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ANALYSIS OF DATA FROM THE THERMAL IMAGING INSPECTION SYSTEM PROJECT

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16. Abstract

The goal of this study was to use temperature measurements derived from infrared cameras to identify trucks with potential brake, tire, or hub defects. Data were collected at inspection sites on six different days and vehicles were subjected to CVSA inspections. Based on the inspections, axle ends were classified into three brake problem categories: yes, no, maybe. Subsequently, the data were analyzed in order to find associations between the temperature measurements and the brake problem classifications. Metrics were developed to identify outliers or large variation in temperatures within or between trucks. Many of the measures focus on differences between axles, left side and right side, and single outlying temperatures. The analysis is restricted to trucks with five axles.

Various truck and environment variables were recorded. The maximum brake temperature was most closely associated with the brake problem variable. The coefficient of variation and standard deviation identified ten of the fourteen trucks classified with at least one brake problem correctly. In conjunction with other metrics, additional trucks with brake problems were also identified.

Associations between trucks with single outlying temperatures on axle ends and brake problem classifications were not strong. However, it is possible that these outliers could be indicative of brake problems not captured by results produced from inspections.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Analysis of Data from the Thermal Imaging Inspection System Project

1. Introduction

This portion of the study is devoted to the analysis of thermal imaging data taken on tractor semitrailers with five axles at vehicle inspection sites on six different days. The goal of the analysis is to use temperature measurements derived from infrared cameras to identify trucks with potential brake, tire, or hub defects. Trucks with particularly cold or hot components that exceed temperatures generally encountered during ‘normal’ operation are candidates for further investigation or identification. Based on operating characteristics such as cargo load, a hot temperature for one truck may not be considered hot for another truck. Similarly, a component that appears to be cold for one truck may not be considered cold for another truck. Therefore, much of the analysis focuses on measures used to identify outliers or large variation in temperatures within or between trucks. Absolute temperature measures as well as relative measures are considered. Many of the measures presented focus on differences between axles, left side and right side, and single outlying temperatures.

Several studies have been completed that investigate the use of thermal imaging to identify defective truck components. The National Highway Traffic Safety Administration (NHTSA) compared infrared temperature measurements of heavy vehicles to those measured using thermocouples welded to the surface of the brake drums.[1] The temperature comparisons were found to be good, but the results were sensitive to aiming of the sensors. Brake temperature was found to be a poor indicator of brake adjustment since misadjusted brakes usually develop enough force to generate brake temperatures similar to those of fully adjusted brakes.

The Federal Motor Carrier Safety Administration (FMCSA) sponsored a study to evaluate the effectiveness of the Infrared Inspection System (IRISystem) to identify primarily malfunctioning brakes on commercial motor vehicles. [2] The vehicles were screened by IRISystem at scale sites and subsequently subjected to a Level 1 inspection. Fifty-nine percent of the vehicles screened by the system as problematic were placed out-of-service (OOS) in the Level 1 inspection.

In Colorado, a study was conducted to detect hot or defective brakes on trucks using infrared thermometers. [3] Brake temperatures were measured and Level 4 brake inspections were performed on trucks travelling eastbound on I-70, west of Denver, Colorado. The goal was to develop brake temperature thresholds to identify potential brake-related problems. A low-temperature threshold of more than 101 F below the average brake temperature of the truck, and a high-temperature threshold of 500 F produced the best association with the brake inspection data.

In this study, as part of the Smart Infrared Inspection System (SIRIS) project, various temperature measurements were recorded on the tires, brakes, and hubs at each axle end of a truck. Trucks were then subjected to either a CVSA Level 1 or Level 2 inspection. Based on results from the inspections, personnel at IEM Corporation classified brakes into three brake problem categories: yes, maybe, no. Subsequently, the data were analyzed in order to find associations between the temperature measurements and the brake problem classifications. In some cases, temperatures were fairly uniform throughout a truck, yet the brake problem variable was classified as ‘yes’ for several axle ends. In other cases, temperatures within a truck were quite variable, yet the brake problem variable was classified as ‘no’ for all axle ends. However, in general it was found that trucks with at least one axle end classified with brake problem ‘yes’ had greater variability in temperatures than trucks classified with no brake problems. Therefore, statistics were created to identify trucks with outlying cold or hot temperatures. Note that it is possible that some trucks with unusually cold or hot components as recorded by thermal imaging sensors were not flagged for violations by a CVSA inspection. The recorded cold or hot temperatures could be indicative of defective components not captured by an inspection.

Many temperature measurements were made at each axle end of the truck and the surrounding environment at the time of inspection. For example, measurements related to the truck included the 95^{th} and 99^{th} percentiles, and the maximum brake temperature. Similar measurements were made for the axle hubs. Measurements were also recorded on the tires including the minimum, the maximum, the mean, certain percentile values, and measures of shape (skewness) and variance. In addition, environmental variables recorded at the time of inspection included road temperature, dew point, relative humidity, and ambient temperature.

Examination of the data suggests that maximum brake temperature was most closely associated with the brake problem variable in which brakes were classified into the three brake problem categories based on the results of CVSA inspections. In general, trucks with brakes classified with brake problem ‘yes’ showed more variation in temperatures throughout the vehicle than trucks with brakes classified into the ‘maybe’ or the ‘no’ categories. Therefore, maximum brake temperature, and variables derived from maximum brake temperature, were used for identifying trucks with potential brake defects. Derived variables, for example, are those calculated by taking temperature differences between the left and right sides or differences between front and back axles.

With respect to the environmental measurements such as road temperature, dew point, relative humidity, and ambient temperature, it will be shown that there are strong correlations between most of these variables. For example, there are strong linear trends between road temperature, ambient temperature, and relative humidity. Therefore, any one of these variables should be sufficient for inclusion into an algorithm for identifying trucks with potential problems. However, it was found that measures derived from these variables did not contribute significantly in identifying trucks with defective components based on the CVSA inspection results.

Although inspections were made on various truck configurations, results are presented for tractor semitrailers with five axles. Some data were collected on trucks with two, three, four, or six axles, but 53 percent of the vehicles selected for inclusion in this study were trucks with five axles. Restricting analysis to this vehicle configuration presents the greatest opportunity for identifying trucks with potential defects by reducing variability among vehicle types. In addition, trucks with five axles contain enough data for making temperature comparisons between axles and between left and right sides of the truck. A vehicle with only two axles, for example, does not contain this level of detail and has operating characteristics quite different from the tractor semitrailer with five axles. Furthermore, the tractor semitrailer is the most common heavy truck configuration operated on the nation's highways.

In Section 2 an initial scope of brake violations, brake out-of-service (OOS) conditions, tire/wheel violations, and tire/wheel OOS conditions is presented using data from the Large Truck Crash Causation Study (LTCCS) and the Motor Carrier Management Information System (MCMIS) databases.[4,5] Section 3 describes the study data. Section 4 is devoted to data processing performed prior to analysis, and Section 5 is an analysis of the maximum brake temperature to identify trucks with large variation in temperatures and to find associations between these temperatures and the brake problem classifications. Section 6 concludes with a summary discussion and final comments.

2. Initial Scope of Heavy Truck Databases

Some preliminary statistics from publicly available transportation-related databases provide information about brake and tire/wheel violations for medium and heavy trucks. In particular, violation and OOS condition information for brakes and tire/wheels is presented from the Large Truck Crash Causation Study (LTCCS) and the Motor Carrier Management Information System (MCMIS) Inspection File.

2.1 The Large Truck Crash Causation Study

The Large Truck Crash Causation Study (LTCCS) was conducted by the U.S. Department of Transportation's (DOT) Federal Motor Carrier Safety Administration (FMCSA) and National Highway Traffic Safety Administration (NHTSA). It is a multiyear, nationwide study of factors that contribute to truck crashes with a focus on pre-crash events. The goal of the LTCCS is to identify countermeasures to reduce the number and severity of truck crashes.

The LTCCS was conducted at 24 sites in 17 States by researchers from NHTSA's National Automotive Sampling System (NASS) and State truck inspectors. Data were collected on crashes from 2001 through 2003. The design of the study is a sample survey of 1,123 trucks with a gross vehicle weight rating (GVWR) of 10,001 pounds or more that includes provisions for clustering, stratification, and probability weighting. In theory, this design makes it possible to calculate national estimates along with associated standard errors. A crash was eligible for sampling if it involved a fatality (K), an incapacitating injury (A), or a non-incapacitating but evident injury (B). Therefore, the LTCCS is a survey of serious injury crashes.

Table 1 below shows the distribution of medium and heavy trucks in the LTCCS. Based on probability weighting, the total number of trucks in the survey is estimated at 141,200. The two largest categories are represented by tractors pulling one trailer (69.1 percent) and single unit trucks (SUT) with GVWR>12,000 kg[1] (17.4 percent). Since tractor semitrailers represent the largest category by far, the remaining results in this section are restricted to tractor semitrailers.

Table 1 Distribution of Medium/Heavy trucks, LTCCS

Body type	N	%
Step van	194	0.1
SUT, 4500kg<GVWR<=8850kg	4,610	3.3
SUT, 8850kg<GVWR<=12,000kg	3,689	2.6
SUT, GVWR>12,000kg	24,602	17.4
SUT, GVWR unknown	666	0.5
Truck tractor, no trailer (bobtail)	3,552	2.5
Truck tractor, one trailer	97,613	69.1
Truck tractor, two or more trailers	5,073	3.6
Unknown medium/heavy truck	1,200	0.8
Total	141,200	100.0

The LTCCS database contains a set of 43 files. One of these files is the Truck Inspection file which combines information on Federal inspection violations. Although the Truck Inspection file contains information on a wide range of violations and out-of-service conditions, the focus of this exercise is on brake and tire/wheel violations and out-of-service conditions. The idea is to estimate the frequency of violations and out-of-service conditions related to brakes and tires/wheels.

