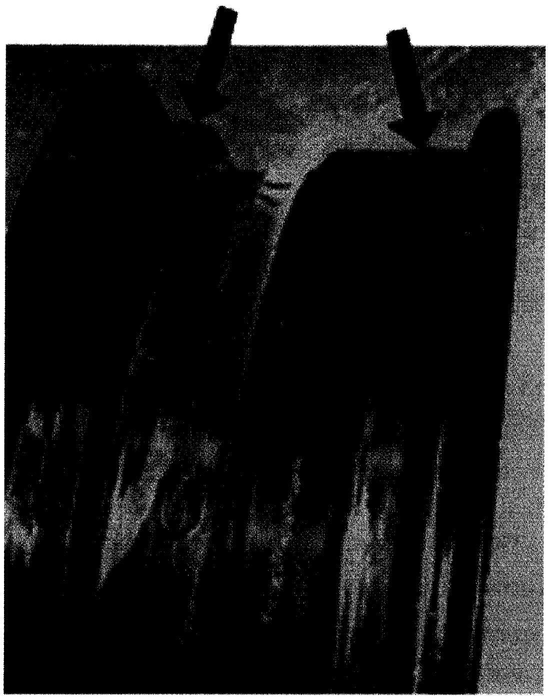

Figure 5. Light-Truck Wheel with "humps"

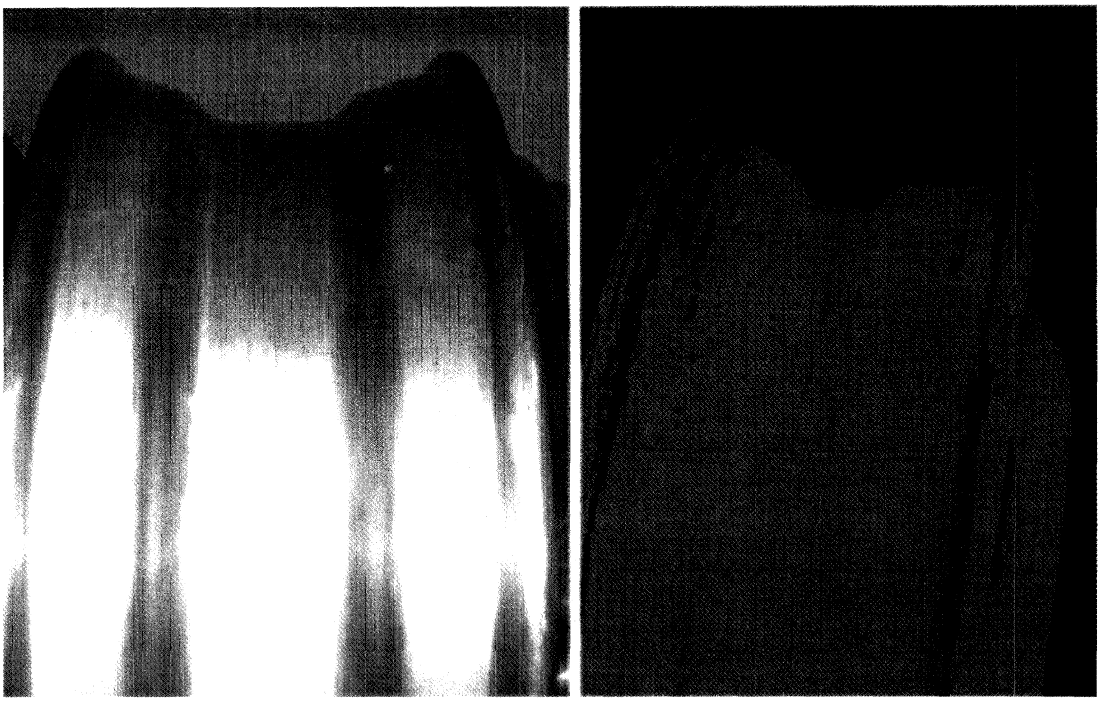

Figure 6. Smooth Truck Wheels

Hutchinson makes another anti tire-failure system, which is a rubber filling of the whole tire cavity. The rubber has "bubbles" which serve as air-chambers to provide cushioning and spring action. However, the heat generated during high-speed, highway operation prevents the application of this system in heavy commercial trucks. (This also applies to polyurethane filling that tends to break down and deteriorate when heated).

