Developing Sustainable New Drum Brake System through Life Cycle Assessment: A Case of US Trucks

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***Abstract*— As technologies for sustainability are more improved, not only direct environmental contaminations from using fuels and chemicals but also indirect environmental pollutions from a whole process of product life cycle are more concerned by consumers, manufacturers, and governments. This study presents how much environmental impact would be yielded by a brake system which consists with drum brakes and drums and how the impact would be related with weight, durability and re-manufacturability of the system based on the market segments of class 8 trucks in US through a life cycle assessment (LCA). From the results of LCA, several recommendations are suggested for development of a new brake system in US. This study provides practical guidelines for making decision on how a new brake system can be optimized in terms of sustainability.**

Keywords—Life cycle assessment, Automotive industry, Drum brake system, Sustainability, Environmental impact, Energy efficiency

I. INTRODUCTION

Environmental benign design for consumer products has been regarded as essential strategy to expand competitive advantage of manufacturing firms. The design considers high energy efficiency, less usage of related resources, less greenhouse gas, and less wastes throughout product life cycle while maintaining sustainability in terms of functionality, cost and quality. Through international cooperation formalized in compacts such as the Montreal Protocol and the Kyoto Protocol, countries are attempting to regulate and control the total greenhouse gas (GHG) emissions and ozone depletion from themselves and their fellow nations. With the addition of popular and successful documentaries such as An Inconvenient Truth, companies and consumers have also begun monitoring and controlling their own environmental footprints. Countries are now engaging in carbon emissions trading and are actively seeking to reduce their carbon footprint.

As technologies for sustainability are more improved, not only direct environmental contaminations from using fuels and chemicals but also indirect environmental pollutions from a whole process of product life cycle are more concerned by consumers, manufacturers, and governments. Most products which consumers purchase would yield a negative environmental impact through a whole product life from the process of raw materials to the disposal of the products. Therefore, an approach to estimate the environmental impact of a product or service throughout its lifecycle is needed. In this manner, life cycle assessment (LCA) is the most popular approach and stimulates lots of researches about environment.

While LCA is being applied for various studies, automotive industry is one of the most active LCA research areas. The automotive and commercial vehicle industries have been leading members in carbon footprint reduction. Original equipment manufacturers (OEMs) in the automotive industry have already developed multiple vehicle technologies that reduce their carbon footprint and now OEMs in the commercial truck industry have begun to develop technologies that reduce the weight or the diesel dependence of their vehicles. Environmentally, weight reduction is the current best solution to reduce the vehicle's carbon footprint in commercial vehicle industry while keeping the product viable for customers. The weight reduction allows customers to carry more cargo weight, earning more revenue per trip, eliminating trucks from the road by requiring fewer trips to transport the same amount of cargo and reducing each fleet's carbon footprint.

Influenced by newly emerging technologies and a consumer-driven trend towards renewable energy and carbon footprint reduction, several manufacturers in the commercial vehicle industry have begun to prefer environmentally sustainable sub-component systems. Customers are even willing to pay a slight premium in order to have sub-component systems that are both sustainable and long lasting. This situation provides brake suppliers with the opportunity to reduce their environmental footprint and thereby support and promote national and international goodwill.

In this study, the environmental impact of a drum brake system for trucks in US is researched through LCA based on three kinds of end-users. From this research, the relationship among the weight, re-manufacturability and durability is identified for suggesting several recommendations on a new drum brake development.

II. Literature Review

The LCA approach is widely recognized as a useful framework and attempts are underway to integrate life-cycle thinking into business decisions. A major international initiative in this direction is the series of environmental management standards (EMS) proposed by the International Standards Organization, widely known as ISO 14000. Standards developed for inclusion under ISO 14000 contained principles and guidelines for conducting LCA for product evaluation [1]. Similarly, the document "Guidance on acquisition of environmentally preferable products and services," prepared by the United States Environmental Protection Agency, US EPA, to help implement the President's Executive order 12873, recommends LCA approach in all federal procurement [2].

The increased awareness of the importance of environmental protection, and the possible impacts associated with products, both manufactured and consumed, has increased interest in the development of methods such as LCA to better understand and address these impacts. Early LCA studies such as Curran [3] and Alting & Jogensen [4] provided theoretical approaches on LCA with guidelines, processes and tools for companies and research institutions. Recently, as environmental contamination comes to be one of the most important society issues, researches about extended and refined LCA approaches and implementations are more dominated [1] [5]. In addition, the fields of LCA are widely expanded including chemical, construction, medicine, manufacturing and automotive industries [6]-[8].