2.1.1 Brake Violations and Out-of-Service Conditions from the LTCCS

Using the Truck Inspection file, the number of tractor semitrailers with at least one brake violation was calculated. Table 2 shows that about 37.6 percent of tractor semitrailers had at least one brake violation. Note that *at least one* means that some of these trucks had more than one violation. The percentage of trucks with two violations was 11.9 percent, but the percentage with more than two violations was only 4.5. Some of the violations were due to brakes out of adjustment, air compressor violations, defective drums, inadequate brake linings, inadequate tubing and hoses, connections with leaks, and defective parking brake systems. Table 2 also provides lower and upper 95 percent confidence limits for the percentages.

[1] Note that 12,000 kg is greater than 26,000 pounds.

Table 2 Brake Violations for Truck Tractors Pulling One Trailer, LTCCS

Brake violations	N	%	95% LCL	95% UCL
None	60,924	62.4	55.3	69.5
At least 1	36,688	37.6	30.5	44.7
Total	97,613	100.0		

The Truck Inspection file also contains a variable which indicates whether or not a specific violation was classified as out-of-service. Table 3 shows that about 19 percent, or about half the number shown in Table 2, of tractor semitrailers had at least one brake-related violation that was classified as out-of-service.

Table 3 Brake Out of Service for Truck Tractors Pulling One Trailer, LTCCS

Brake OOS	N	%	95% LCL	95% UCL
None	79,083	81.0	76.6	85.5
At least 1	18,529	19.0	14.5	23.4
Total	97,613	100.0		

2.1.2 Tire/Wheel Violations and Out-of-Service Conditions

The percentage of tractor semitrailers with tire/wheel violations was also calculated. Table 4 shows that the percentage of tire/wheel violations is considerably less than the percentage of brake violations. About 17.6 percent of tractor semitrailers had tire/wheel violations. Some of these violations were due to cracked or broken wheels or rims, wheel fasteners loose or missing, flat tire or fabric exposed, tire ply or belt material exposed, air leaks, tire tread or sidewall separation, tire under inflated, and tread depth too small.

Table 4 Tire/Wheel Violations for Truck Tractors Pulling One Trailer, LTCCS

Tire/wheel violations	N	%	95% LCL	95% UCL
None	80,423	82.4	78.5	86.3
At least 1	17,189	17.6	13.7	21.5
Total	97,613	100.0		

Similarly, Table 5 shows that the percentage of tractor semitrailers with at least one tire/wheel violation classified as out-of-service was relatively small, 5.5 percent.

Table 5 Tire/Wheel Out of Service for Truck Tractors Pulling One Trailer, LTCCS

Tire/wheel OOS	N	%	95% LCL	95% UCL
None	92,275	94.5	91.9	97.1
At least 1	5,338	5.5	2.9	8.1
Total	97,613	100.0		

2.1.3 Associations Between Brake Condition and Tire/Wheel Condition

The motivation for the following analysis is to determine if trucks with brake violations are more likely to also have tire/wheel violations. Suppose that for some reason certain brakes have not been used and are therefore *cool*, as may be the case if a truck has driven on a relatively flat grade for an extended period of time. In that case it may be difficult for thermal imaging devices to detect faults or failures in brake equipment even when they are present. However, tires/wheels are always in use and cannot be disengaged either on level roadways or on a grade. Tire/wheel condition could be a possible surrogate for brake condition, although if the results presented in Table 2 and Table 4 are accurate percentages of brake and tire/wheel violations, then the prevalence of tire/wheel violations is less than half the prevalence of brake-related violations.

Associations between two categorical variables are often judged by odds ratios. Table 6 shows a 2x2 contingency table of brake violations by tire/wheel violations. The odds ratio is simply the cross-product ratio

$$\frac{10{,}897 \times 54{,}632}{6{,}293 \times 25{,}792} = 3.67$$

Table 6 Brake Violations by Tire/wheel Violations for Truck Tractors Pulling One Trailer, LTCCS

	Brake violation		
Tire/wheel violation	At least 1	None	Total
At least 1	10,897	6,293	17,189
None	25,792	54,632	80,423
Total	36,688	60,924	97,613

This odds ratio suggests that tractor semitrailers with at least one brake violation are about 3.7 times more likely than tractor semitrailers with no brake violations to also have at least one tire/wheel violation. This is a fairly strong association. The 95 percent confidence interval for the odds ratio is (2.35, 5.72).

2.2 The Motor Carrier Management Information System (MCMIS) Inspection File

Every year, the Motor Carrier Safety Assistance Program (MCSAP) allocates funds to the States to support roadside inspection programs to identify trucks with mechanical defects and to remove them from the road. The FMCSA Motor Carrier Management Information System (MCMIS) Inspection data set provides information similar to that obtained from the MCSAP roadside inspections. The Inspection file analyzed here contains records for inspections conducted from 2002 through 2005. The database is large with separate tables for recording information about truck units, inspections, and violations. The following analysis is restricted to units classified as truck tractors or semitrailers. This distinction is made since the MCMIS Inspection file contains inspection information according to vehicle unit. In addition, only results for inspections classified as Level 1, or full inspections, are shown.

There are only two categories for identifying brake violations in the violation table: brakes out of adjustment, and all other brake violations. Thus, brake violations other than brakes out of adjustment are grouped into one category. Table 7 shows that 33.1 percent of the 4,546,451 truck tractors or semitrailers had at least one brake violation. This number is just slightly less than the 37.6 percent reported in Table 2 based on the LTCCS data. It should be noted that Table 2 contains information on brake violations for trucks in fatal and serious injury-related crashes, while Table 7 records information on brake violations for trucks during mostly roadside inspections.

Table 7 Number of Tractors or Semitrailers with at Least One Brake Violation, Restricted to Level 1 Inspections, MCMIS Inspection File 2002-2005

Brake violations	N	%
None	3,041,893	66.9
At least 1	1,504,558	33.1
Total	4,546,451	100.0

In the violation table there is one category for tire violations and another category for wheel violations that includes wheels, studs, and clamps, etc. Table 8 shows that about 9.7 percent of truck tractors or semitrailers had at least one tire/wheel violation. This number is somewhat less than the 17.6 percent found in the LTCCS data. Again, trucks in the LTCCS database were involved in fatal or serious injury-related crashes, while data in the MCMIS Inspection file were collected mostly during roadside inspections.

Table 8 Number of Tractors or Semitrailers With at Least One Tire/wheel Violation, Restricted to Level 1 Inspections, MCMIS Inspection File 2002-2005

Tire/wheel violations	N	%
None	4,107,191	90.3
At least 1	439,260	9.7
Total	4,546,451	100.0

3. The Study Data

Data were provided to the University of Michigan Transportation Research Institute (UMTRI) by International Electronic Machines (IEM) Corporation. Table 9 shows truck variables and environment variables. Truck variables identify the truck, the number of axles, the inspection level, the brake problem classification at each axle end, and the axle end at which temperature measurements were taken. The axle end is determined by the side and the axle number. The table also shows the environment variables that are unique to each truck at the time of inspection.

Table 9 Recorded Truck and Environment Variables

Truck Variables	Environment Variables (Truck level)
Truck number	Ambient temperature
Truck side (left-right)	Relative humidity
Truck axle number	Dew point
Number axles	Road temperature
Inspection Level (1-2)	
Brake Problem - each axle end (no, maybe, yes)	

For each truck, temperature measurements were made at each axle end, meaning that there are two observations per axle. For example, for a tractor semitrailer with five axles, ten observations were recorded. However, due to special thermal properties associated with the first axle that are potentially confounded with other components of the truck, such as the engine that generates heat, the first axle is excluded from analysis. Table 10 shows temperature measurements that were made by thermal imaging cameras at each axle end for the tires, the brakes, and the hub. In addition to these variables many variables were derived, such as the difference between the left and right side, and the difference between front and back axles. Section 4 provides more detail about the study data with an emphasis on data processing prior to analysis.

Table 10 Recorded Temperature Variables at each Axle End

Tire	Brake	Hub
Minimum	95th percentile	95th percentile
Mean	99th percentile	99th percentile
Standard deviation	Maximum	Maximum
1st percentile		
5th percentile		
95th percentile		
99th percentile		
Maximum		

4. Data Processing Prior to Analysis

Table 11 below shows number of trucks by number of axles for data collected in this study. In total, data were collected on 118 trucks on six different days. The majority of trucks appear to be tractor semitrailers with five axles (53.4 percent). The second most common configuration is trucks with two axles (28.8 percent).

Table 11 Number of Trucks by Number of Axles

Axles	Trucks	%
2	34	28.8
3	13	11.0
4	4	3.4
5	63	53.4
6	4	3.4
Total	118	100.0

In total, three trucks do not have complete observations depending on the axle number and side number. These three are tractor semitrailers with five axles that had Level 1 inspections. It is difficult to compare trucks with missing data to those with complete data for various reasons. Table 12 shows the axle number and side where data are missing. Two of the trucks are missing data only on the first axle. Since measurements on the first axle are excluded from analysis in this study, missing data on these two trucks does not affect the results presented here. However, one truck (Sirisnum 4, 6/5/2008) has missing data on the left side for axles 1-3, and is excluded from further study.

Table 12 Trucks with Missing Data

Sirisnum	Inspection Date	Number Axles	Missing	Inspection Level
4	6/5/2008	5	Left side, axles 1-3	1
273	6/5/2008	5	Right side, axle 1	1
44	7/29/2008	5	Left side, axle 1	1

Table 13 shows that nine trucks did not have Level 1 inspections. The inspection dates along with number of axles are also presented. Seven of the inspections occurred on the same date. Five of the trucks are tractor semitrailers with five axles. Because these trucks did not receive Level 1 inspections, they are excluded from further study.

