HEAVY TRUCK TRAILER SKIDWEAR AS A FUNCTION OF ABS BRAKE CONFIGURATION

by

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ABSTRACT

JARED JOHAN ENGELBRECHT. Heavy truck trailer skid wear as a function of ABS brake configuration (Under the direction of DR. PETER T. TKACIK)

Most commercial heavy-duty truck trailers are equipped with either a two sensor, one modulator (2S1M) or four sensor, two modulator (4S2M) anti-lock braking system (ABS). Previous research has been performed comparing the performance of different ABS modules, in areas such as longitudinal and lateral stability, and stopping distance.

This study focuses on relating ABS module type, and wheel speed sensor placement to trailer wheel lock-up and subsequent impact to tire wear for tandem axle trailers with air-ride suspension. Prior to tire wear inspection, functionality of the ABS system was testing using an ABS scan tool communicating with the SAE J560 plug access port on the trailer. Observations were documented on trailers using the 2S1M system with the wheel speed sensor placed on either the front or rear axle of a tandem pair. As a result of wheel lock-up and subsequent flat spotting; the compromised wear pattern propagates throughout the tire rapidly due to high trailer loads.

From observed trends in the collected information it has been determined that tire wear from flat spotting due to wheel lock-up tends to occur on the axle opposite of sensor placement. Therefore, it is the recommendation of this study to encourage increased use of anti-lock brake systems with four wheel-speed sensors and two modulators (i.e., 4S2M) be used in applications involving air-ride heavy-duty truck trailers. Such a configuration acts as a defense against skid wear of the trailer tires improving truck and trailer safety while reducing the financial impact from pre-mature tire replacement.

DEDICATION

I dedicate this thesis work to my family and friends who served as sources of encouragement for the duration, with special thanks to my parents and sister; Ann, Johan, and Brooke Engelbrecht.

I also dedicate this thesis work to my late grandfather, Hans Botha who was a tireless motivator and academia supporter.

ACKNOWLEDGEMENTS

I will start by thanking the advisory council and specifically Dr. Peter T. Tkacik for his guidance and enthusiasm during this research. Dr. Tkacik provided insights from the tire industry from his personal and professional experience which further deepened my own interests for career development.

I would also like to thank Zachary Merrill at Michelin North America for sharing his insights into the world of heavy commercial vehicles. Much of this research is founded on his deep understanding of the details of this ubiquitous but mostly invisible world of trucking all around us.

A definite thank you to PhD student Jerry Dahlberg for always being willing to lend a hand while navigating through the graduate program.

Some fellow students deserve acknowledgement Piyush Gulve, Nagarjun Chandrashekar and Tony Martin for their assistance with research activities.

Lastly I would like to thank the Mechanical Engineering Department for their professionalism, support, and encouragement to be involved with on campus projects pursuant with my own career interests.

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CHAPTER 1: INTRODUCTION

1.1 Organization of Thesis

Chapter 1 provides the reader with a brief introduction to the functionality of ABS systems and provides the motivation behind this research.

Chapter 2 is a literature review section which provides information on ABS systems specific to tractor trailers, rules and regulations for installation, maintenance programs, trailer suspension types, axle configurations, tire types, wheel lock-up wear patterns and complimentary research underlying the importance of mitigating wheel lock-up to ensure maximum yaw stability and keeping stopping distances to a minimum.

Chapter 3 provides background for the field test procedures, information on how data collection was performed and organized to reveal trends.

Chapter 4 summarizes results and conclusions, along with a future scope of work.

1.2 ABS System Functionality

Vehicle safety for occupants and their surrounding environment continues to be an area of continued and deliberate development. One of the most impactful safety innovations to come from the 20th century is the Anti-Lock Braking System (ABS) which was pioneered in 1929 by a French automobile and aircraft expert, Gabriel Voisin.

The ABS system allows the wheels on a motor vehicle to maintain tractive contact with the road surface while responding to driver inputs such as braking, and steering. A primary goal is to prevent the wheels from locking up during braking, keeping stopping distances to a minimum and allowing the driver to steer the vehicle under heavy threshold braking. This provides an increased level of longitudinal and lateral stability (here-in referred to as yaw stability).

1.3 ABS Components

Uniformly, ABS systems consist of the following: An electronic control unit (ECU), wheel speed sensors, and regulator valves plumbed within the brake air system.

A unique operating parameter to tractor trailers which is not seen in passenger vehicles is the fact tractor trailers use an air brake system, whereas passenger vehicles use a hydraulic brake system. In principle, ABS installed in either hydraulic or air brake systems operate with the same intentions, components however, are somewhat different.

The ECU monitors rotational speed of each wheel via signals received from individual wheel speed sensors. When the ECU detects a condition indicative of wheel lock, such as a wheel or pair of wheels rotating largely slower than the others, it actuates the regulator valves to reduce the line pressure, thus reducing the braking force at each of the slower rotating wheels. With this intervention, rotational speed will increase, mitigating chances for wheel lock-up.

The wheel speed sensors are used to determine the rotational velocity at each wheel and any acceleration or deceleration compared to free rolling velocity. The sensor consists of a magnate and a Hall Effect sensor, or a toothed wheel and an electromagnetic coil to generate the signal [1]. As the wheel rotates, a magnetic field is induced around the sensor. The fluctuations within the magnetic field generate a voltage, and this voltage correlates to wheel velocity. The increases and decreases in this voltage signal communicate to the ECU whether the wheel is impending lock-up or free-rolling.

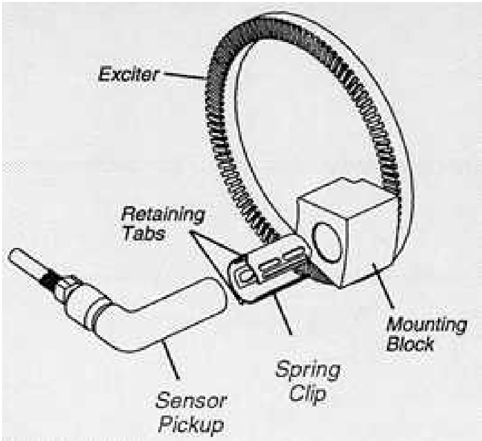

Figure 1.1: Wheel speed sensor and toothed wheel [2]

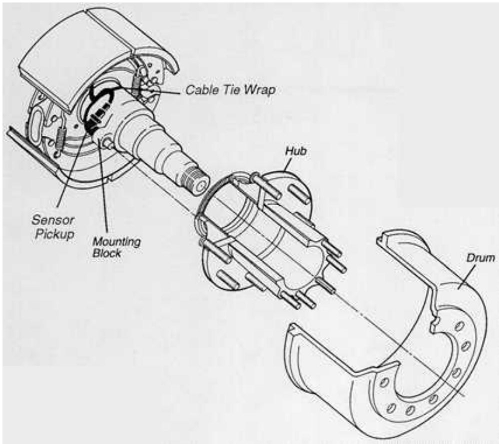

Figure 1.2: Exploded view for wheel speed sensor install location [2]

The regulator valve contains two solenoids which operate diaphragms controlling the air flow to the front or rear axles, or individual corners, depending on how the system is plumbed. When the ECU detects wheel slip from signals sent by the wheel speed sensors, the solenoids are activated to divert air from the supply port, and through the exhaust port, lessening brake force at that wheel.

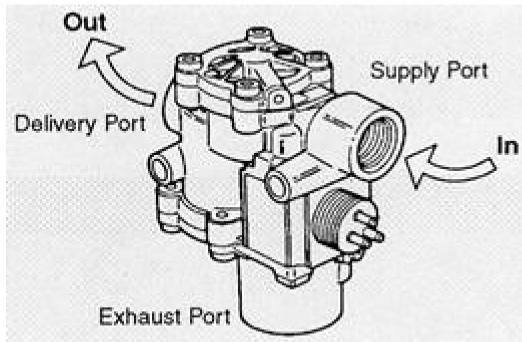

Figure 1.3: ABS air regulator [2]

CHAPTER 2: LITERATURE REVIEW

2.1 Tractor Trailer ABS

2.1.1 History and regulations

Commercial trucks are an integral component for commerce transport, world-wide. According to the Bureau of Transportation Statistics (BTS) of the U.S. Department of Transportation (DOT), 66 percent of the $89.8 billion worth of freight conveyed in May 2016 between the U.S. and its North American Free Trade Agreement (NAFTA) partners, Canada and Mexico, was transported by commercial trucks [3]. Heavy-duty trucking ranks as the leading method of transportation for goods and services in the United States [3]. A heavy-duty truck is defined as a truck that tows a trailer with a gross weight of at least 10,001 pounds [4]. The National Highway Traffic Safety Administration (NHTSA), through FMVSS 121, requires that ABS be installed on commercial vehicle trailers built on or after March 1, 1998. ABS on trailers must control at least one axle of the vehicle, thus at a minimum, a two sensor one modulator (2S1M) system must be installed on the trailer [4].