The products can be broadly divided into material intensive and energy intensive products based on the results of the LCAs. Material intensive products such as laptops and medicines means the phases related with the materials such as a process of the raw materials yield more environmental than other areas such as use phase. On the other hand, energy intensive products such as vehicles have a major environment impact on spending energies usually during the use phase of the products. Reducing greenhouse gas (GHG) emissions from motor vehicles have been a major challenge for climate policy. Modest increases in vehicle efficiency have been offset by increased total travel so that transportation has accounted for about 40% of the growth in carbon dioxide (CO_2) emissions from all energy-using sectors since 1990. Also, combustion emissions from US automobiles and light-duty trucks accounted for approximately 60% of GHG emissions from the U.S. transport sector, or 17% of total US GHG emissions [9]. In this manner, LCA is being applied for various studies in automotive industries for reducing GHGs which caused by energy consumption [10]-[15]. Samaras & Meistering [16] conducted the LCA of hybrid, plug in hybrid and conventional gasoline vehicles to compare each environmental impact. Puri et al. [17] applied the LCA to find a better material alternative among steel, aluminum and glass-fiber reinforced polypropylene composite, for an automotive exterior door skin. In addition, the more technologies such as various new materials, machines and devices are developed, the more researchers apply the LCA to light weight, renewable materials and recycling [18][19].

As many studies conducted for the automotive industry have been conducted, most researches are mainly focused on energy consumption by burning fuels during the use phase. However, in case of replaceable automotive components such as brake systems and tiers, without considering the re-manufacturability and durability of the subparts based on different characteristic of end-user, it is hard to understand the environmental impact only from the energy consumption. Therefore, the LCA for brake systems has been conducted with extended consideration in weight differences among several brake options and replacement options between new or re-manufactured subparts based on various characteristics of the end-user in this study.

III. Methods

A. *Life Cycle Assessment*

LCA is the study of product's life cycle from its "cradle" or raw material acquisition, to its "grave" or final disposal. Through two standards regarding LCA, ISO Standard 14040 and ISO Standard 14044, consistency is maintained despite multiple users with varying LCA goals [20][21]. While these two documents standardize the processes, the authors realized that quantifying environmental effects would be difficult as various situations would have multiple environmental metrics and priorities. In order to give the LCA process some standardization without compromising its flexibility, the process is defined in general terms with no specific format, and divided into four phases as follows:

- Goals and Scope Definition: LCA must be outlined in detail in order to orient a study towards producing useful deliverables; the depth and breadth of LCA can vary drastically dependent on its goal. This includes defining system boundaries and the system environment, identifying key assumptions, and selecting a functional unit, if applicable.

- Inventory Analysis: A complete list of all material inputs, outputs, and processes (both direct and indirect), to include use and disposal, must be collected from available data. System boundaries must be kept constantly in view in order to avoid scope creep.

- Interpretation: All of the data and impact identification will enable conclusions to be drawn by establishing causality and tracing processes both backwards and forwards. At this point the original purpose of the study should be addressed, key lines of questioning be answered, and recommendations be made.

The overall process is iterative and each phase continuously interacts with the others. As the LCA process continues, each phase is explored at greater depth, ultimately culminating in the final analysis. The LCA is assessed on a functional unit basis in order to accurately compare throughout the phases.

B. *Calculation for Energy Consumption of Use Phase*

The energy needed for the use phase of the truck can be split up into three different sections as follows:

- Acceleration**:** This is the energy required to accelerate the truck from a lower velocity to a higher velocity. Corresponding to the energy required to affect a positive change in the kinetic energy of the brake and drum and the rotational energy of the drum.

- Constant Velocity: This is the energy required to overcome the rolling resistance of the truck. Several natural retarding forces act on the truck during use, but the only natural retarding force that is affected by the drum brake due to its weight is the rolling resistance.

- Deceleration: This is the energy required to actuate the brake system when the truck is decelerating from a higher velocity to a lower velocity. This energy is only required if the truck is decelerating more quickly than the natural deceleration.

Using the duty cycle information given, the energy of each section of the use phase can be calculated for each different duty cycle. All GHG emissions are considered dependent on the fuel consumed and MPG of each truck. 6 duty cycles are selected to calculate the acceleration, the constant velocity and the deceleration of trucks; HHDDT Cruise, HHDDT Transient, New York City, City Suburban, UDDS and HHDDT65 Cruise in this study.