Table 13 Trucks without Level 1 Inspection

Sirisnum	Inspection Date	Axles	Inspection Level
15	5/21/2008	5	2
44	5/21/2008	5	2
57	5/21/2008	6	2
67	5/21/2008	3	2
106	5/21/2008	3	2
161	5/21/2008	5	2
184	5/21/2008	5	2
393	6/5/2008	5	2
537	6/5/2008	4	2

Table 14 shows the numbers and percentages of trucks with complete data. In addition, all of these trucks had Level 1 inspections.

Table 14 Distribution of Trucks with Complete Data by Number of Axles

Axles	Trucks	%
2	34	31.4
3	11	10.2
4	3	2.8
5	57	52.8
6	3	2.8
Total	108	100.0

In the data file, brake problems are classified into three categories: no, maybe, yes. Each classification pertains to an axle end. For example, a tractor semitrailer with five axles has ten axle ends. Table 15 shows the distribution of brake problem by axle number. There are 832 axle ends corresponding to the 108 trucks available for study. The first axle of each truck is excluded

Table 15 Classification of Brake Problem by Axle Number

	Brake Problem			
Axle Number	No	Maybe	Yes	Total
1	200	10	6	216
2	203	8	5	216
3	134	6	8	148
4	107	11	8	126
5	101	7	12	120
6	5	0	1	6
Total	750	42	40	832
Percentages				
Axle Number	No	Maybe	Yes	Total
1	92.6	4.6	2.8	100.0
2	94.0	3.7	2.3	100.0
3	90.5	4.1	5.4	100.0
4	84.9	8.7	6.3	100.0
5	84.2	5.8	10.0	100.0
6	83.3	0.0	16.7	100.0
Total	90.1	5.0	4.8	100.0

from analysis. This is due to special thermal properties associated with the first axle that are potentially confounded with other components of the truck, such as the engine, that generates heat. Results for axle 1 are highlighted in Table 15.

Excluding axle 1, there are 616 axle ends of which 550 are classified as having no brake problem. Thirty-two axle ends are classified in the "maybe" category, while 34 axle ends are classified in the "yes" category. Percentages are shown in the lower portion of the table. There is an increasing trend in the percentage of brake problems classified as "yes" as axle number increases. For these data, brake problems were more likely recorded on the trailer of the truck.

5. Methods for Tractor Semitrailers (Trucks with Five Axles)

In these data, 57 tractor semitrailers have complete data on all axle ends and had Level 1 inspections. As shown in Table 14, tractor semitrailers represent approximately 53 percent of the sample of 108 trucks. Since this truck configuration is most prevalent in the data and represents the most common configuration of heavy trucks in transport over the nation's highways, it is the focus of this analysis. Trucks with two axles provide only one axle with two axle ends for analysis if the first axle is excluded. Therefore, tractor semitrailers with five axles provide the greatest opportunity for detecting differences in temperatures between the left side and right side, the front and the back, and single axle ends of the same truck.

Environment variables were recorded and Figure 1 shows a matrix scatter plot of ambient temperature, relative humidity, dew point, and road temperature for trucks with five axles. There are strong linear associations between ambient temperature, relative, humidity, and road temperature. Therefore, any one of these three variables should be sufficient for inclusion in a model used to detect defective components. However, environment variables did not show a strong association with trucks classified with potential brake problems as determined by Level 1 inspections. There appears to be almost no association between relative humidity and dew point.

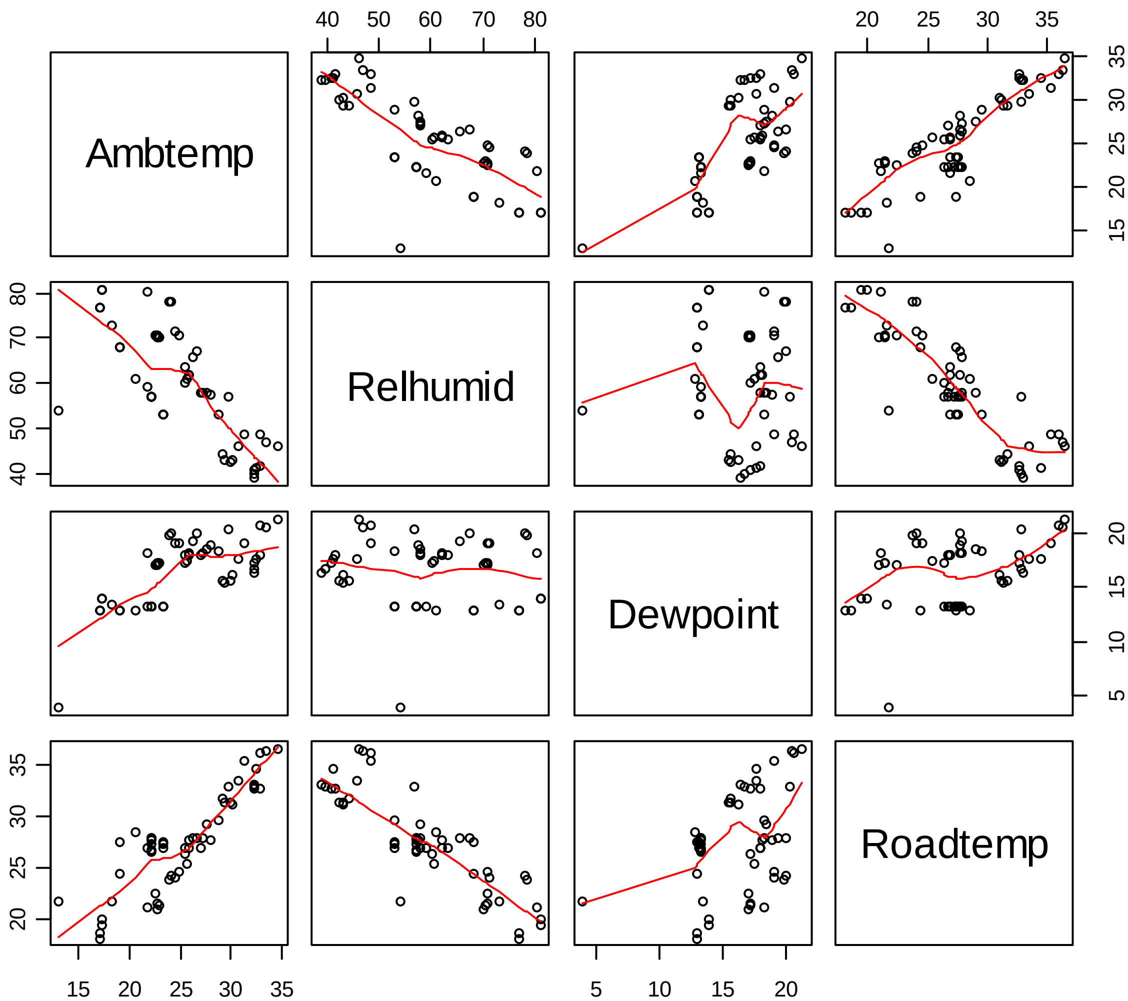

Figure 1 Matrix Scatter Plot of Environment Variables for Trucks with Five Axles

Of all variables in the analysis file, maximum brake temperature was most associated with trucks classified with brake problems as determined by Level 1 inspections. Within a truck, large variation in maximum brake temperature was associated with axle ends classified with brake problems. Therefore, analysis of maximum brake temperature is the focus with an emphasis on detecting trucks with large variation, trucks with hot or cold single outliers, trucks with large differences in temperatures between front and back axles, and trucks with large differences between left and right sides. The tractor semitrailers were assigned unique truck numbers from 1 through 57 for identification.

Box plots are used throughout to display distributions of temperatures. The line in the middle of each plot is the median value. The middle 50 percent of the distribution is contained within the box. The lower end of the box represents the 25th percentile, while the upper end represents the 75th percentile. Extreme *outliers* are designated by circles. Since temperatures are positive measurements, distributions of these quantities tend to be skewed to the right. Therefore, the natural log transformation of the maximum brake temperature is presented which *tends* to be more normally distributed and symmetric about the mean.

5.1 Maximum Brake Temperature

Appendix A shows tables of maximum brake temperature by axle number and side number for each of the 57 tractor semitrailers. The tables are grouped into three sets: trucks with at least one brake problem classified as “yes”, trucks with at least one brake problem classified as “maybe” (only “maybe”), and trucks classified with “no” brake problems. Comments are also provided that describe potential sources of variability and differences between trucks classified with brake problems and those without brake problems.

Based on maximum brake temperature, Table 23 in Appendix A shows that brake problems tend to cluster in certain trucks. For example, of the 57 tractor semitrailers, 14 trucks represent all trucks that have at least one brake problem classified as “yes”. In trucks 27 and 38, six of the eight axle ends are classified with brake problems. In addition, truck 28 has five axle ends classified with brake problems.

Of the trucks shown with at least one brake problem classified as “only maybe” in Table 24, the maximum brake temperatures tend to be cooler in general. Eight tractor semitrailers fall into this category. Truck 3, which is hot in general and particularly so on axle 3, is an exception to the other cooler trucks. Truck 7 also appears to be hotter on axle 4 compared to the other axle ends in this group.

The remaining 35 trucks in Table 25 were classified with “no” brake problems. It is clear, however, that several trucks have outlying observations or show variability between front and back axles, or between left and right sides. For example, trucks 12, 17, 31, and 35 show temperatures on certain axle ends that tend to deviate from other axle ends on the same truck.

Examination of recorded temperatures for each truck shows that distributions on the original scale tend to be skewed to the right. This is common for measurements such as temperature that are constrained to be positive. The natural logarithm is a transformation that is often applied to make distributions approximately symmetric or close to normal in appearance. Figure 2 shows box plots of the log maximum brake temperature for the 57 tractor semitrailers. Each boxplot is based on 8 axle ends for each truck.