SmartTire

This system uses wireless technology to monitor the air pressure and temperature in the tires. It consists of a display receiver mounted within sight and reach of the driver and wheel sensors.

One sensor is mounted on each wheel, and the tire is then mounted over the sensor enclosing the unit for protection from the elements. Each wheel sensor contains: (1) a pressure transducer, (2) a temperature transducer, (3) a centrifugal switch, (4) a radio transmitter, (5) a unique ID code, and (6) a lithium battery. The interactive display module (see Figure 7) shows: (1) the required pressure, (2) the actual pressure, (3) the pressure status, and (4) the temperature.

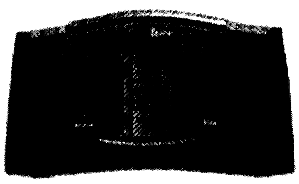

Figure 7. SmartTire Concept

Using two simple buttons, drivers can check the status of each tire. The sensors are activated with a centrifugal switch and transmit only when the vehicle is in motion.

When the vehicle stops, the sensors return to sleep mode but the driver is still able to see the last signals sent while the vehicle was moving. Sleep mode extends the life of the lithium battery.

Tyron Band

The Tyron Band, seen in Figure 8. is fitted to the vehicle's wheel and converts the standard drop-center tubeless wheel to what they call a "safety wheel." Following tire deflation, the deflated tire is locked to the wheel (see figure) to provide the driver with better control.

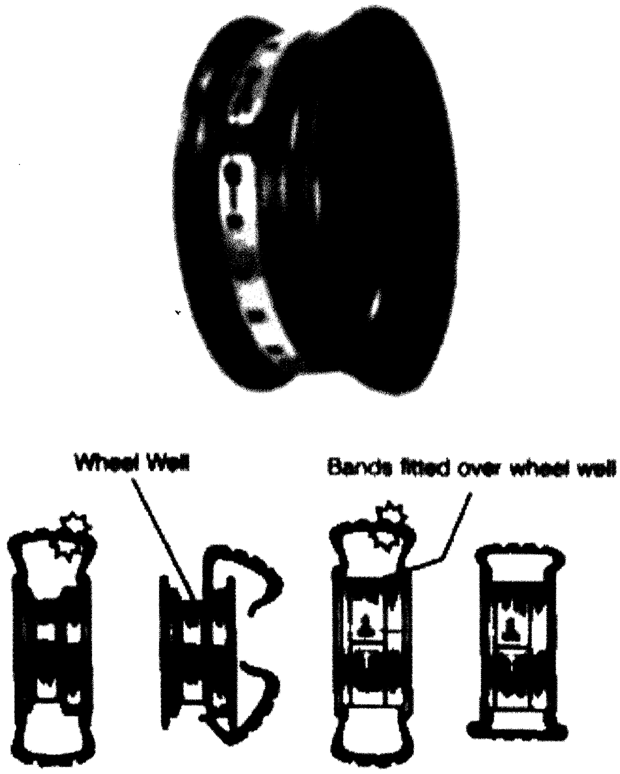

Figure 8. Tyson Band System

Principal Contacts And Information Resources For This Section

1. Peggy Fisher (*Maintenance Council of ATA*)
2. Gloria Bartholomew (*Rubber Manufacturers Association, RMA*)
3. Harvey Brodsky (*Tire Retread Information Bureau, TRIB*)
4. Arnold Pacis (*TACOM*)
5. Marlon Pena (*TACOM*)
6. Ray Schandelmeier (*Radian*)
7. Stephen M. Padula (*Michelin*)
8. Mark Berry (*Michelin*)
9. http://www.michelin-us.com/us/eng/innov/f_innova.htm
10. Al Cohn (*Goodyear*)
11. Rob Whitehouse, (*Goodyear*)