2.1.2 Tractor Trailer ABS types

The purpose of ABS on the trailer axles is to improve stability under braking by protect individual wheels from lock-up, increasing yaw stability and decreasing the tendency to jackknife during emergency maneuvers. The two most common types of

ABS systems found on tractor trailers consist of either two wheel speed sensors and one modulator (2S1M) or two wheel speed sensors and two modulators (2S2M). With two wheel speed sensors, both sensors can be installed on a single axle, or sensors can be installed in a diagonal configuration which allows for one sensor on each axle. The least commonly installed system is a four wheel speed sensor and two modulator (4S2M) system which can actively sense wheel speeds at all four corners of a tandem axle pair. Configurations of each system are shown below.

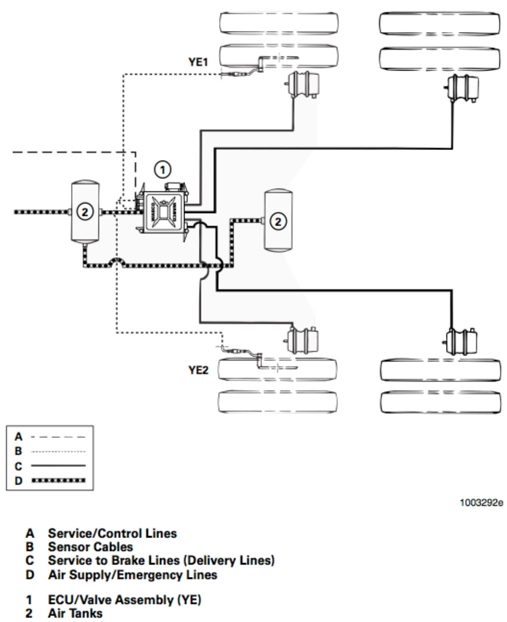

Figure 2.1: 2S1M ABS architecture [5]

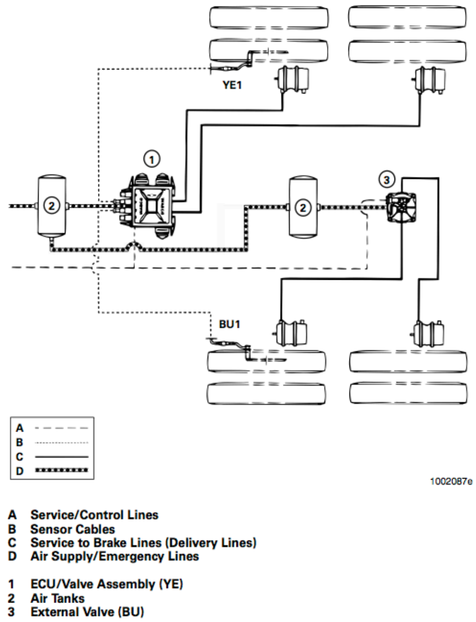

Figure 2.2: 2S2M ABS architecture [5]

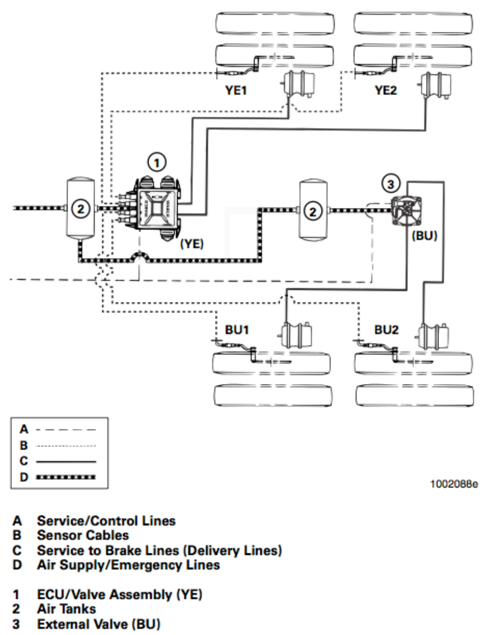

Figure 2.3: 4S2M ABS architecture [5]

Numerous factors are considered when a trailer manufacturer selects an ABS system for a trailer. Factors such as trailer life expectancy, trailer operating environment, trailer initial cost, ABS initial cost and tire and axle configuration. The two most common tire and axle configurations are: dual axle super-single and dual axle tandem pair (the focus of this study). The super single set-up will have a single wheel installed at each corner, whereas the tandem pair will have two wheels installed at each corner.

Figure 2.4: Super single dual axle trailer [6]

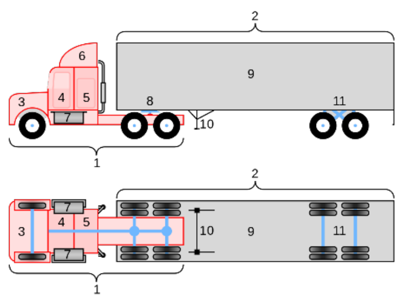

Figure 2.5: Example of a two tire tandem axle trailer [7]

2.1.3 ABS Installation

The goal of a trailer ABS system is to sense the lighter loaded axle, and reduce braking pressure to this axle. The reason being, with less normal load acting on their tire contact patches, these tires, if not sensed, will tend to lock-up first. When a trailer manufacturer uses a 2S1M or 2S2M ABS system, the axle onto which the sensors are installed depends on the type of suspension the trailer is riding on. Freight companies may install ABS sensors diagonally across the two axles as an attempt to sense wheels on both axles, however this is not considered best practice [8]. With a 4S2M, ABS is installed on both axles of a tandem pair.

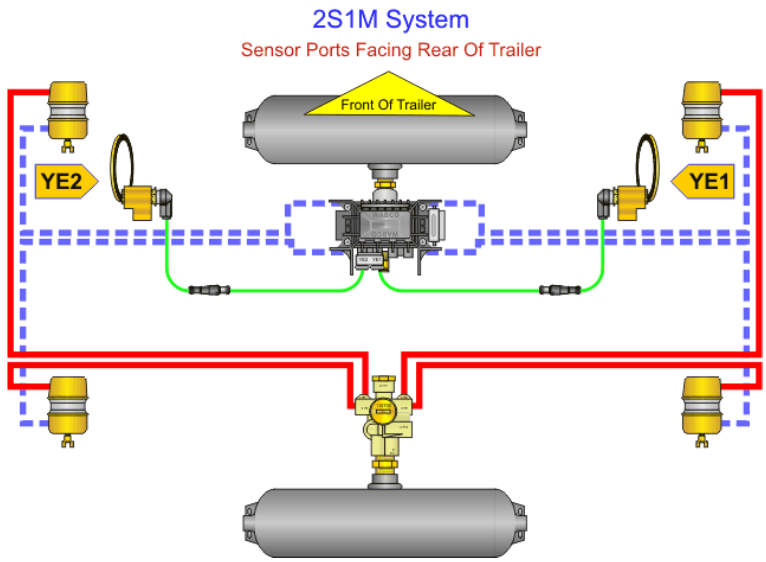

Figure 2.6: 2S1M ABS system [9]

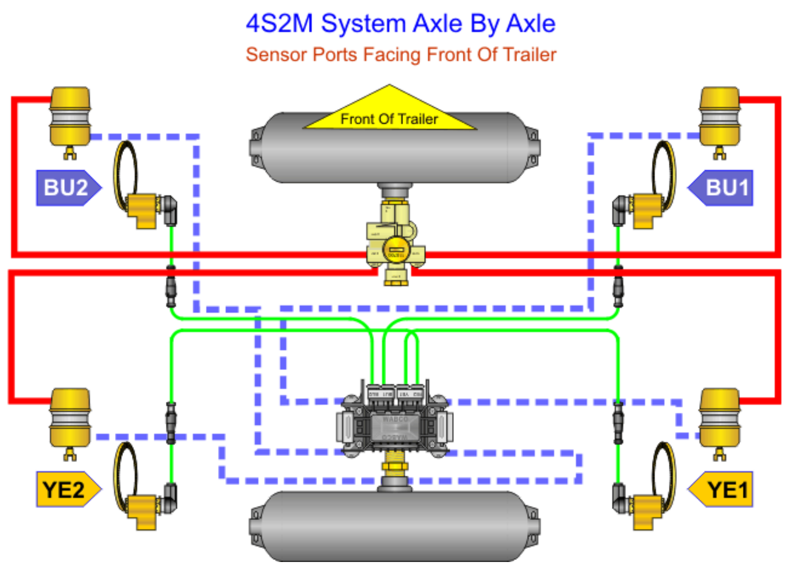

Figure 2.7: 4S2M ABS System [9]

2.2 Trailer Suspension Types

There are two main types of trailer suspension in use today; leaf spring and air-ride. Each of these systems has their inherent tradeoffs with respect to complexity, cost, and control and ride harshness. Air ride suspension systems are most commonly used today.

Figure 2.8: Leaf spring tandem axle [10]

Figure 2.9: Air-ride suspension set-up [11]

Both suspensions serve the same purpose, however their layout and componentry result in very different kinematic reactions to load distribution, and load shift, as well as braking forces.