The plots are color-coded whereby trucks with at least one brake problem classified as “yes” are red, those with at least one brake problem classified as “maybe only” are blue, and those classified with “no” brake problems are green. Road temperature and ambient temperature are also displayed on the log scale, and the plot is divided by vertical lines to show the six separate days in which data were collected.

From Figure 2 several results are immediately clear. Trucks classified with at least one brake problem “yes” tend to have distributions with greater variability than trucks classified with brake problem “only maybe” or “no”. They also tend to have distributions with outliers, such as shown by trucks 8, 13, and 34. It also appears, except for truck 3, that trucks classified as “only maybe” have cooler temperatures in general.

Although large variability and outlier detection appears to be a useful tool for identifying trucks with brake problems, there are some clear exceptions. For example, trucks 10, 12, 17, 31, 35, 45, 46, and 51 are classified with “no” brake problems, yet clearly exhibit large variability or outlying observations. On the other hand, the reason for a brake problem as assigned by a brake inspection may have little to do with the thermal properties of the truck. For example, a violation may result from a slack adjuster being out of adjustment. In that case, detection of outliers based on properties of thermal imaging may provide added support for identifying inoperative brakes. In other words, a hypothesis could be that these trucks have defective components not captured by inspection.

The ambient temperature and road temperature for each of the six days of data collection show an increasing trend from the morning hours until the afternoon hours. Some of the trucks have axle end temperatures that are close to the road temperature. For example, trucks 14, 19, 38, 45, and 49 have temperatures close to the road temperature. A useful metric may be one that examines the difference between a truck’s minimum brake temperature and the road temperature. However, that metric was not conclusive based on these data.

Note that although trucks 18 and 27 are classified with brake problems, it may be very difficult to identify these two with any problems based on thermal properties because their distributions show little variability and do not exhibit any outlying observations. The same may be true for truck 57. These cases could be examples of trucks with violations due to brakes out of adjustment as discussed above, or with other violations not related to thermal properties.

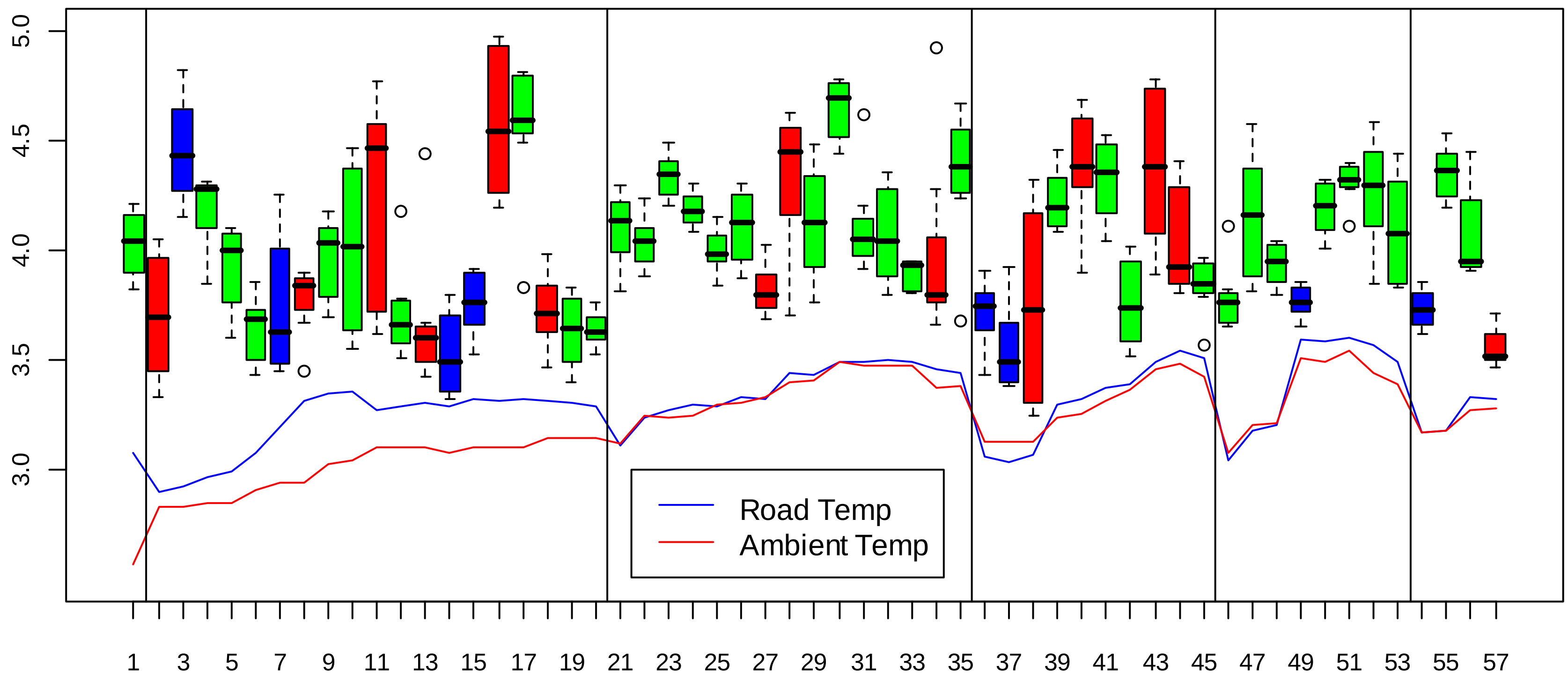

Figure 2 Boxplots of Log Maximum Brake Temperature for 57 Tractor Semitrailers (each boxplot 8 observations, Axles 2-5, 2 Sides)
Red = at least one "yes" brake problem, Blue = at least one "only maybe" brake problem, Green = no brake problems
Vertical Lines Represent 6 periods of Data Collection

5.1.1 Measures of Variation

The box plots in Figure 2 are useful for showing that trucks classified with brake problems tend to have distributions that exhibit more variation than trucks classified without brake problems. Two measures of variation that are considered here for identifying these trucks are the *standard deviation* and the *coefficient of variation*. The coefficient of variation is the standard deviation divided by the average and is a unit less measure.

Figure 3 shows distributions of the standard deviation and the coefficient of variation for each of the three groups of brake classifications. Note that the 14 trucks classified with at least one brake problem tend to have larger measures of variation than the other two groups. Horizontal lines in the plots suggest possible cutoff values for discriminating between the groups. For the standard deviation the cutoff value is 0.25, for the coefficient of variation the cutoff value is 0.06.

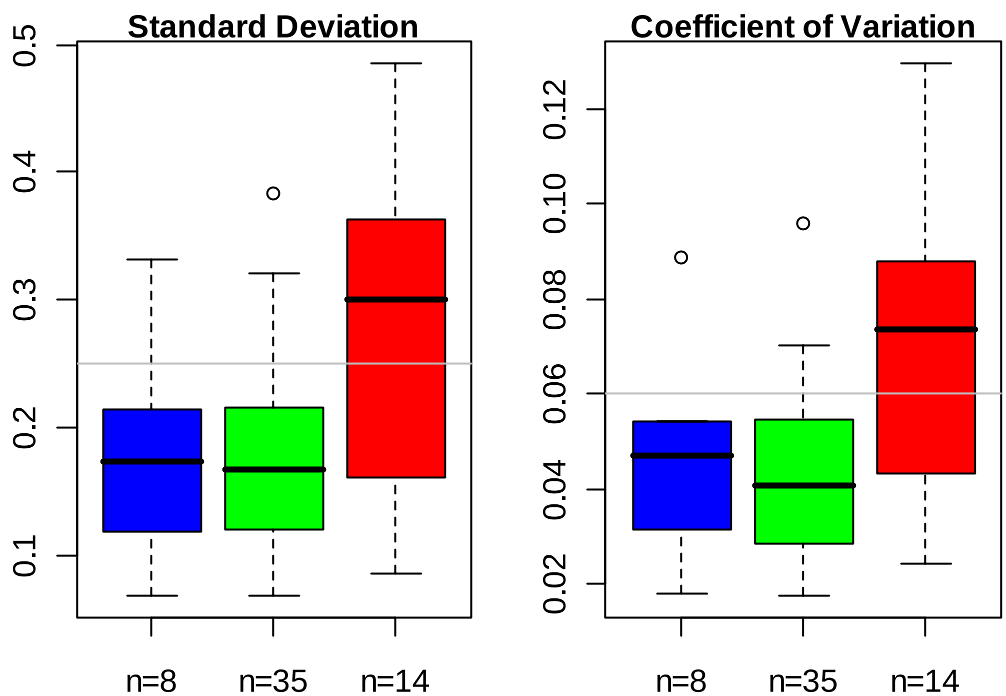

Figure 3 Standard Deviation and Coefficient of Variation, Log Maximum Brake Temperature for Tractor Semitrailers Classified with Brakeproblem
Red = Yes, Blue = Only Maybe, Green = No

Table 16 shows the tractor semitrailers identified by the measures of variation and the respective brake problem classifications. The two measures agree closely except that the standard deviation identifies truck 40 and the coefficient of variation identifies truck 44. Together, the two measures identify 10 of the 14 trucks classified with brake problems. They also identify 5 of the 35 trucks classified with “no” brake problems, and 1 of the 8 trucks classified with “only maybe” brake problems.

Table 16 Tractor Semitrailers Identified by Standard Deviation and Coefficient of Variation, Brake Problem Classification (y=yes, m=only maybe, n=no)

	Truck Number														
Standard deviation > 0.25	2	7	10	11	13	16	17	28	34	35	38	40	43	47	53
Brake problem class	y	m	n	y	y	y	n	y	y	n	y	y	y	n	n
Coefficient of variation > 0.06	2	7	10	11	13	16	17	28	34	35	38	43	44	47	53
Brake problem class	y	m	n	y	y	y	n	y	y	n	y	y	y	n	n

As expected, even though trucks 18, 27, and 57 are classified with at least one brake problem, they are not captured by these metrics. Examination of Figure 2 gives good reasons why. In addition, although truck 8 has one outlying observation, it is not captured by this metric because the overall variance is not too great.