12. John Bruce (*Bridgestone*)
13. Dave Laubie (*Bridgestone*)
14. Phil Hall (*Hutchinson*)
15. http://www.hutchinsoninc.com/
16. http://www.smartire.com
17. http://www.lascointl.com/flat_tire_protection.html
18. http://www.psi-atis.com/
19. http://www.cycloid.com/

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5. Summary Observations

Summary of Crash Data Analyses (from Section 2)

Crash files surveyed included the Trucks Involved in Fatal Accidents (TIFA) file, which is based on the Fatality Analysis Reporting System (FARS); the nationally-representative sample of police-reported crashes in the General Estimates System (GES) file; and state files from the states of Michigan, North Carolina, Texas, and Washington. Analyzing these data produced the following findings:

- Tire defects are the second most common vehicle defect noted on trucks in fatal crashes, behind brakes. Nevertheless, coded tire defects are rare — 0.87 percent of trucks involved in a fatal crash are coded with a tire defect.
- Blowouts accounted for 40 percent of tire defects coded for trucks involved in a fatal crash.
- Blowouts occur in 0.35 percent of fatal truck crashes. There are 0.094 fatal truck crash involvements due to blowout per billion miles of truck travel.
- In fatal crashes involving blowout, 35 of 52 blowouts occurred on the front axle. The left steering tire suffered the blowout in 22 cases; the right steering tire in 13.
- Front axle blowouts in fatal truck crashes nearly always involved a loss of control. Drive and trailer axle blowouts usually do not lead to loss of control; in 9 of 12 such cases, the blowout did not directly cause the crash.
- Blowouts account for 0.25 percent of truck crash involvements of all severities. The rate of tire blowouts in all crashes, estimated from the GES data, is 1.695 blowout-related truck crashes per *billion* miles of truck travel. This rate compares with an overall truck crash rate of 671.16 truck crash involvements per *billion* miles of travel.
- Most (87.97 percent) blowout crashes are single-vehicle, except where a fatality is involved. In fatal crashes, 44.23 percent of tire blowout crashes involved only the truck.
- Between 1995 and 1997, 62 persons were killed in truck tire blowout crashes and 663 (± 643, — large variance due to small sample size) were injured. Over the same period, 16,101 persons were fatally injured in a truck crash, and an estimated 357,000 (±46,000) were injured.
- Of the state data files examined, only Washington state directly identified tire puncture as a vehicle defect. Between 1994 and 1996, 0.29 percent of truck crash involvements in Washington included a tire puncture.
- Crashes related to debris from truck tire blowouts in the roadway cannot be identified directly in any data, but using as a surrogate the more general category of object in the roadway, 0.16 percent of fatal crashes and 0.53 percent of all crashes are related to objects in the roadway. These percentages form the upper limit to the proportion of crashes caused by debris from tire blowouts. It is likely the true percentage from blowouts alone is much lower.

Summary of Information Review

When compared to the magnitude and significance of today's trucking industry, and its rapid growth during the last few decades, the amount of literature related to truck tire blowouts is relatively small. Furthermore, very little crash analysis and corresponding data exist. Only six truck crashes investigated by the NTSB since 1972 involved what they refer to as "tire failure." While it is understood that NTSB investigates only a limited numbers of crashes, the identification of just six tire failure crashes serves as another indicator that blowout-related crashes are quite infrequent.

Relevant findings from the literature are:

- Most of the documented research on this subject was performed between the 1960s and the 1980s.
- Tire-failure crashes are very rare.
- Based on a 1976 study [2], BMCS data (1973) shows front tire failure crashes to have a higher fatality rate and property damage costs than for all truck crashes.
- The availability of crash-site data is limited, and tires are often wrongfully cited as the cause of the crash.
- When a tire blowout results in a crash, it usually involves a front-axle tire.
- A front-tire blowout significantly degrades the directional control of the vehicle.
- Maintenance issues (e.g., under-inflation, overloading, tire mismatching, excessive wear, inadequate inspections, and associated matters leading to increased heat and tire operating temperatures) are the major causes of tire blowout.
- Road hazards are another contributing factor causing tire blowout.
- Testing of devices aimed at minimizing the negative effect of blowout on directional control showed that some have the potential for improving a truck's post-blowout stability.