2.2.1 Suspension Braking Reactions

During braking inputs with a leaf spring suspension, there is vertical motion of the front and rear axles, and this movement is reacted at the pivot point on the equalizer. The front axle unloads during braking, decreasing normal force acting at the front tire contact patches, and increases normal load at the rear axle. Thus, the axle with greatest likelihood of lock-up, and the most critical to sense with ABS is the front axle.

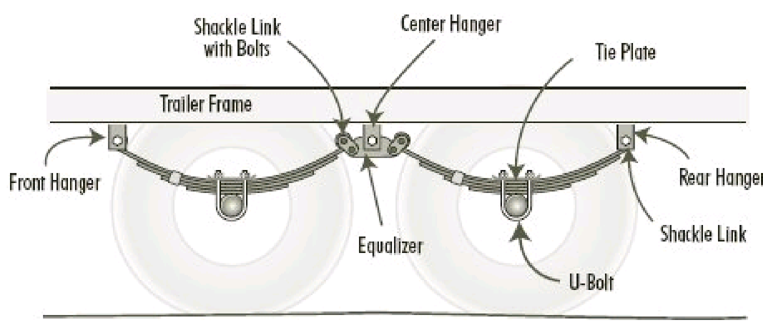

Figure 2.10: Leaf spring equalizer [12]

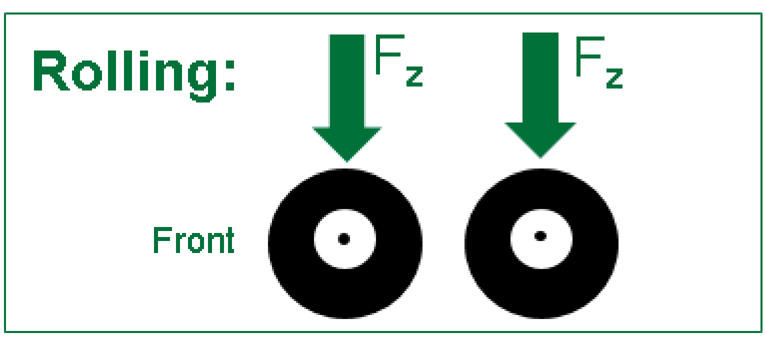

Figure 2.11: Leaf spring suspension forces in rolling [13]

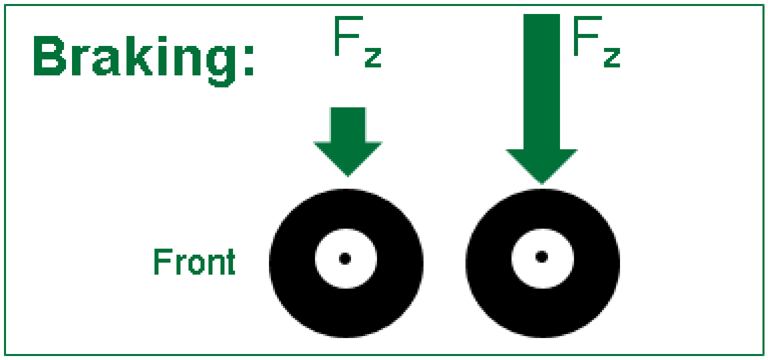

Figure 2.12: Leaf spring suspension forces in braking [13]

During braking inputs with an air-ride suspension, there is vertical motion of the front and rear axles. The vertical motions are reacted independently of each other as each axle pivots about different axes. The front axle unloads during braking, increasing normal force acting at the front tire contact patches, and decreases normal load acting at the rear axle [8]. Thus, the axle with greatest likelihood of lock-up, and the most critical to sense with ABS is the rear axle [14].

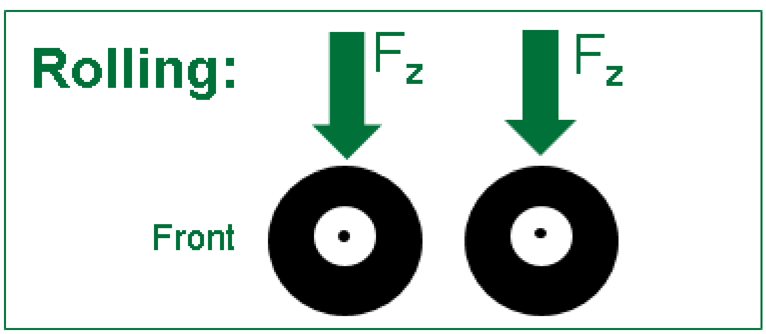

Figure 2.13: Air-ride suspension forces in rolling [13]

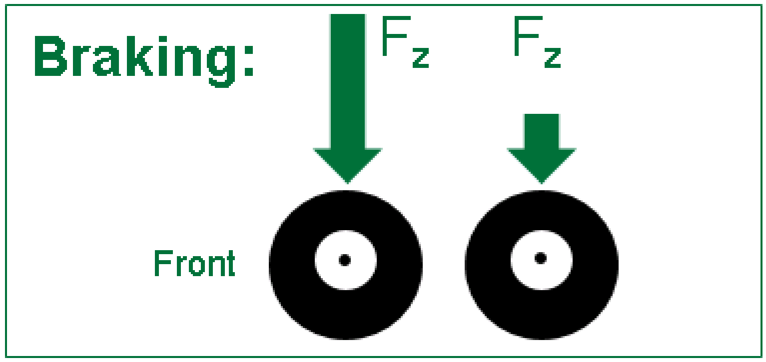

Figure 2.14: Air-ride suspension forces in rolling [13]

The different behaviors inherent to each type are why suspensions are taken into consideration when outfitting a trailer with an ABS system. Brake manufacturer Bendix suggests when using a 2S1M system on an air-ride suspension, the components are most effective at controlling wheel lock-up when the sensors are installed on the rear axle, and the front axle of a leaf spring suspension [8]. Trailer manufacturer Wabash International uses a different standard brake supplier, Wabco, and Wabash International states Wabco's suggested brake placement is in agreement with Bendix suggestions [15]. These recommendations are based on the behaviors exhibited under braking; the goal being to sense the lighter loaded axle to prevent wheel lock-up.

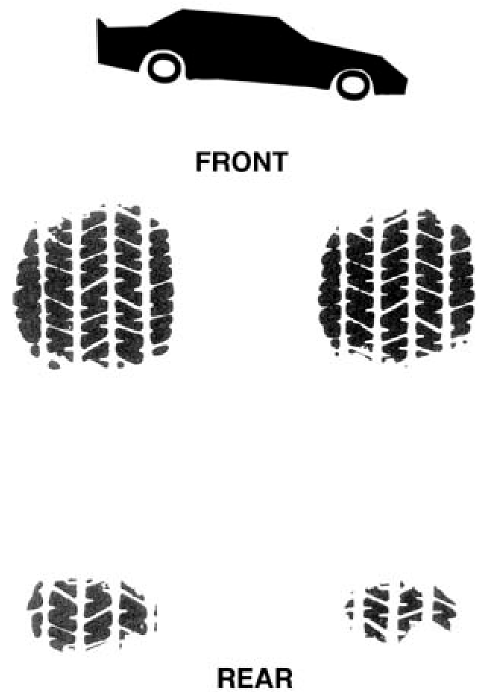

Figure 2.15 Contact patch load under braking [16]

2.3 ABS system inspection and diagnostics

2.3.1 ABS system inspection

Proper trailer maintenance is imperative to maintaining a safe and reliable environment. In order to realize the full potential of an ABS system, components which impact braking and handling performance must be inspected at suggested intervals. Tire tread and sidewall condition, tire pressure, brake drums, brake lines, S-Cam actuators, and all sub components responsible for providing stability to the trailer must be functioning as intended before the full potential of an ABS system can be realized. Brake systems that are out of adjustment can lead to increased component wear, increased stopping distances, and reduced yaw stability of the trailer [17]. Industry best practice for trailer maintenance per the Great Dane Trailer maintenance manual involves inspection at maximum intervals of 25,000 miles [17]. As part of a trailer preventative maintenance program, the following brake components are inspected for wear and safe operation:

- Air leaks inside air brake couplers
- Brake shoes
- Brake shoe return spring
- Brake liners
- Brake shoe roller cams and adjusters
- Spiders
- Anchor pins

The following inspection procedures are based on recommendations by [18].

- Check lining wear across each shoe. An uneven pattern or excessive grooves can indicate the drums need replacing. An uneven pattern can also indicate bent spiders or bell-mouth drums, or weak shoe return springs.
- Inspect lining surface for grease or oil. Never reuse a grease or oil soaked brake shoe. Grease or oil on the friction material will cause the lining to glaze and not do its share of the braking. Never do a one wheel brake job.
- Inspect interior drum surface for even wear, glazing and/or heat checking. Heat checks, cracks and blue spots are indicators of excessive heat (hairline heat checks not over 1" are normal). Never reuse a drum if: wear is over .080” or several heat checks are aligned across the braking surface or hard spots exist.