A possible decision rule for capturing tractor semitrailers with large variation is

- Standard deviation > 0.25 or coefficient of variation > 0.06.

In addition to the two measures described above, another possible measure is the maximum log temperature divided by the minimum log temperature. Like the coefficient of variation, this measure is also unit less. Figure 4 shows distributions of this measure for each of the three groups of brake classifications.

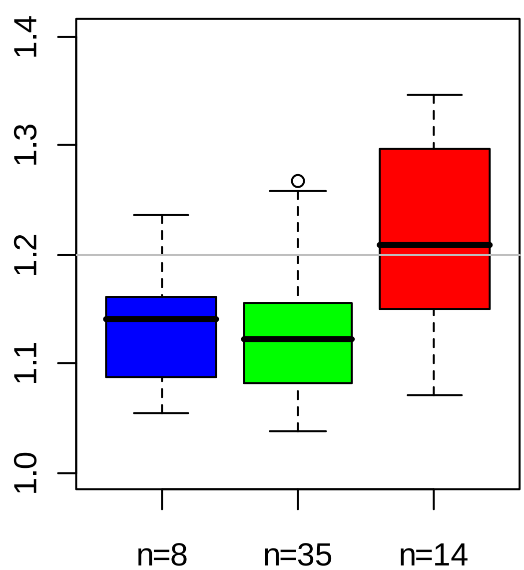

Figure 4 Maximum Divided by Minimum, Log Maximum Brake Temperature for Tractor Semitrailers Classified with Brakeproblem Red = Yes, Blue = Only Maybe, Green = No

Again, it is clear that trucks classified with at least one brake problem exhibit greater variation in temperature compared to trucks classified without brake problems. For the maximum divided by the minimum, a possible cutoff value is 1.2. Table 17 shows the tractor semitrailers identified by this measure and the respective brake problem classifications. This measure does not identify any additional trucks with brake problems that are already captured by the standard deviation or the coefficient of variation. However, it does not identify trucks 47 or 53, both of which are classified without brake problems. Overall, it identifies 8 trucks with brake problem classified as “yes”, 1 truck with brake problem classified as “only maybe”, and 3 trucks classified with brake problem classified as “no”.

Table 17 Tractor Semitrailers Identified by Maximum Divided by Minimum, Brake Problem Classification (y=yes, m=only maybe, n=no)

	Truck Number											
Max/Min > 1.2	2	7	10	11	13	17	28	34	35	38	40	43
Brake problem	y	m	n	y	y	n	y	y	n	y	y	y

5.1.2 Detection of Single Outliers

A truck with one axle end that is significantly different in temperature than the others is a candidate for further investigation. One way to detect outliers is to calculate the difference in temperature of an axle end from the mean temperature of the truck in standard deviations. Any distance greater than two standard deviations in absolute value is a potential outlier. The measure used here is

$$z_i = \frac{x_i - \bar{x}}{s} \qquad i = 1, \ldots, 8$$

where $\bar{x}$ is the average and s is the standard deviation of the 8 axle ends. These measurements are made on the log maximum brake temperature scale. Distributions tend to be more normally distributed on this scale.

Figure 5 shows distributions of the standardized variable z for each of the 57 tractor semitrailers. Horizontal lines are shown at +2 and -2 to distinguish hot outliers from cold ones. The horizontal line at 0 represents the value of an axle end that has the same temperature as the average temperature of the truck. This plot represents all 456 axle ends, 8 axle ends for each truck.

In total there are 10 outliers, 5 of which are hot and 5 of which are cold. It can be seen that only 3 trucks (8, 13, 34) classified with brake problem “yes” have outlying axle ends. However, note that truck 8 is identified and was not identified by either the standard deviation or coefficient of variation measures. The remaining 7 trucks with outliers are classified with “no” brake problems. Therefore, this measure does not appear to correlate well with trucks classified with brake problems. However, outliers indicate that one axle end is significantly different in temperature from the other axle ends and are potential sources of brake problems.

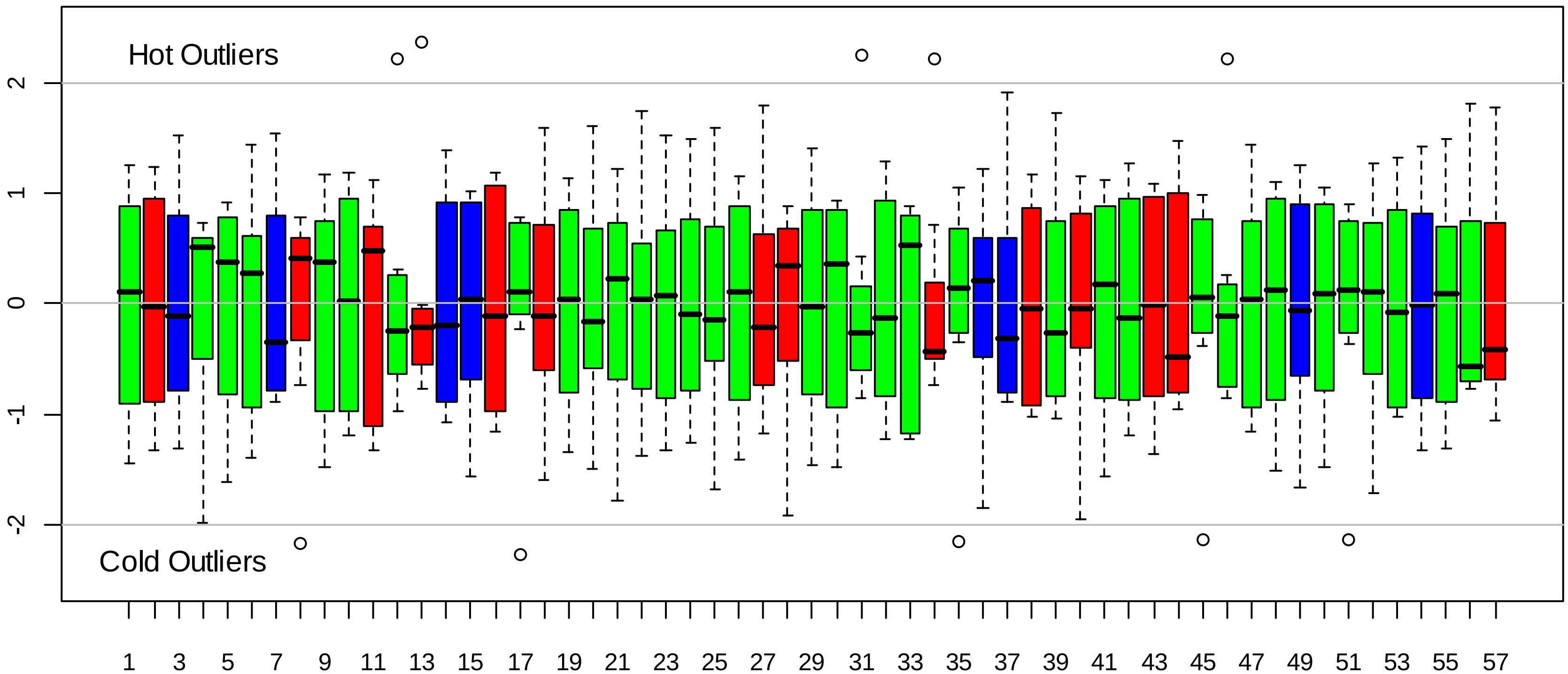

Figure 5 Detection of Tractor Semitrailers with Single Outlying Observations (Log Maximum Brake Temperature)

Table 18 shows the truck number, the axle number, and the side corresponding to the ten outlying axle ends. The outliers are grouped according to whether they are cold or hot. The brake problem refers to the axle end, not the truck. For example, truck 8 has at least one brake problem classified as yes, however, the axle end associated with the outlier, which occurs on axle 3 on the right side, is classified with brake problem “no”. There does not appear to be any systematic association between outliers and axle number. Four of the “hot” outliers occur on the right side. Only one of the outlying axle ends (truck 34, axle 2, side L) has a brake problem classified as “yes”.

Table 18 Log Maximum Brake Temperature, Single Outliers for Tractor Semitrailers

Cold Outliers				Hot Outliers			
Truck number	Axle	Side	Brake problem	Truck number	Axle	Side	Brake problem
8	3	R	no	12	4	R	no
17	2	L	no	13	3	R	maybe
35	2	L	no	31	2	R	no
45	4	L	no	34	2	L	yes
51	5	R	no	46	5	R	no

5.1.3 Front (Axles 2-3) Minus Back (Axles 4-5) Test

A brake problem may be evident if there is a significant difference in temperature between the front and the back of the truck. On a tractor semitrailer with five axles, axles 2-3 are generally drive axles on the power unit, while axles 4-5 are located on the trailer. Two measures to detect differences in temperature between front and back are

$$D = \overline{X}_F - \overline{X}_B \qquad \text{and} \qquad T = \frac{\overline{X}_F - \overline{X}_B - \Delta}{\sqrt{\frac{S_F^2}{4} + \frac{S_B^2}{4}}}$$

where *D* is the difference in means between front and back, and *T* is a standardized version of *D*. The measure *T* is standardized in the sense that the denominator is an estimate of the standard deviation of *D*. The denominator is the square root of the sum of the estimated variances of the front mean and the back mean. The value 4 represents the number of axle ends on the front and back, respectively. Since brake temperatures tend to be hotter on the trailer axles than the drive axles, Δ is an adjustment term to account for this difference.