Summary of New Tire Technology Developments

The information pertaining to development and application of tire technology reviewed under this work included traditional library printed media (journals, reports, news articles, professional magazines), electronic and internet media (websites of manufacturers, suppliers, and organizations, online press releases), telephone interviews, personal meetings with industry and trade association personnel, and observing demonstrations of technology. The main findings are as follows:

- The surveyed industry views inadequate maintenance as the primary cause for tire blowout.
- Attempts to solve the problem are best accomplished by addressing the source. Significant effort goes into helping fleets develop proper maintenance procedures and driver education.

- The common view in the tire-manufacturing industry is that a properly maintained tire blows only upon impacting road hazards. Further, an alert and well-trained driver will not lose control of the rig when a front tire blows.
- Potential devices aimed at the blowout problem are:
  1. Central inflation/monitoring system — the most promising and accepted method in terms of cost-benefit and applicability.
  2. Integral monitoring by computer chip technology — under development by all major manufacturers with very high expectations as to the positive impact it will have on maintenance and in-service tire failures.
  3. Add-on monitoring by special on-the-wheel devices — often used in combination with a central-inflation system, but more limited since it cannot actively intervene and correct for improper inflation levels.
  4. Supporting inserts — potentially helpful but currently used only in military and security applications on heavy vehicles. It may begin to penetrate the "civilian" markets of passenger cars and light trucks over time.
  5. Tire filling (e.g., with some rubber substance) — not applicable for highway trucks due to heat build-up.
- Retreads are very widely used, primarily on non-steering, rear axle locations. Retread manufacturing processes do not appear to contribute significantly to tire blowouts.
- The military experiences more blowout failures than do commercial fleets, primarily due to the nature of its operation. Central inflation/monitoring systems are used on many military tactical vehicles.
- TACOM and a commercial partner are developing an inspection system based upon an infrared thermal imaging technology. The objective is to detect tire defects that can lead to tire failure.
- Front-tire blowouts are not viewed by carrier fleets as a significant issue.

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Appendix A. — Example Computer Simulation of a Front Tire Blowout on a Loaded Triples Combination.

This appendix material provides an example calculation produced by an UMTRI computer model for a loaded triples combination vehicle experiencing an assumed tire blowout on the front steer axle of the tractor. Separate calculations were performed for both left front and right front tire blowout cases. Key assumptions in this example are:

- the vehicle (10-ft wheelbase tractor pulling three loaded 27-ft trailers) is initially travelling in a straight line at 55 mph
- the tire blowout results in a steady drag force on the blown tire of 0.4 x (tire load) (i.e., a friction drag of 0.4 at the blowout tire location)
- the driver ideally responds in 0.25 seconds after the blowout event with continuous corrective (counter) steering behavior to bring the vehicle back into its initial travel lane
- the driver takes another 1.5 seconds to fully adapt to the loss of one front tire and increase steering gain accordingly to compensate for the tire blowout (i.e., more corrective steering effort/magnitude is required to steer a tractor having only one front tire available)

Using these basic assumptions for the triples combination vehicle (and this would apply similarly to loaded tractor-semitrailer configurations with comparable short wheelbase tractors), the model indicates a significant lateral excursion of the vehicle towards the blowout-side of the vehicle. That is, a left-side blowout produces a leftward path motion of the vehicle, and vice versa. The primary physical mechanism for this response is the applied yaw moment on the tractor due to the wheel drag force after the blowout, thereby causing the tractor to turn toward the direction of the blown tire.

Differences exist between left- and right-side blowout cases. Left-side blowouts result in slightly more severe path disturbances. This is primarily due to the nature of the tractor steering system and the fact that the right-front wheel is steered by a track rod connected to the left-front wheel, which in turn, is steered more directly by the driver through the gearbox connection. When a left-front blowout occurs, the initial torque impulse to the steering system can pulse the right side tire, causing an initial steering pulse from the right-side tire that contributes to a leftward movement of the tractor. For right-side blowouts, a similar (but opposite polarity) initial steering torque impulse is transmitted to the left-side tire, but because of its additional connection restraint to the gearbox, a smaller echo steer impulse is produced at the left tire in this case. The asymmetry in these initial steering system pulse responses produce corresponding asymmetries in initial tractor yaw rate responses that then become manifest as subsequent asymmetric path displacements. In this particular example calculation, peak lateral path excursions by the vehicle following left-side blowouts are seen to be about 30% or so larger than for right-side blowouts under comparable conditions.