- Check s-cam for wear at the inner and outer bushing surfaces, s-cam head and spline areas. Worn s-cam or worn s-cam bushings will contribute to longer than normal pushrod stroke.
- Check brake adjusters for proper settings and operation. Check clevis pins and anchor brackets for wear. Never mix automatic brake adjusters with manual brake adjusters, or use different makes of automatic brake adjusters on the same axle. Never operate automatic brake adjusters with worn components.
- Check the wear difference between the front and rear axle shoes (if relining a truck or trailer). If the wear is not equal, this can indicate an air timing imbalance or different rated friction materials. Check for inconsistent use of elbows in air lines (90° elbow is equal to 7' of extra hose).
- Inspect spiders. Pay special attention to the anchor pin-hole area and for squareness and s-cam bushing bore, and to anchor surfaces that are not replaceable

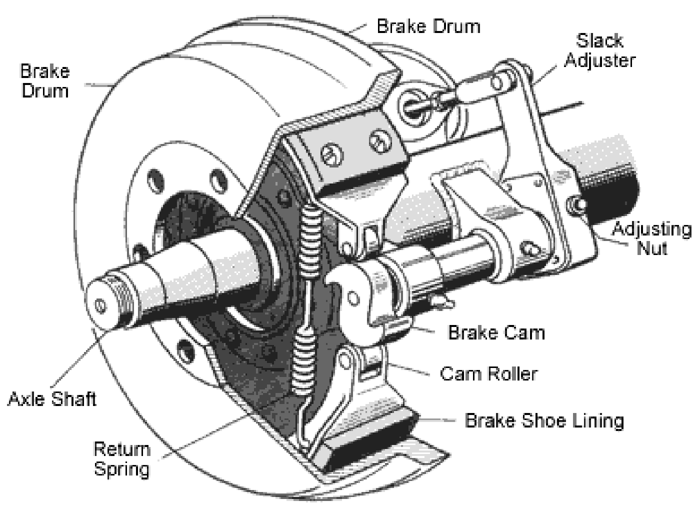

Figure 2.16: Tractor trailer drum brake assembly [5]

2.3.2 ABS system diagnostics

All air-brake ABS systems offer the ability for self-diagnosis. This information can be provided through the malfunction indicator light using the blink code system, or through the use of a scan tool plugged into the onboard J560 diagnostic port.
During this study, a Bendix Trailer Remote Diagnostics Unit (TRDU) was used to scan the trailer ABS system for malfunctions and record trailer mileage. Details of how the TRDU was incorporated will be covered in chapter 3.

In an effort to alert the operator of issues with the ABS system, vehicles are required to have a yellow ABS malfunction indicator lamp inside the cab and in set exterior locations on the trailer. Trailer locations were mandated until February 2009.

US requirement is for all air braked trucks and tractors manufactured on or after March 1, 2001 which are equipped to tow air braked trailers to feature an interior ABS indicator lamp which must be in plain view of driver. This is in addition to the trailer mounted ABS indicator lamp and the ABS indicator lamp on the power-unit itself.

The interior lamp is a means to easily alert drivers to any ABS malfunctions on the units they are towing. Both the power-unit and the towed units must communicate for this feature to work, thus the combination (truck and trailer) must have been manufactured with this capability.

Figure 2.17: Interior ABS lamp [19]

The warning lamp will turn on at start-up and perform an electronic detection of the modulators and wheel speed sensors. When no issues are found, the lamp will turn off. Should the lamp remain on at speeds above 4mph, this is an indication of an ABS malfunction. The lamp remains illuminated when there is a malfunction that affects the generation or transmission of response or control signals [4]. The ECU can detect two types of faults; active and stored [4]. An active fault is a continuous failure and needs immediate repair, a stored fault is an intermittent failure.

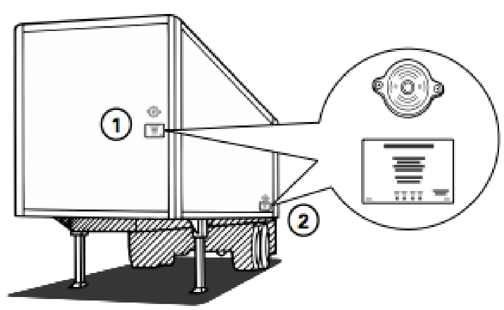

Figure 2.18: ABS warning lamp trailer locations [1]

2.4 Tire wear

2.4.1 Tire wear defined

Abrasion or wear occurs when sliding friction occurs between two bodies in relative motion. Material transfer takes place, from one body to another. Wear is associated with friction and occurs on many length scales [21]. The intensity can vary from a low of dusting wear to higher intensity rubber chunking or tearing. Tire wear is a function of operating parameters such as temperature, pressure, axle normal load, and wheel slip and suspension alignment.

2.4.2 Suspension Alignment

Alignment refers to angles of all steer axle geometry, and also geometry of all tracked axles, such as trailer axles. The purpose of a proper alignment is to minimize tire wear, and maximize vehicle handling. The number one cause of irregular wear in a tracked axle is parallelism (skew) and thrust angle (tracking) [22].

Parallelism is critical because this alignment impacts all tires on the trailer. Axles that are not parallel tend to steer each axle in a different direction. Thus the trailer will track straight, however the axles are not in plane with one another, and the tires are scrubbing across the road surface [22].

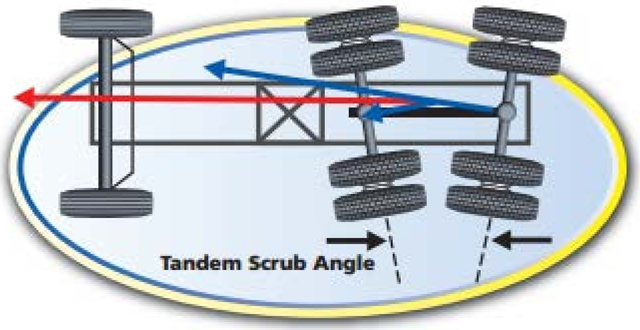

Figure 2.19: Skew misalignment [22]

Thrust angle, or “tracking” refers to the relationship of the trailer centerline to the direction of the axle. The goal is to have a 0 degree thrust angle, with the axles aligned perpendicularly to the trailer centerline. Any misalignment here will cause the trailer to travel off center, causing excess tire scrub [22].

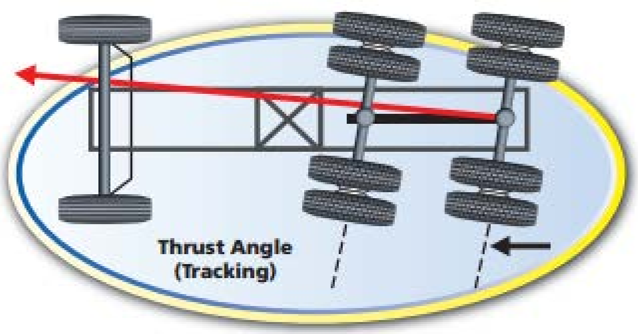

Figure 2.20: Thrust angle misalignment [22]

Camber is the angle formed by an inward or outward tilt in reference to a vertical line [21]. Camber is positive when the wheel is tilted outward at the top, and negative when the wheel is tilted inward. Excessive camber, either positive or negative can cause shoulder wear on the inside or outside shoulders of the tire.

Generally the tire wear is isolated to the shoulders, the degree of which depends on tire width and aspect ratio [23]. Camber angle is not adjustable on trailer axles as it is on a steered axle, however depending on trailer loads, the axle will deflect, causing a change in camber alignment. Trailer axles deflect to allow -0.5 degree of camber at 17,000 pounds per axle loading.

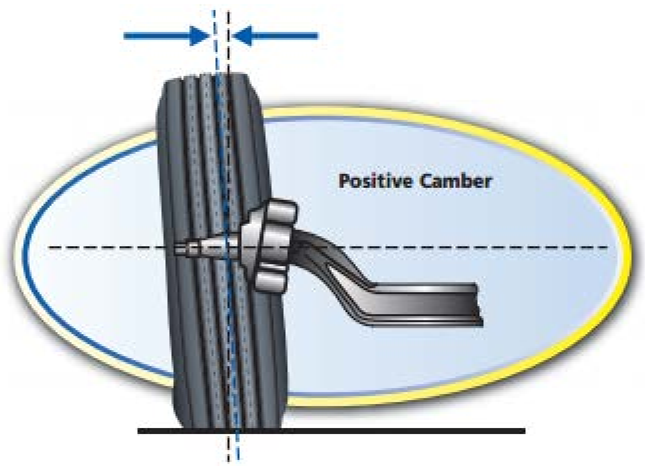

Figure 2.21: Camber alignment [22]

2.4.3 Tire Wear

Tires that are not operating at perpendicular angles to the road surface will produce uneven tire wear. Tires rotating in planes which are against one another can produce irregular wear. Wear patterns are most largely a resultant of the vehicle's suspension alignment, and can appear individually or be compounded as a result of multiple suspension alignment settings being out of spec.