Figure 6 shows distributions of *D* and *T*. From the distribution of *D* it can be seen that trucks classified with brake problem “yes” have a larger variance and are also more likely to have hotter temperatures on the front (horizontal line at median = 0.16>0). On the other hand, temperatures for trucks classified with brake problem “only maybe” or “no” are more likely to have hotter temperatures on the back (median = -0.23 and median = -0.11, respectively). The horizontal line at -0.5 represents a possible value where the back is significantly hotter than the front.

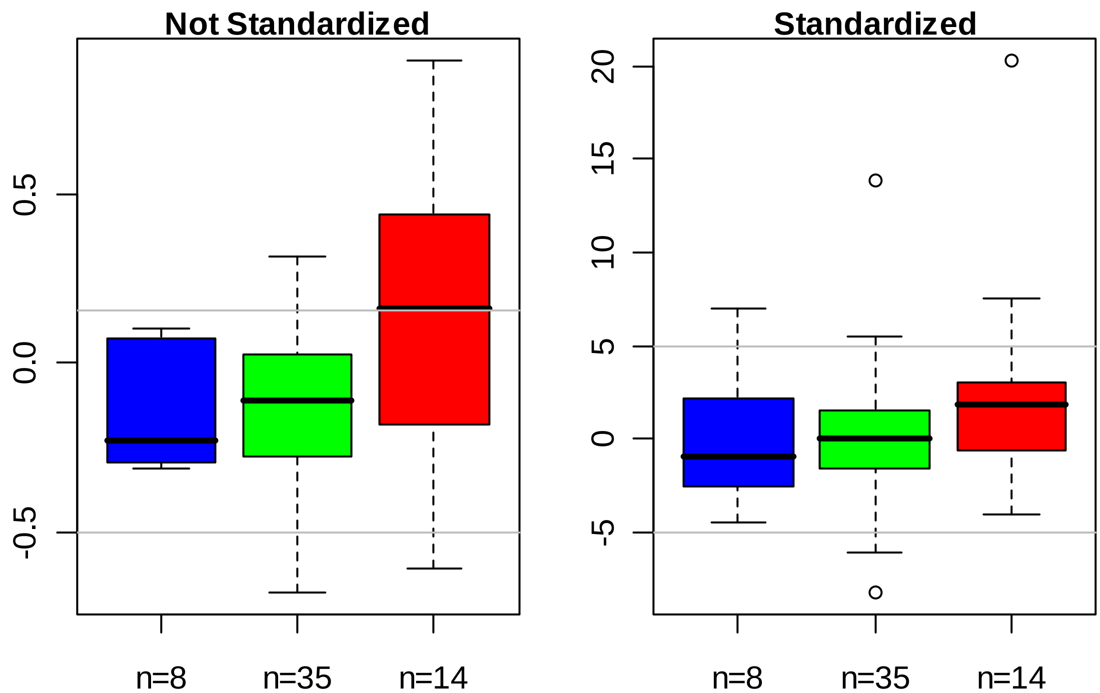

Figure 6 Front (Axles 2-3) Minus Back (Axles 4-5), Log Maximum Brake Temperature for Tractor Semitrailers Classified with Brakeproblem Red = Yes, Blue = Maybe, Green = No

The right hand plot in Figure 6 shows the distribution of *T*. The value $\Delta = -0.11$ is chosen because it is the median of *D* for the 35 trucks classified with brake problem classified as "no". This causes the distribution for these 35 trucks to be centered close to 0. Possible cutoff values for *T* are 5 and -5. Note that *T* exhibits more extreme outliers than *D*.

Table 19 shows two tables of trucks identified by the measure *D*. The first table is represented by trucks with cooler brakes in the back. This accounts for half, or 7 of the trucks classified with brake problem "yes". It also identifies 5 of the 35 trucks classified with brake problem "no". The second table is represented by 3 trucks with hotter brakes in the back. Since brake temperatures tend to be hotter in the back, the possible cutoff value is more extreme (-0.5).

Table 19 Tractor Semitrailers Identified by Front (Axles 2-3) Minus Back (Axles 4-5) Average, Not Standardized, Brake Problem Classification (y=yes, m=only maybe, n=no

	Truck Number											
D = Front - Back > 0.16	2	4	9	13	16	19	21	28	34	38	40	45
Brake problem	y	n	n	y	y	n	n	y	y	y	y	n

	Truck		
D = Front - Back < -0.5	10	43	47
Brake problem	n	y	n

Table 20 is analogous to Table 19 except that it applies to the plot on the right side of Figure 6. The measure *T* identifies six trucks with temperatures significantly hotter on the front than in the back. Of these trucks, three have at least one brake classified with brake problem “yes”, two are classified with “no” brake problems, and one has at least one brake problem classified as “only maybe”. Five trucks are identified by *T* as having significantly hotter brakes in the back, but all of these trucks are classified with brake problem “no”.

Table 20 Tractor Semitrailers Identified by Front (Axles 2-3) Minus Back (Axles 4-5) Average, Standardized, Brake Problem Classification (y=yes, m=only maybe, n=no

	Truck					
T = Front - Back > 5	2	16	19	21	38	49
Brake problem	y	y	n	n	y	m

	Truck				
T = Front - Back < -5	10	32	42	47	53
Brake problem	n	n	n	n	n

Measures of spread or variation seem to identify those trucks classified with brake problems best. Figure 7 shows distributions of the estimated standard deviation of the front minus the back mean brake temperatures. This measure is the denominator of the *T* statistic calculated above. Trucks classified with brake problem “yes” tend to have the largest standard deviations. A horizontal line is drawn at the value 0.18 to suggest a possible cutoff value.

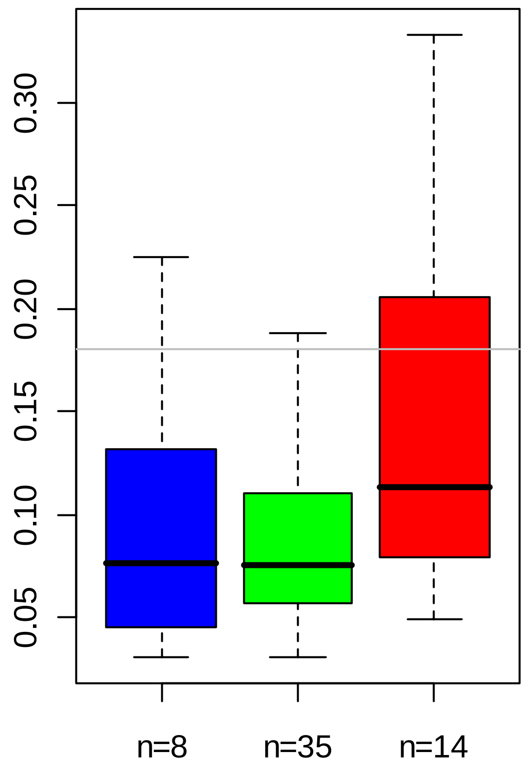

Figure 7 Front Minus Back Log Maximum Brake Temperature Standard Deviation for Tractor Semitrailers Classified with Brakeproblem
Red = Yes, Blue = Maybe, Green = No

Table 21 shows that seven trucks are identified with standard deviations of the front minus the back means greater than 0.18. Except for truck 52, all of these trucks are identified by the standard deviation or the coefficient of variation presented in Subsection 5.1.1.

Table 21 Tractor Semitrailers Identified by Front (Axles 2-3) Minus Back (Axles 4-5) Standard Deviation, Brake Problem Classification (y=yes, m=only maybe, n=no

Standard deviation	Truck Number						
Front - Back > 0.18	7	11	13	17	28	34	52
Brake problem	m	y	y	n	y	y	n

5.1.4 Left Side Minus Right Side Test

Another potential measure examines differences in temperature between the left and right sides of the truck. There should not be significant differences between the two sides. Measures to detect differences are

$$\overline{D} = \frac{1}{4}\sum_{i=1}^{4} L_i - R_i \qquad \text{and} \qquad T_D = \frac{\overline{D} - \Delta}{\sqrt{\frac{s_d^2}{4}}}.$$

The measure $\overline{D}$ is the average of the left minus the right side over the four axles (2-5). If there are no differences, this average should be close to zero. The measure T_D is a standardized version in the sense that it is $\overline{D}$ divided by an estimate of its standard error. As before, the term Δ is used to adjust the center of the distribution near zero.

The distributions of $\overline{D}$ for the three classifications of brake problems are shown on the left side of Figure 8. One would expect the distributions to fluctuate about the value zero if there are no differences. Note that all three distributions have means less than zero (indicated by the horizontal line), suggesting that the right side tends to be hotter than the left side overall. Although the distribution for those trucks classified with brake problem "yes" tends to show more variability than the other two, there is not great difference between the groups.

The distributions of T_D are shown on the right side of Figure 8. The value of $\Delta = -0.08$ is used to center the distribution of the 35 trucks with brake problem classified as "no" at zero. Cutoff values of plus or minus 3.2 are shown. This rule identifies truck 18 as being significantly hotter on the left side, and trucks 11 and 41 as being significantly hotter on the right side. Recall that truck 18 showed little variability overall, but is identified by this measure (see Figure 2).