For the above assumptions, a left-side blowout produces about a 5-foot peak excursion to the left prior to recovery by the simulated driver; a right-side blowout under identical conditions produces about a 3.5-foot peak displacement. The two attached figures show a simple animation sequence for each case. The frames in the animation sequence are at 1 second intervals and the blowout event occurs just prior to the second frame.

For cases in which a driver is assumed to be very alert and reacts almost immediately to the blowout (i.e., the driver steering response and the blowout recognition delays noted above in the assumptions are both 0.25 seconds), the peak lateral path excursions noted above are shown to be reduced by about one-third.

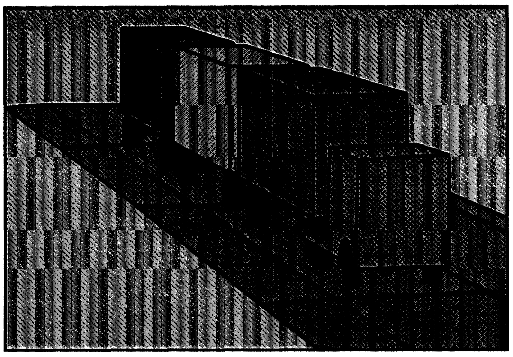
The model also indicates that tractors having longer wheelbases suffer smaller lateral path disturbances than shorter wheelbase tractors. This is reasonable since longer wheelbase tractors are heavier and possess larger yaw moments of inertia that help resist external disturbances. Longer wheelbase tractors also provide a longer moment arm over which corrective steering control inputs by the driver (i.e., the lateral tire force from steer inputs) can act to help arrest the disturbance moment on the tractor caused by a front tire blowout.

Smaller or larger friction value assumptions for post-blowout wheel/road contact will reduce or increase the lateral motion responses accordingly. The example calculation used here corresponds to value of 0.4 at the blown tire location.

Driver reaction and compensatory steering behavior also plays an important role in affecting peak lateral displacement of the vehicle during a post-blowout recovery. The driver behavior in this example is idealized in the sense that driver corrective steering reaction occurs within 0.25 seconds and is further improved 1.5 seconds later by additional steering gain corrections (driver adaptation) that account for the loss of available lateral tire force from the blown tire. For cases in which a driver is not particularly attentive and adapts more slowly to the blowout disturbance and its steering control requirement, significantly larger lateral path motions would be expected.

Left Front Tire Blowout Example

Loaded Triples @ 55 mph



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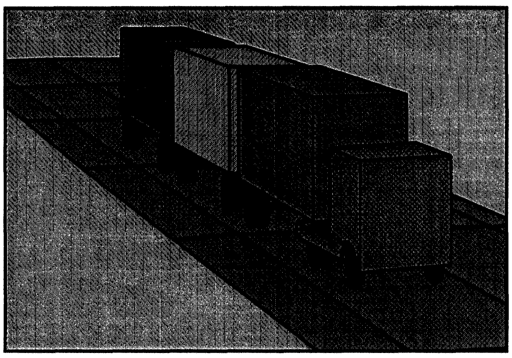

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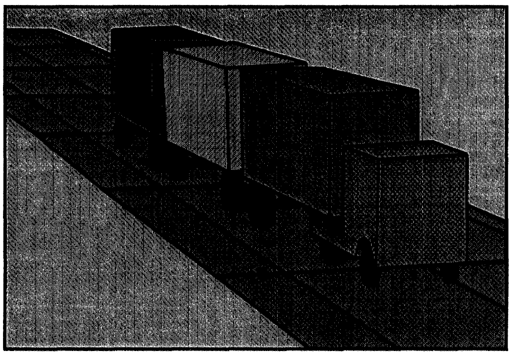