The six primary tire wear patterns are shown below:

- Toe wear
- Free rolling wear
- Camber wear
- Cupping wear
- Flat spotting wear
- Diagonal wear

Figure 2.22 Toe wear [22]

The wear pattern that develops from excessive toe is a feather edged scuff across the tire crown. This pattern is usually only seen in steered tires [22].


Free Rolling Wear

Figure 2.23 Free rolling wear [22]

Free rolling wear can appear as wear at the edge of a rib, without overtaking the entire rib width. Intermittent side forces due to wheel assembly instability cause contact patch pressure variations [22]. The instability can be a result of loose suspension components, or compliance from worn components such as bushings.


Camber Wear – Trailer

Figure 2.24 Camber wear [22]

With camber wear, partial or complete shoulder wear will occur. The intensity of camber wear will depend on the camber angle, and tire size. Shoulder wear can rapdily reduce tire life.

Figure 2.25 Cupping wear [22]

Cupping wear is generally due to any lose or worn component in the suspension system such as loose wheel bearings, worn shock absorbers and worn tie rod ends [22].

Figure 2.26 Flat spot wear [22]

Flat Spotting – Trailer

Figure 2.27 Flat spot wear [22]

Flat spotting wear is more localized across the tread width compared to other wear forms. Flat spotting can be caused by brake lock, or axle hop, axle skip, and being parked stationary for extended periods of time [22]. Once a flat spot has appeared, irregular wear will rapidly propogate across the circumference of the tire, requiring an early replacement.

Figure 2.28 Diagonal wear [22]

Diagonal wear is also a localized wear form spanning across the tread width. Diagonal stresses are caused in the contact patch from side forces generated by camber and toe misalignments. For trailer axles, causes include tandem axle misalignment, skew, thrust, negative camber or worn components [22].

2.4.4 Tire Abrasion

When rubber abrasion takes place repeatedly in the same direction, a characterstic surface pattern appears. A series of ridges lying perpindicularly to the sliding direction, with abrasion mostly taking place at the base of the ridges are known as the Schallamach patterns [21]. Two abrasion processes occur; a small scale 1-5µm in size, and larger scale when fragments breach from the ridge tips [21].

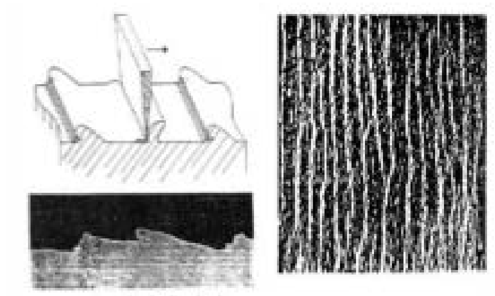

Figure 2.29 Schallamach abrassion pattern [21]

When the frictional force is increased and reaches the tear strength of rubber, gross gouging of rubber particles will take place. Two reactions can occur during abrasion, oxidative degradation due to fricitonal heating in the contact area, and mechano-chemical degradation due to a shear-induced rupture of chemical bonds [21].

Tire tread compound has three properties which can impact the susceptibility to tire wear: intrinsic abradability, lateral and longitudinal compliance, and resilience. These properties are all influencers, but are not all related. For example, a harder, less compliant compound may be less resilient.

2.5 Tire Safety

Tires are subject to a variety of operating conditions, depending on the vehicle in service, use and maintenance tendencies of the operators, and the operating environment. Tire failure while in-use can have devastating consequences, and therefore the issue of tire safety is paramount.

In general, there are two primary areas of tire saftey that relate to a tire failure: Tire servicing and maintenance, and on-vehicle, in-service conditions [21].

For the purpose of this study, we were concerned with the on-vehicle and in-service segment of tire safety.

Some basic recommendations to abide by for tire safety are the following [24]

- Check tire inflation on a monthly basis, and confirm alignment with the trailer manufacturer's suggestion.
- Avoid overloading the trailer; do not exceed the tire load capacity.
- Perform routine tire evaluations such as tread depth, and inspection for irregular wear patterns such as those described in section 2.4.

2.6 Braking Forces

2.6.1 Longitudinal Force

To accelerate or brake a vehicle, longitudinal forces must be developed between the tire and ground, in the tire contact patch. Braking torque applied at the axle produces the braking force reacted at the contact patch. The force distorts the tread elements, and moves them rearward as compared to the axle, compressing the tread elements aft of the contact patch [25].

During modest braking forces, the tread elements will adhere to the road, distorting in the contact patch due to longitudinal shear stress. There will be some stick-slip in the contact patch as tread elements cycle between adhesion and slippage.

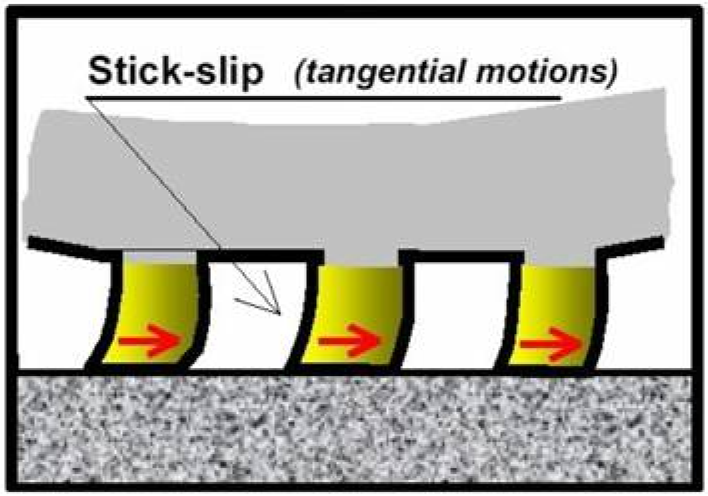

Figure 2.30 Stick-Slip longitudinal forces [26]

2.6.2 Longitudinal Slip Ratio

Society of Automotive Engineers (SAE) J670 defines longitudinal slip ratio as the different between the angular velocity of the driven or braked wheel, and the angular velocity of the free-rolling wheel [25]. Tractive and braking forces developed in the contact patch are a function of slip ratio. Forces will increase proportionally with slip ratio, up to a maximum, after which forces will decrease. Below the maximum force, forces developed are a function of the elastic properties of the tread and carcass [25]. Beyond the peak, forces developed are a function of road texture, surface conditions, vehicle speed, and tire temperature and pressure [25].

Once a tire exceeds the slip ratio corresponding to maximum longitudinal force, stability will decrease, and the tire can lock-up, at 100% slip.

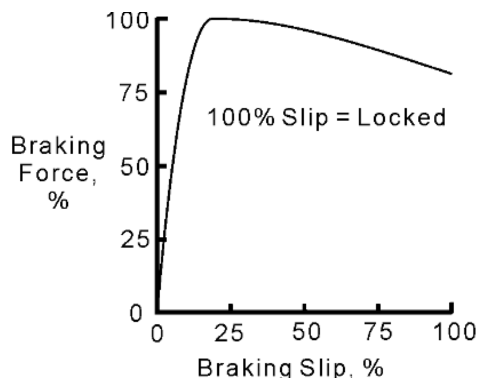

Figure 2.31 Longitudinal braking force vs slip ratio [27]

2.6.3 Wheel Lock-Up

As mentioned in the previous section, wheel lock up will occur from an abrubt deceleration when the available frictional force is overcome at the tire contact patch. Compressive and stretching deformations on the tire will increase through the contact patch until slip takes place.

When a wheel locks-up under braking, the stability of a trailer in tow becomes compromised, and the tires run a risk of becoming flat spotted. The severity of flat spotting can vary, and in some cases, a tire may need immediate replacement. Regardless of the severity, the irregular wear patterns in the tread elements are permanent, and will not fix themselves, eventually propagating around the tire circumference.

Figure 2.32 Tractor Trailer skid marks [28]

2.7 Tractor Trailer ABS Performance

2.7.1 National Highway Traffic Safety Administration

Crash data from National Highway Traffic Safety Administration (NHTSA) State Data System and Fatality Analysis Reporting System are used to determine the effectiveness of ABS brakes in tractor-trailer combinations [29]. NHTSA considers four possibilities when conducting their effectiveness studies, both tractor and trailer do and do not have ABS, only the tractor has ABS, and only the trailer has ABS.

In the 2010 study, data from seven states were included in the analysis. Florida, Georgia, Indiana, North Carolina, Missouri, Ohio and Wisconsin. The primary method used in the report was based on comparing a response group of crashes where ABS could be influential to a control group of crashes where ABS should be considered irrelevant.