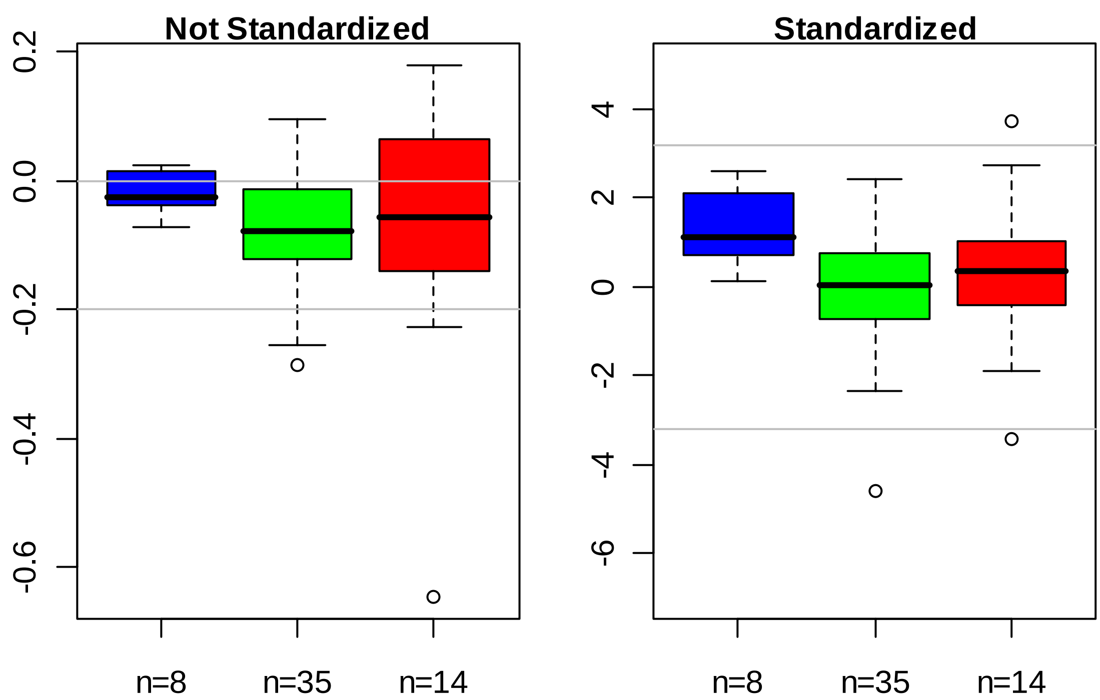

Figure 8 Paired T-Test, Left Side Minus Right Side Log Maximum Brake Temperature for Tractor Semitrailers Classified with Brakeproblem Red = Yes, Blue = Maybe, Green = No

Figure 9 shows distributions of the estimated standard error of $\overline{D}$ which is the denominator of the statistic T_D. Trucks classified with brake problem "yes" have the largest standard deviations. The horizontal line at 0.25 represents a possible cutoff value.

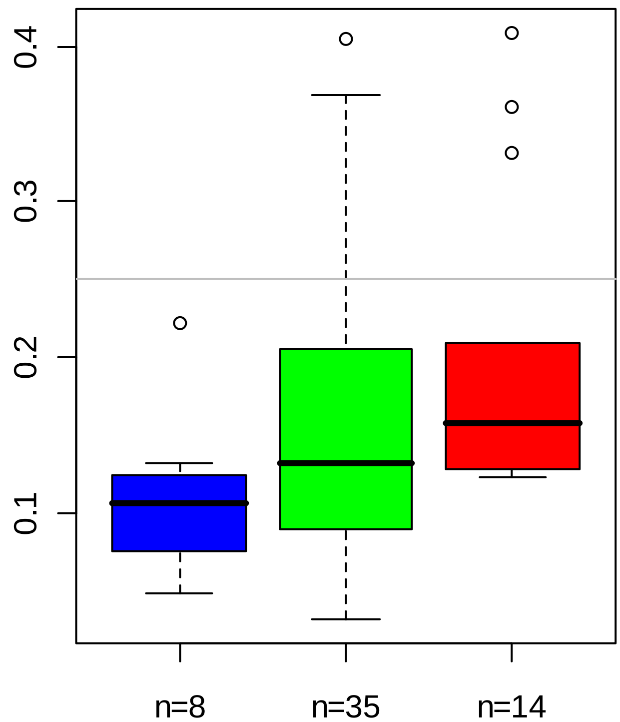

Figure 9 Standard Deviation of Left Side Minus Right Side Log Maximum Brake Temperature for Tractor Semitrailers Classified with Brakeproblem
Red = Yes, Blue = Maybe, Green = No

Table 22 shows those trucks with left minus right standard deviations greater than 0.25 and their respective brake problem classifications. In total, nine trucks are identified, but only three are classified with at least one brake problem "yes". However, these three trucks have relatively large standard deviations as shown as extreme outliers in Figure 9.

Table 22 Tractor Semitrailers Identified by Left Minus Right Standard Deviation, Brake Problem Classification (y=yes, m=only maybe, n=no

Standard deviation	Truck Number								
Left - Right > 0.25	1	5	11	12	13	17	31	34	52
Brake problem	n	n	y	n	y	n	n	y	n

6. Summary and Discussion

The goal of this analysis was to use temperature measurements derived from infrared cameras to identify trucks with potential brake, tire, or hub defects. Data were collected at vehicle inspection sites on six different days. The analysis focused on measures used to identify outliers or large variation in temperatures within or between trucks with five axles. Trucks with particularly cold or hot components that exceed temperatures generally encountered during 'normal' operation were candidates for further investigation or identification. Absolute temperature measures as well as relative measures were considered.

Preliminary analysis of publicly available transportation-related databases was performed to estimate percentages of brake and tire/wheel violations and out-of-service conditions for heavy trucks. In the Large Truck Crash Causation Study (LTCCS), about 38 percent of tractor semitrailers had at least one brake violation and about 19 percent had at least one brake-related violation that was classified as out-of-service. In a recent study of LTCCS data, among mechanical systems, violations in the brake (36 percent of all) were the most frequent, and a brake out-of-service condition increased the odds of the truck assigned the critical reason (identifying the precipitating vehicle) by 1.8 times. [6]

In this study, various temperature measurements were recorded on the tires, brakes, and hubs at each axle end of a truck. Trucks were then subjected to a CVSA inspection. Based on the inspection results, brakes were classified into three problem categories: yes, maybe, no. Subsequently, the data were analyzed in order to find associations between the temperature measurements and the brake problem classifications. Two points are made with respect to the analysis using this design. First, an inspection may result in violations not related to thermal properties of a truck. Brakes out of adjustment is an example. Therefore, a truck may be classified with a brake problem, yet temperature measurements may exhibit little or no variation among brake components. Second, an inspection may result in no violations, yet temperature measurements may exhibit large variation among brake components. Therefore, large variation or outlying brake temperatures measured by thermal imaging cameras could be indicative of mechanical problems not captured by an inspection.

The results are limited to the 57 trucks with five axles. Among trucks with GVWR greater than 10,000 pounds, this is the most prevalent configuration operating on the nation’s highways. The steer axle is excluded from analysis due to special thermal properties that are potentially confounded with other components of the truck, such as the engine that generates heat. The remaining four axles with eight axle ends provides data for detecting differences in temperatures between the left side and right side, the front and the back, and single axle ends of the same truck. Trucks with two axles, for example, provide only one axle with two axle ends for analysis if the first axle is excluded, making outlier detection much more difficult.

Maximum brake temperature was found to be most closely associated with vehicles classified with brake problems. Since temperatures are positive measurements, distributions of these quantities tend to be skewed to the right. The natural log transformation of the maximum brake temperature was presented which *tends* to be more normally distributed and symmetric about the mean. Examination of the distributions of maximum brake temperature for each truck showed that large variation in temperature was associated with axle ends classified with brake problems. Therefore, *outlier* analysis was performed with an emphasis on detecting trucks with large variation, trucks with hot or cold single outliers, trucks with large differences in temperatures between front and back axles, and trucks with large differences between left and right sides.

The standard deviation in combination with the coefficient of variation beyond certain thresholds identified ten of the fourteen trucks classified with at least one brake problem. They also identify 5 of the 35 trucks classified with “no” brake problems, and 1 of the 8 trucks classified with “only maybe” brake problems. Several of the trucks classified without brake problems exhibited very little variation and had average temperatures close to the averages of all trucks.

Analysis for detecting single outlying axle ends was also performed. A truck with one axle end that is significantly different in temperature than the others is a candidate for further investigation. Any distance greater than two standard deviations from the mean in absolute value is a potential outlier. This method yielded five trucks with cold single outliers and five trucks with hot single outliers. However, only three trucks classified with brake problems had outlying axle ends. Therefore, this measure does not appear to correlate well with trucks classified with brake problems. However, outliers indicate that one axle end is significantly different in temperature from the other axle ends and are potential sources of brake problems. These could be cases where brake problems do in fact exist, but are not captured by the inspections.

Statistics were also developed to detect differences in temperatures between front and back axles and between the left and right sides of the truck. The front was defined as axle ends associated with the drive axles (axles 2-3), and the back was defined as axle ends associated with the trailer axles (axles 4-5). Large differences would be indicative of potential defects. While both of these metrics identified outliers in general, neither correlated as well as the coefficient of variation with trucks classified with brake problems. However, trucks identified by these metrics could be used in conjunction with the other metrics, since trucks with large variation in temperature suggest potential problems. Note that the metric for left side minus right side identified truck 18, which had small variation overall, but which none of the other metrics identified (see Figure 2).

7. References

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5 Motor Carrier Management Information System (MCMIS) Database and Documentation, http://mcmiscatalog.fmcsa.dot.gov/

6 Blower, D.F., Green, P.E. and Matteson, A. Vehicle Condition and Truck Crash Involvement: Evidence from the Large Truck Crash Causation Study, to be presented at TRB, January, 2010.