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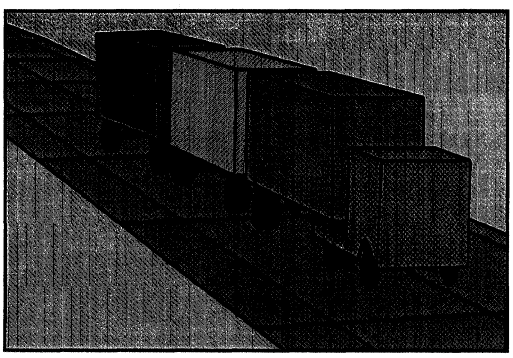

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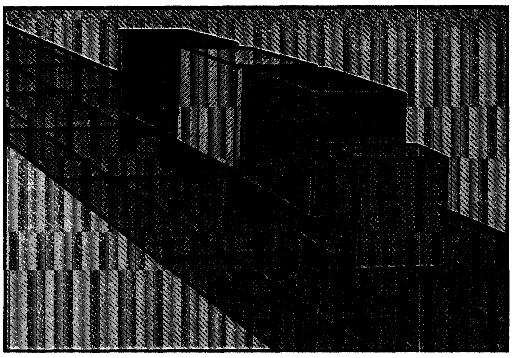

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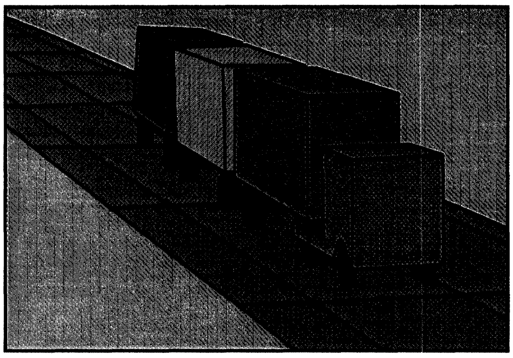

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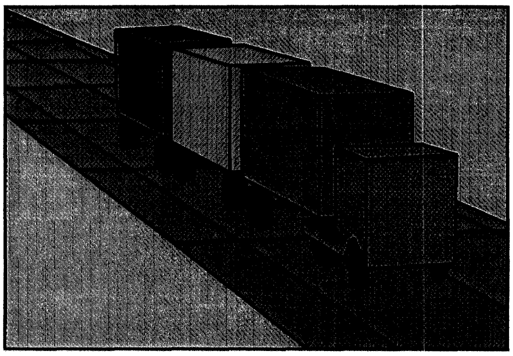

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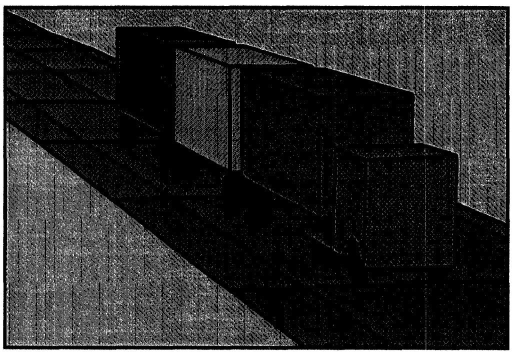

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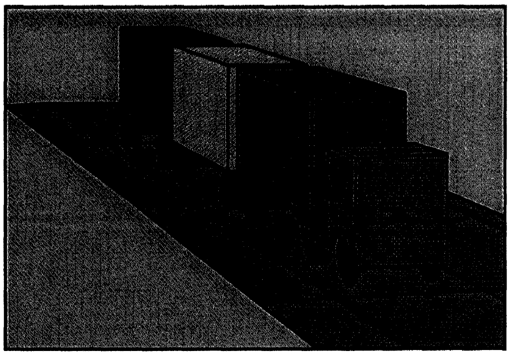
Right Front Tire Blowout Example

Loaded Triples @ 55 mph



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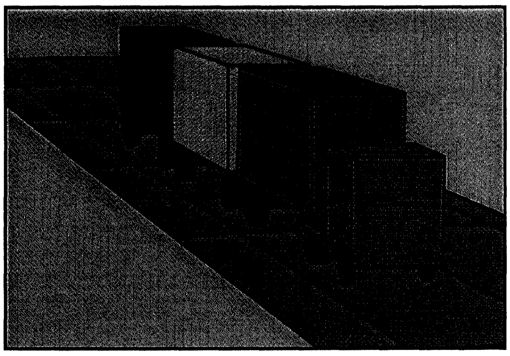