Table 1: Incident count for Florida, Georgia, Indiana and Missouri 1998-2007

	FL		GA		IN		MO	
Tractor/Trailer ABS	ABS NO	ABS YES	ABS NO	ABS YES	ABS NO	ABS YES	ABS NO	ABS YES
Control	7663	11620	20090	25520	2485	6946	2826	7663
All Response group	4599	5937	20158	22686	4205	10619	4956	11726
All Single Vehicle	1700	1708	5188	5082	1490	3797	1858	4550
Overturn	210	274	819	774	53	99	193	412
Other	550	557	2084	1966	213	581	1012	2581
Animal/Ped/Bike	68	119	306	412	181	627	90	379
Jackknife	118	56	246	86	81	134	42	61
Other	754	702	1733	1844	962	2356	521	1117
All multi-vehicle crashes	2899	4299	14970	17604	2715	6822	3098	7176

Table 2: Incident count for North Carolina, Ohio, Wisconsin 1998-2007

	NC		OH		WI	
Tractor/Trailer ABS	ABS NO	ABS YES	ABS NO	ABS YES	ABS NO	ABS YES
Control	2469	6168	11187	20340	7179	9312
All Response group	3666	7591	14478	22943	8559	10010
All Single Vehicle	1310	2504	6469	10823	4223	4828
Overturn	285	336	446	683	262	321
Other	388	798	2271	3694	1255	1385
Animal/Ped/Bike	48	195	760	2474	312	477
Jackknife	83	58	285	263	161	98
Other	506	1117	2707	3709	2233	2547
All multi-vehicle crashes	2356	5087	8009	12120	4336	5182

Table 3: Incident count overall comparison

	MED	MIN	MAX
All Response group	13%	10%	7%
All Single Vehicle	12%	8%	34%
Overturn	21%	6%	53%
Other	15%	2%	33%
Animal/Ped/Bike	-24%	-79%	-6%
Jackknife	53%	41%	72%
Other	16%	12%	39%
All multi-vehicle crashes	10%	4%	17%
Overall Reduction	7%	5%	9%

The National Highway Traffic Safety Administration (NHTSA) estimates a reduction by ABS in police reported crashes for air-braked trailers to be 3 percent. This 3 percent reduction represents a significant 6 percent reduction in crashes where ABS is assumed to be influential [29]. The types of crashes that ABS systems influence the most are a reduction in jack-knives, off-road overturns and at-fault involvements in collisions [29].

2.7.2 ABS On/Off Comparison

The importance of a fully functioning ABS system on a trailer has been well documented since the government mandate in March of 1998. A research study compared stopping distance, lateral stability in terms of trailer swing, and longitudinal deceleration for a box trailer with ABS enabled versus disabled [30]. The test trailer had a WABCO 4S2M ABS system installed, and the gross vehicle weight (GVW) was 65,320lb.

Test procedure required the driver to apply full braking at 66mph and initiate a rightward swerve. Test results revealed with ABS engaged, trailer swing was maintained between two to three degrees with stopping distance as low as 262ft, and a deceleration rate of .55g. Completing the same maneuver with ABS disabled resulted in an increased stopping distance between 12 and 30ft, an increased total trailer swing 12 to 13degrees, and a reduced deceleration rate between .53G and .49G.

With ABS engaged, the tires will usually leave a light mark on the pavement. With ABS disengaged, or not functioning, wheel lock up will occur which imparts a negative impact on stopping distance and lateral stability. Longitudinal stability is not the only benefactor, as lateral stability and yaw control are both increased as evidenced by the reduced trailer swing thus allowing the operator have greater control of the tractor trailer during an emergency maneuver.

Figure 2.33 ABS engaged [31]

Figure 2.34 ABS disengaged [31]

In the tire tracks with ABS engaged, you can see the trailer follows the tow vehicle’s path, as opposed to with ABS disengaged. Measuring the trailer swing off center is an approximation of the trailer’s tendency to jack-knife during an emergency braking and steering manuever [31]. Observing the results for trailer swing show this is the area of most improvement with ABS engaged. NHTSA data presented in the previous section supports that ABS engaged makes the largest impact to a reduction in jack-knife occurences. One can decipher that an ABS systems largest impact is to maximizing yaw stability of the trailer.

CHAPTER 3: METHODOLOGY

3.1 Test Object

Trailer ABS systems from commercial heavy duty trucks were the object in this study. A commercial heavy duty truck is defined as a truck that tows a trailer with a gross weight of 10,001lb or more [4]. This study included numerous different trailer manufacturers, and two ABS manufacturers, Bendix and Wabco. All of the trailers featured air-ride suspension representing different suspension manufacturers, and all trailers from the field samples had 2S1M ABS installed. Freight companies both large and small, as well as truck and trailer combinations that travel both regionally and long haul. The study focused on trailers which had a pair of axles, each with four wheels, and a total wheel count of eighteen between the truck and trailer. A total of 391 trailers were sampled.

Figure 3.1: Example of a two tire tandem axle trailer [32]

3.2 Trailer Remote Diagnostic Unit

3.2.1 Device Features

The Bendix Trailer Remote Diagnostic Unit (TRDU) provides the opportunity to troubleshoot ABS component problems using the Diagnostic Trouble Code (DTC) reporting function via LED readout. Blink codes are activated when the TRDU is attached to trailers with a TABS-6 ECU. Resetting DTC codes is a corrective action function, and the ABS odometer data is able to be collected. The odometer information is displayed as soon as the TRDU is plugged in and repeats every 10 seconds [33]. This specific TRDU is compatible with Bendix, Wabco and Haldex brake systems. The TRDU uses an adaptor to connect with a 7-pin J560 plug on the trailer. Multiple colored LEDs follow a blink code sequence that represents numerous possible malfunctions.

Figure 3.2 Main Trailer Electrical Connecter [34]

Figure 3.3 Bendix TRDU LED Display [33]

Figure 3.4 Bendix TRDU LED Display [33]

3.2.1 TRDU Operation

When the TRDU is plugged in and receives power through the 7 pin adaptor, all LEDs will illuminate for .5 seconds, and the green VLT LED will flash four times to confirm communication with the ABS system. If the ABS ECU has no DTC, the green VLT LED will remain illuminated. If the ABS ECU has atleast one DTC, the TRDU displays the first DTC by illuminating the red LEDs, which indicate the component and location. If there are multiple DTCs, then the TRDU will display one DTC at a time, and after the first DTC is cleared, the next code will be displayed. LEDs on static in a circular pattern, this means no communication with the ABS ECU. An example code is RHT+SEN, this corresponds with right sensor.

There are some limitations when the TRDU is used with non Bendix ABS units. Only one LED will illuminate for a fault, a second LED indicating the component location will not be shown.

Once corrective action has taken place, Bendix recommends cycling power to the ECU, then re scanning to see if previous DTCs have been succesfully removed [5].

Odometer (ODO) mileage for the ABS system is displayed with a blue LED on the ODO section. This is displayed as soon as communication between the TRDU and ABS ECU has been established. Odometer data is displayed in increments of 1000 miles. For example, an actual mileage of 153,756 would be read as: 1 blink – pause, 5 blinks – pause, 3 blinks – pause. Zeros are displayed as two quick pulses of the blue ODO LED.

3.3 Field Sample Procedures

Field samples were taken at various different trucking yards. Visual and physical inspections were made at each trailer tire, with the objective to identify areas of tire flat spotting due to service brake skids. Careful examination of each flat spot region was required as to confirm an offender. Once a single flat spot had been identified, that tire was subject to further scrutiny because of the inherent nature of flat spot propagating around the tire circumference; every possible flat spot needed to be identified. Tire location (if flat spotted), ABS type, ABS installation location, and ABS mileage (if flat spotted) were all documented. Recall, the sample set was controlled to consist of trailers with air-ride suspensions and dual tandem axles. All of the documented information was required to encapsulate all variables which impact the targeted trend inside the data.

The TRDU was used to confirm communication with the ABS ECU, this was done for every trailer. ABS odometer readings were taken for every trailer, only if flat spots had been noticed. The reason this was done is to look for trends in the data relating ABS mileage and flat spotting. The TRDU was not used to perform diagnostic inspections on the ABS ECU and system, trailers with no communication to the ECU were not included in the data set if that trailer had tire flat spotting.

3.4 Cost Comparison

3.4.1 ABS Cost

There are two options for a freight company to incorporate 4S2M ABS systems within their fleets. Initially, ABS systems are installed at the trailer manufacturer. Up-front trailer costs can vary depending on options, however in terms of ABS, most box-type and lower end trailers are outfitted with a 2S1M ABS system as standard issue, with either a leaf spring or air-ride suspension. More expensive trailers, such as those used in refrigeration applications are also using 2S1M as standard issue, however in comparison to box-type trailers, refrigeration trailers are more likely to have 4S2M installed from the factory [36]

The commercial vehicle aftermarket industry supports a complete portfolio of ABS products. Individual components as well as finished systems can be purchased. Market studies reveal complete 2S1M and 4S2M systems purchased in the aftermarket average less than $3000. A 4S2M will generally carry a 25%-30% premium over a 2S1M [9].

3.4.2 Tire Cost

Calculating tire cost based on operational parameters is a complex problem with variables such as trailer type, axle alignment, operating environment and trailer usage such as long haul versus regional transport. Long haul trailer tires can last anywhere from 50% to more than double the life of non-steer tires used on trailers for regional transport The reason for this difference is due to how the tires are used. For regional fleets, tires are regularly subject to tight turns inside city limits. In many cases with a tandem axle, the front axle will pivot in place, and the back axle will slide across the pavement when making tight turns. With high repetition, tire life is severely reduced. Regional non-steer tires last around 80K miles [37]. Long haul fleets are rarely subject to tight turns within city limits, and therefore can last upwards of 200K miles or more, depending on the tire chosen [37]. Tire mileage also depends on a disciplined maintenance program to achieve maximum useable life from the tires. The threshold tread depth for replacement may vary amongst different logistics companies. According to the Commercial Vehicle Safety Alliance the minimum allowable tread depth for a non-steer tire is 2/32” [38].