Appendix A Maximum Brake Temperature by Axle and Side

Table 23 Maximum Brake Temperature for Tractor Semitrailers with at Least 1 Brake Problem Classified as "Yes" (1=Left Side, 2=Right Side) (1=No, 2=Maybe, 3=Yes)

		Axle				Max Brake Temp				
Truck	Side	2	3	4	5	2	3	4	5	Comments
2	1	1	1	2	3	53.0	44.2	36.6	28.0	
	2	1	1	2	2	53.0	57.3	32.7	30.5	Cold in the back
8	1	1	1	1	1	48.8	44.1	39.1	49.3	
	2	1	1	1	3	47.0	31.5	46.4	46.9	Possibly cold on 3rd axle right side
11	1	1	3	1	3	39.8	37.3	43.1	99.3	Big difference between left side and right side. Much hotter on right side
	2	1	1	1	1	88.2	94.2	86.3	117.8	
13	1	1	3	1	1	36.5	39.2	37.1	32.3	Cold all over, except one outlier on 3rd axle right side
	2	1	2	1	1	38.2	84.8	33.4	30.6	
16	1	1	1	3	1	141.9	144.6	90.6	70.3	Hot truck, but much hotter at front (drive axles) than the back (trailer axles)
	2	1	1	1	1	97.8	135.9	66.6	72.0	
18	1	1	3	1	1	38.7	40.3	53.6	47.7	Possibly cold at 2nd axle right side and 5th axle right side
	2	1	1	1	2	32.0	41.3	45.3	36.6	
27	1	1	3	3	3	39.9	45.7	43.1	50.7	This truck appears to be an anomaly. Fairly uniform throughout. Flag for consideration.
	2	1	3	3	3	40.8	43.3	55.9	47.3	
28	1	3	1	3	3	85.3	78.3	40.5	102.2	
	2	3	1	3	1	99.2	85.5	52.7	92.0	4th axle colder than others
34	1	3	1	1	1	137.9	44.1	38.9	42.3	
	2	1	1	1	1	72.4	44.7	43.7	46.3	Hot on axle 2
38	1	1	3	3	3	62.1	61.9	27.9	27.9	
	2	1	3	3	3	75.2	67.5	25.8	26.4	Cold in the back
40	1	3	1	2	3	75.0	94.6	76.5	49.4	
	2	1	1	2	2	108.1	104.2	83.6	71.2	Hot at front, colder in back
43	1	1	1	1	3	69.9	49.5	119.0	89.1	3rd axle different. Hot in back
	2	1	1	1	1	71.6	48.8	114.7	113.4	
44	1	1	3	1	1	48.3	45.3	52.2	69.4	
	2	1	1	1	1	49.2	45.0	77.0	82.2	Possibly hot on right side in back
57	1	1	2	2	3	32.8	33.3	34.3	33.4	
	2	1	2	3	3	40.9	38.7	32.0	36.1	Cold all over

Table 24 Maximum Brake Temperature for Tractor Semitrailers with at Least 1 Brake Problem Classified as "Maybe" (Only Maybe)

		Axle				Max Brake Temp				
Truck	Side	2	3	4	5	2	3	4	5	Comments
3	1	1	1	1	1	63.7	114.7	81.9	86.3	Tends to be hot on 3rd axle, but truck is hot in general
	2	2	1	1	1	69.6	123.7	94.6	74.1	
7	1	1	1	1	2	43.8	33.1	70.7	31.4	Hot on 4th axle
	2	2	1	1	1	31.9	38.8	69.6	36.3	
14	1	1	1	2	1	31.7	29.4	34.0	44.6	Generally cold, but warmer on 5th axle (probably Ok)
	2	1	1	1	1	27.8	28.0	37.6	44.2	
15	1	2	1	1	1	39.0	38.5	47.7	49.7	Generally cold, but warmer on 4th and 5th axle (probably Ok)
	2	1	1	1	1	34.0	39.1	50.0	48.8	
36	1	1	1	1	2	43.1	30.9	42.1	47.0	Probably Ok
	2	1	1	1	2	41.5	35.0	42.7	49.6	
37	1	2	2	1	1	29.3	31.0	34.7	40.4	Generally cold, but warmer on 5th axle (probably Ok)
	2	2	2	1	1	30.1	29.6	38.1	50.6	
49	1	1	1	1	2	47.2	43.1	38.6	42.0	Ok
	2	1	1	2	1	45.6	46.5	40.8	43.0	
54	1	1	1	2	1	45.9	37.9	39.6	42.5	Ok
	2	1	1	2	1	47.4	44.0	41.0	37.2	

Table 25 Maximum Brake Temperature for Tractor Semitrailers with Brake Problem Classified as "No" (Only No)

		Axle				Max Brake Temp				
Truck	Side	2	3	4	5	2	3	4	5	Comments
1	1	1	1	1	1	45.6	67.6	57.9	50.8	
	2	1	1	1	1	63.8	47.8	56.3	64.0	Ok
4	1	1	1	1	1	73.1	71.9	54.6	47.0	
	2	1	1	1	1	72.3	73.2	74.7	67.2	Probably Ok
5	1	1	1	1	1	36.8	47.1	57.6	59.5	
	2	1	1	1	1	58.0	51.3	39.1	60.5	Ok
6	1	1	1	1	1	31.0	42.3	41.3	47.4	
	2	1	1	1	1	34.7	38.6	31.8	41.1	Ok
9	1	1	1	1	1	60.3	60.4	40.2	42.6	
	2	1	1	1	1	56.9	56.0	45.6	65.1	Cooler in back
10	1	1	1	1	1	34.8	40.6	87.1	65.7	
	2	1	1	1	1	35.7	47.1	74.9	84.3	Hot in back
12	1	1	1	1	1	43.8	42.8	33.5	35.2	
	2	1	1	1	1	39.3	38.5	65.2	36.5	Marginal - 4th axle right side
17	1	1	1	1	1	46.0	89.0	123.2	99.7	
	2	1	1	1	1	98.2	97.0	122.0	120.0	Hot, except 2nd axle left side
19	1	1	1	1	1	43.3	44.4	33.3	32.4	
	2	1	1	1	1	46.2	43.5	29.8	33.6	Generally cool, but cooler in back (Ok)
20	1	1	1	1	1	36.8	37.8	38.7	33.9	
	2	1	1	1	1	43.2	37.4	35.9	41.7	Cool but uniform (Ok)
21	1	1	1	1	1	64.8	69.0	55.2	45.3	
	2	1	1	1	1	73.6	67.2	53.1	60.6	Probably Ok
22	1	1	1	1	1	48.5	58.2	50.8	59.2	
	2	1	1	1	1	53.2	69.3	55.8	61.7	Ok
23	1	1	1	1	1	67.0	69.7	77.8	86.1	
	2	1	1	1	1	70.7	76.9	77.4	89.4	Ok

Table 25 Maximum Brake Temperature for Tractor Semitrailers with Brake Problem Classified as "No" (cont)

		Axle				Max Brake Temp				
Truck	Side	2	3	4	5	2	3	4	5	Comments
24	1	1	1	1	1	59.6	60.0	68.1	63.8	
	2	1	1	1	1	74.2	63.7	72.0	66.9	Ok
25	1	1	1	1	1	54.5	52.4	51.4	63.6	
	2	1	1	1	1	57.8	46.4	53.2	58.8	Ok
26	1	1	1	1	1	51.1	53.8	71.5	73.8	
	2	1	1	1	1	57.4	47.9	66.6	69.5	Ok
29	1	1	1	1	1	43.2	50.2	88.4	76.9	
	2	1	1	1	1	51.3	61.8	76.9	61.7	Marginal
30	1	1	1	1	1	113.8	85.0	87.1	96.4	
	2	1	1	1	1	117.8	118.5	116.5	105.2	Hot
31	1	1	1	1	1	56.0	50.1	59.1	56.7	
	2	1	1	1	1	101.3	50.5	67.2	57.9	One outlier
32	1	1	1	1	1	44.5	47.3	64.3	70.4	
	2	1	1	1	1	50.1	50.4	73.7	78.1	Ok
33	1	1	1	1	1	45.2	50.2	45.1	52.1	
	2	1	1	1	1	51.8	51.8	51.6	45.3	Ok
35	1	1	1	1	1	39.7	72.6	81.3	98.8	
	2	1	1	1	1	69.1	79.0	90.6	106.3	One cold in front, hot in back
39	1	1	1	1	1	61.4	59.5	68.4	86.4	
	2	1	1	1	1	61.0	63.9	77.3	74.4	Ok
41	1	1	1	1	1	62.7	56.9	67.0	76.6	
	2	1	1	1	1	92.4	79.4	85.0	92.6	Hotter on right side, marginal
42	1	1	1	1	1	36.7	37.6	46.5	51.9	
	2	1	1	1	1	33.7	35.2	52.0	55.4	Ok

Table 25 Maximum Brake Temperature for Tractor Semitrailers with Brake Problem Classified as “No” (cont)

		Axle				Max Brake Temp				
Truck	Side	2	3	4	5	2	3	4	5	Comments
45	1	1	1	1	1	50.5	47.1	35.4	44.3	
	2	1	1	1	1	52.2	52.8	45.7	46.6	Cold on 4th axle, left side
46	1	1	1	1	1	39.3	43.0	38.5	44.4	
	2	1	1	1	1	43.1	38.8	45.5	61.1	Ok
47	1	1	1	1	1	46.1	45.3	75.6	74.8	
	2	1	1	1	1	55.3	50.7	97.0	82.7	Hotter in back
48	1	1	1	1	1	44.6	51.6	46.5	55.8	
	2	1	1	1	1	48.1	52.2	56.8	56.0	Ok
50	1	1	1	1	1	55.2	69.7	74.9	64.2	
	2	1	1	1	1	56.3	64.1	75.2	72.9	Ok
51	1	1	1	1	1	73.2	72.0	73.4	77.3	
	2	1	1	1	1	81.0	81.0	78.7	61.0	Warm but fairly uniform, probably Ok
52	1	1	1	1	1	60.5	61.4	84.8	86.6	
	2	1	1	1	1	65.2	82.9	98.0	46.9	Difference
53	1	1	1	1	1	45.9	46.1	70.4	73.0	
	2	1	1	1	1	49.3	47.8	77.0	85.1	Hot in back
55	1	1	1	1	1	66.4	66.3	78.6	82.1	
	2	1	1	1	1	73.3	86.9	78.3	92.8	Ok
56	1	1	1	1	1	52.0	52.1	49.8	74.2	
	2	1	1	1	1	50.7	50.2	63.0	85.4	Ok