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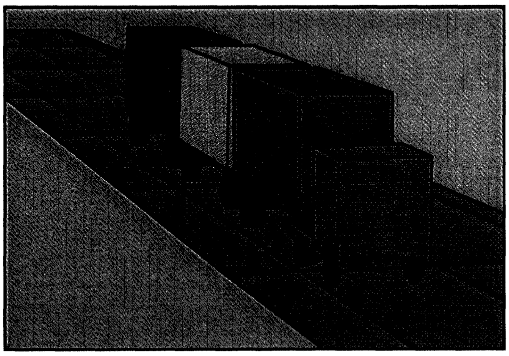

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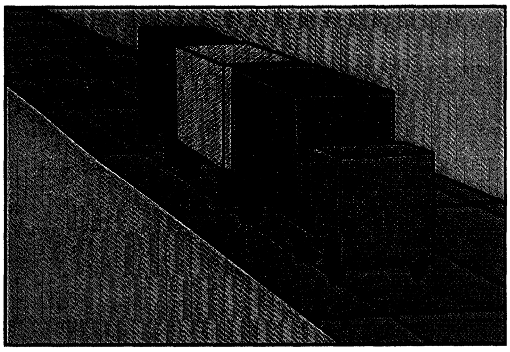

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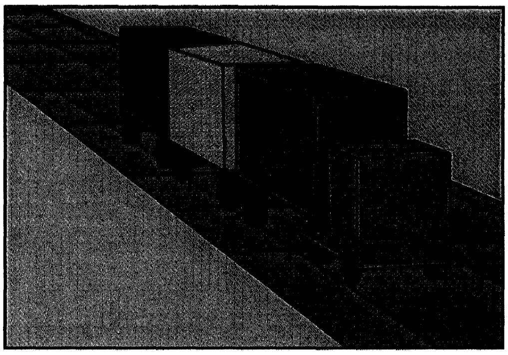

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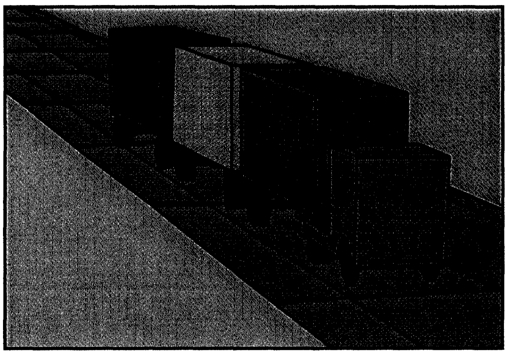

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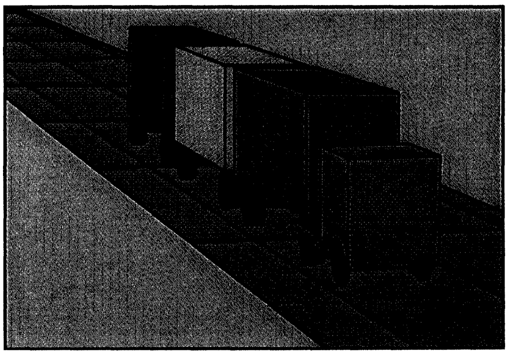

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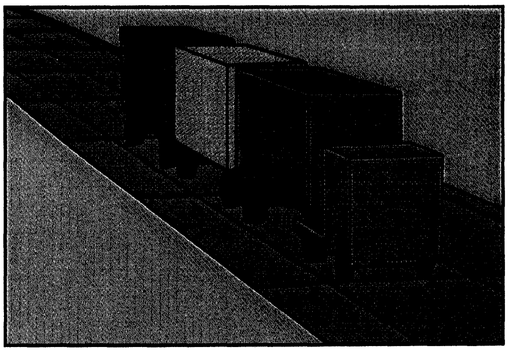

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