Tire replacement costs are in the $300 to $500 range; this is for the tire only. Ultra low rolling resistance tires can cost upwards of $1200 each. Tire casings can last upwards of a million miles using multiple retreads. Fleets generally plan on getting two to three retreads per casing [39]. Retreads costs are more involved. Fleets have the option of purchasing a retread with a casing supplied by their local retreader. Retreading is a limited option depending on the tire carcass condition. Flat spotting, if severe enough, can ruin the tire body plies, eliminating this as a normal cost saving, tire replacement option. Another option is for the fleet to provide their casing and purchase a new tread. Labor and material costs needed to repair a tire must also be accounted for. Mounting, dismounting, balancing and rotating will fall under the labor cost category. There is also a material cost associated with valve caps and valve cores. Some fleets use balancing materials, puncture sealants and tire pressure sensors, which have both a material and labor component. The average service call takes 2.5hr, with a labor rate in the ~$100/hr range for in field repairs [39]

3.4.3 Cost Benefit Analysis

As previously mentioned, absolute cost is difficult to quantify based on operational variables; however there is a direct negative impact to tire life resulting from a severe flat spot. Any action that can be taken to mitigate additional costs and disturbances to freight operations should be explored.

A cost benefit analysis is provided, which takes a conservative approach to estimating tire replacement cost. A regional non-steer tire can generally see upwards of 80,000 miles before needing replacement, and this will serve as the baseline tire, as will an annual trailer mileage of 500,000. For a trailer needing early tire replacement due to flat spotting, only two tires will be replaced, and they will need replacing at 65% of the normal life of the tire (52,000 miles), which aligns with data collected. The remaining six tires will be replaced at normal intervals of 80,000 miles.

Table 4: Baseline Tire Replacement Cost

Baseline Normal Wear Replacement - 500,000 annual miles								
Mileage	**Tire Cost Low**	**Tire Cost High**	**# Tire Changes**	**# Tires Changed**	**Total Cost Low**	**Total Cost High**	**Tire Cost Low (ea)**	**Tire Cost High (ea)**
80000	$300.00	$500.00	6	8	$15,000.00	$25,000.00	$1,875.00	$3,125.00

Seen here is the number of tire changes at six, based on 500,000 miles driven, and replacement increments of 80,000 miles. The tire cost (ea) represents the cost associated with each wheel position over the course of 500,000 miles.

Table 5: Tire Replacement Cost – Flat Spotted Trailer

Two Tire Replacement - 65% Of Normal Tire Life							Increased Cost per Mile	
Mileage	**Tire Cost Low**	**Tire Cost High**	**# Tire Changes**	**# Tires Changed**	**Tire Cost Low (ea)**	**Tire Cost High (ea)**	**Low**	**High**
52000	$300.00	$500.00	10	2	$5,769.23	$9,615.38	$0.07	$0.12

Table 6: Increased Cost per Tire Position

Increased Cost per Tire Position	
Low	**High**
$3,894.23	$6,490.38

This analysis was broken down to indicate the increased cost per tire location needing an early replacement (at 52,000 miles). Each mile a tire needs replaced, prior to 80,000 miles is represented as the increased cost per mile. The costs shown are material costs only, labor costs and interruption to transport were not captured, however these are burdening items that do have an associated cost. This was a conservative approach, as tires within the sample set were replaced with as little as 24,000 miles, however this does cover a broad spectrum of operational conditions. With fleets of varying sizes, and annual mileage driven, these costs can multiply.

This analysis is purely based on known tire costs and surveyed service times, there are implicit costs associated with disturbance to the flow of operations which are a negative financial impact.

CHAPTER 4: RESULTS AND CONCLUSIONS

The goal of this research project was to investigate the proficiency of tractor trailer ABS systems, and to understand if there are opportunities for improvements in the way ABS systems are utilized. Results are a product of in field sampling, and industry research of both componentry and complimentary studies. With a total of 391 trailers being sampled, this is a small segment of road going trailers, however, the data shows a clear and strong trend, which is very likely representative of real world behaviors.

4.1 Results

4.1.1 ABS Communication

As discussed in chapter 3, using the TRDU to confirm communication with the ABS ECU was step number one. Overall, communication with ABS ECUs was successful, with the percentages shown below. If no communication was confirmed with the ECU, the ABS system is not functioning as intended, and therefore full control over wheel lock may not be possible. In this case, tires were not inspected for flat spotting.

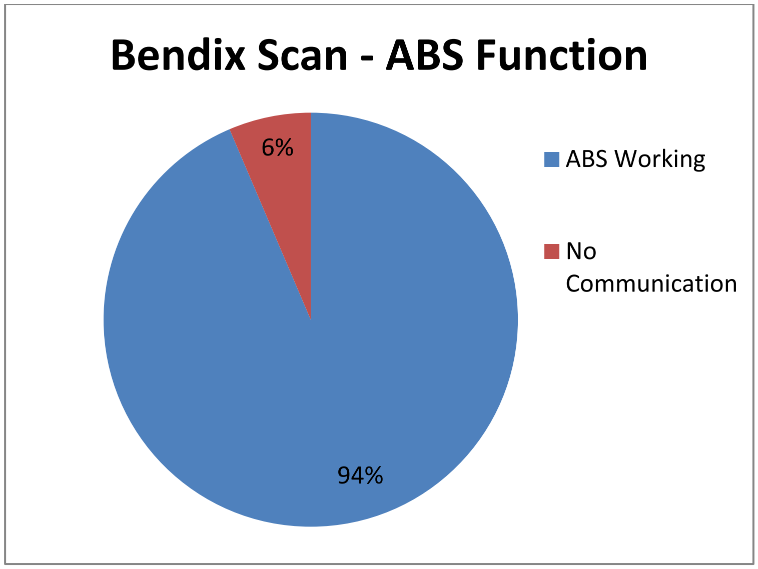

Figure 4.1 Bendix ABS Communication Scan Results

4.1.2 Flat Spotting Totals

With a total of 391 trailers inspected, roughly 10% of those showed signs of tire flat spotting. All of these trailers had air-ride suspension installed, and all had 2S1M ABS systems installed. There was no uniformity amongst installation location; ABS was installed on front or rear axles, depending on the trailer manufacturer. Multiple ABS manufactures were represented, and components amongst ABS manufacturers remained very similar. A challenge was accessibility to each individual tire for inspection. All efforts to identify every possible flat spot was made, however there is a chance a tire may have been rotated in which the trailer was resting on a flat spot. In this case, potential flat spots may have been missed.

4.1.3 ABS Mileage

With the TRDU plugged in, the very first channel scanned was the odometer readings. TRDU scans were available only when successful communication with the ABS ECU was established; therefore 6% of the trucks in this sample set were unable to be scanned for ABS mileage. If communication with the ABS ECU was not successful, then confidence is low that all ABS components are operating as intended, and for how long. These trailers, if flat spotted, were not included in the totals. Trailers with flat spotting were separated within the data set to identify any trends in mileage versus flat spot tire wear, which is the reason for scanning mileage. The method of scanning ABS mileage, and subsequent trends could be made more robust by knowing mileage on individual tires, as well as ABS mileage.

These results show 39% of the trailers showing flat spotting had mileage of under 75,000 miles. This is revealing in terms of the impact to service life that flat spotting can produce. The information shown in this pie chart can be used to support recommending a switch to 4S2M ABS systems, and is prudent information to provide with a cost benefit analysis.

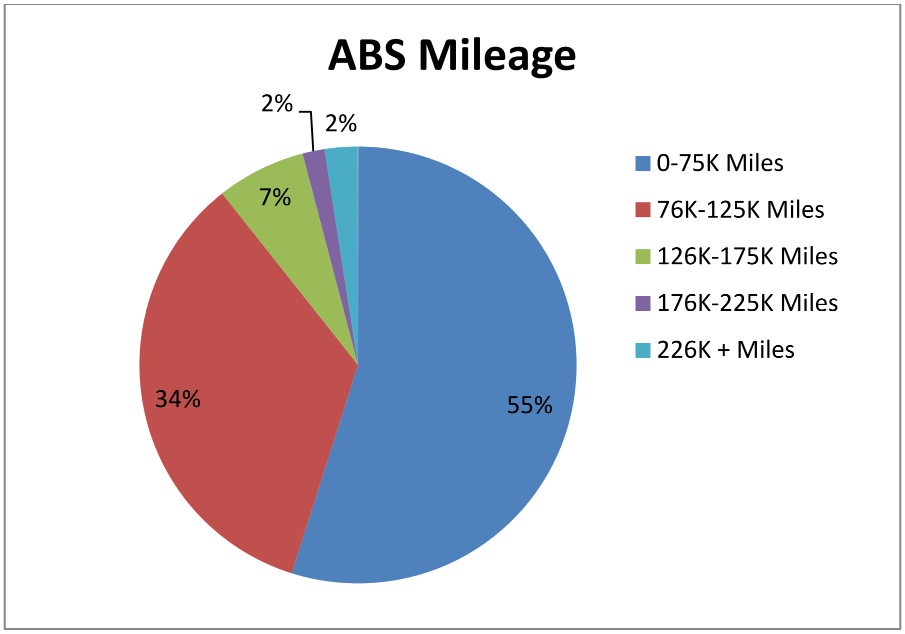

Figure 4.3 ABS Mileage

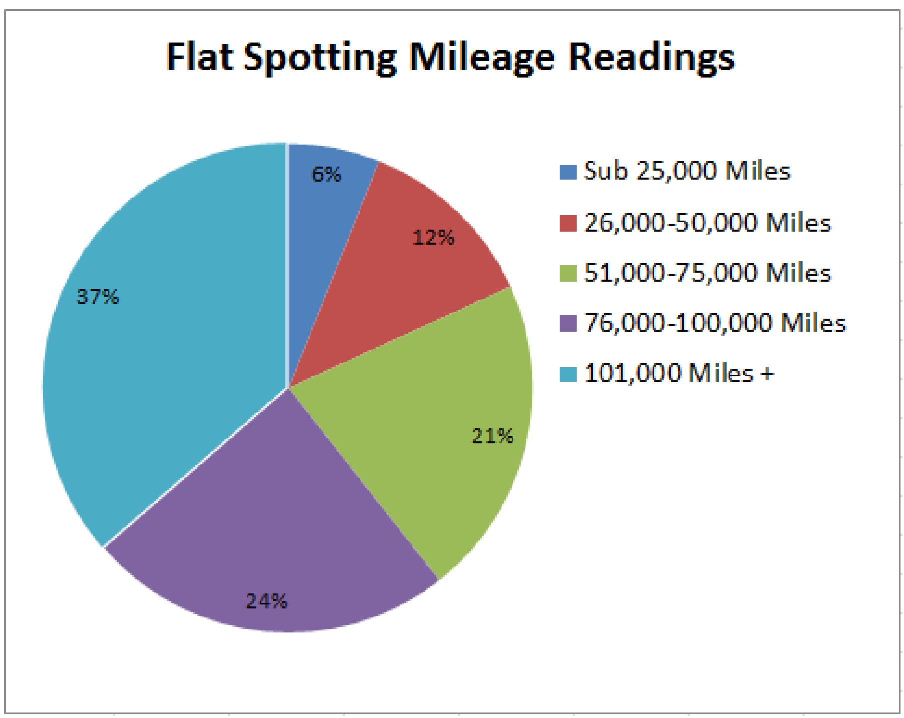

Figure 4.4 Flat Spotting Mileage Readings

4.1.4 Flat Spotting and Axle Location

The goal with taking field samples was to investigate any trends between tire flat spotting, and ABS installation location. Within the sample size of 391 trailers, a trend was revealed. It was noticed that tires on axles, even with ABS installed, remain subject to brake lock and tire flat spotting. Sixteen percent of flat spotted trailers had flat spotting on axles with ABS installed. Eighty-four percent of the flat spotted trailers had flat spotting on axles without ABS installed. The largest percentage of flat spotting occurred on front axles, with ABS installed on the rear; this is the 2S1M configuration as suggested by Bendix and Wabash [15]. The second largest percentage of flat spotting occurred on rear axles, with ABS installed on the front. This particular installation configuration is not in alignment with Bendix or Wabash suggestions [15]. A notable observation given these results is a 2S1M ABS system, which meets NHTSA minimum requirements does leave performance to be desired in terms of controlling brake lock.

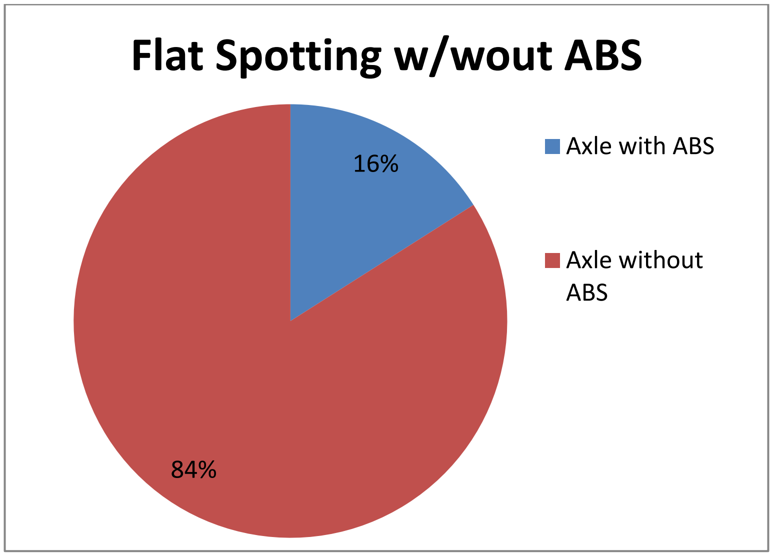

Figure 4.5 Flat Spotting w/wout ABS

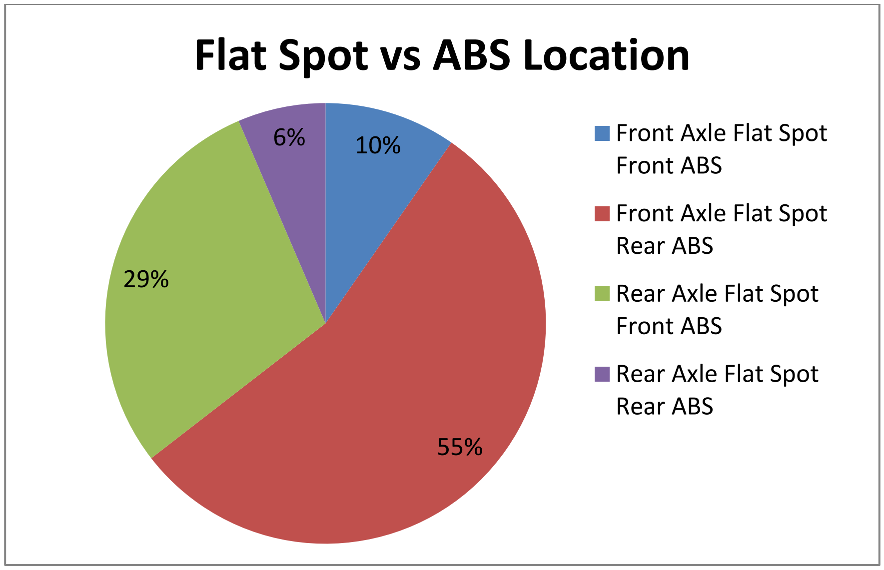

Figure 4.6 Flat Spot vs ABS Location

4.2 Conclusion

A 2S1M ABS system satisfies NHTSA trailer ABS requirements. The primary reason for ABS, as shown in safety stability studies is to control yaw response of the trailer, and reduce the tendency to jackknife during emergency maneuvers – which a 2S1M ABS does do. As the data has shown in this study, a 2S1M does leave much to be desired in terms of protecting trailer tires and maximizing tire life, even when installed on per the brake manufacturer's suggestions. This research revealed a trend that if acted upon per a suggestion to a 4S2M ABS system, can lead to substantial operational cost savings for freight companies; large or small, long haul or regional.

Currently, one of the references used for this research is monitoring a freight company who has recently made a switch to 4S2M from 2S1M. This company switched to 4S2M in November 2016, and has 14 trailers, all with air-ride suspension. In this example, the cost benefit analysis resulted in a switch to 4S2M, and as of April 2017, there have been no flat spots on any trailers inside their fleet, albeit this is somewhat early in the switch.

Based on observations within the field samples, and real world feedback of using a 4S2M ABS system, there is a strong case for suggesting a 4S2M switch, which can be the first line of defense against the burdening cost of early tire replacement due to flat spotting.

4.3 Future Work

The area of future work that would give the most return is not so much in a continuation of random field samples, because the supporting trend is strong. The area which can benefit most is from a refinement in a cost-benefit analysis. There is real opportunity for a deeper dive into operational costs which can be achieved in collaboration with a controlled group of fleet maintenance managers, or operations managers. A study of the operational costs involved with tire purchases, combined with controlled field samples with the same fleet could build a strong argument for why a 4S2M ABS system should be installed on trailers with an air-ride suspension.

Another area where future work which could further support the findings in this research would be to work with a fleet or fleets which are currently using 4S2M ABS systems. Monitoring their trailers for ABS mileage and flat spotting can provide a performance comparison to 2S1M fleets.

The trends and observations from this research are strong and robust, any opportunity to raise awareness of the findings should be taken with confidence, including presentation at industry focused seminars and conventions, such as those with the American Trucking Association.

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