Various standard cycles are simulated for both highway as HHDDT 65 and HHDDT Cruise cycles and transient/urban as HHDDT Transient, UDDS and New York City cycles [22][23]. The Heavy Heavy-Duty Diesel Truck, HHDDT, cycle is a chassis dynamometer test developed by the California Air Resources Board with the cooperation of West Virginia University and contains 4 speed time modes: idle, creep, transient and cruise. HHDDT Transient cycle contains lots of speed changes and heavy accelerations and decelerations. This might be a good approximate of medium traffic or of some sort of off-highway driving. HHDDT cruise cycle consists of one or two accelerations and one or two decelerations for simulating a cruise mode on a highway road. The HHDDT65 cycle combines elements of each of these modes and achieves a maximum speed of 65 mph. New York City Composite cycle is a representative of driving a heavy vehicle through NYC for simulating a city drive. In addition, Urban Dynamometer Driving Schedule, UDDS, cycle was developed for heavy duty vehicles such as dump trucks.

C. *Acceleration*

Using the cycle information, the energy necessary for the acceleration of the drum brake and drum is calculated for kinetic energy and rotational energy by Eqs. (1) and (2). The constants of the equations are factored out to focus on the sections that would vary dependent on the duty cycle.

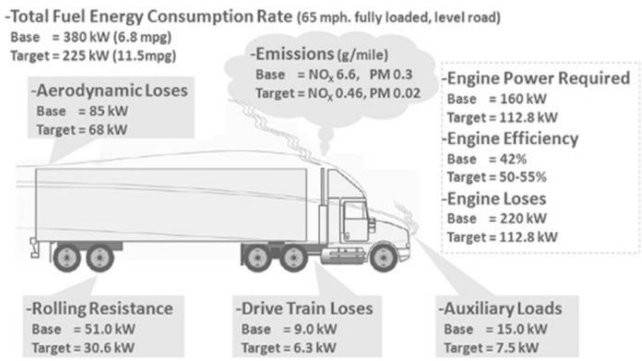

Fig. 1. *Natural retarding forces on truck [24]*

$$Kinetic\ Energy = 0.5 \times m \times v^2 \quad (1)$$

$$Rotational\ Energy = 0.5 \times I \times w^2 = 0.5 \times (\frac{I}{r^2}) \times v^2 \quad (2)$$

where

$m =$ mass

$v =$ velocity

$I =$ moment of inertia

$r =$ radius

Using the information present in each duty cycle, the v^2 total for each duty cycle could be calculated. In order to compare the information from each duty cycle, the v^2 total to the total miles driven in the duty cycle is normalized. Table 1 presents the v^2 per mile for each duty cycle.

TABLE I. ACCELERATION ENERGY PER MILE FOR EACH DUTY CYCLE

Duty Cycle	v^2 per Mile (m^2/s^2)
HHDDT Cruise	110.81
HHDDT Transient	477.19
New York City	738.80
City Suburban	548.54
UDDS	439.71
HHDDT65 Cruise	82.19

Using specific information on the masses of the drum brakes and drums, along with the radius and moment of inertia of the drum brake systems, the energy used per mile of each separate part can be calculated.

D. *Constant Velocity*

At constant velocity, the only forces acting on the truck are the natural retarding forces and the equivalent force from the engine. The only force dependent on the weight of the truck is the rolling resistance so that it is focused for the calculations. To calculate the energy needed to overcome the rolling resistance, Eq. (3) is used for rolling resistance force F_{RR}, the coefficient of rolling resistance *Crr* *and* the normal force *N*, the force perpendicular to the surface on which the wheel is rolling, for a generic truck [25][26]. The rolling resistance energy needed for each duty cycle is calculated as shown in Eq. (4), assuming an 80,000 lb truck. These values are normalized for the total miles driven in each duty cycle.

$$F_{RR} = C_{rr} \times N \tag{3}$$

where

$N =$ normal force

$C_{rr} =$ coefficient of rolling resistance

$$E_{RR}\text{(Rolling Resistance Energy Losses)} = F_{rr} \times \text{distance} = C_{rr} \times N \times d \tag{4}$$

From Eq. (4), all duty cycles have identical E_{RR} per mile as 2807.18 kJ. This means that the E_{RR} per mile turned out to be dependent only on the weight of the truck rather than the type of duty cycle.

E. *Deceleration*

From the vehicle dynamics analysis, the energy removed by the natural retarding forces at each specific point of time for each duty cycle is calculated by Eqs. (5)-(7).

$$E_D\text{(Aerodynamic Drag Energy Losses)} = 0.5 \times \rho \times v^2 \times C_D \times A \times d \tag{5}$$

$$\text{Drivetrain Energy Losses} = \eta_{\text{Drivetrain}} \times v \tag{6}$$

$$\text{Auxiliary Energy Losses} = k \tag{7}$$

where

$\rho =$ mass density of air

$v =$ velocity

$C_D =$ drag coefficient

$A =$ reference area

$d =$ distance

$C_{rr} =$ coefficient of rolling resistance

$N =$ normal force

$\eta =$ driveline inefficiency

Duty cycle information is used to calculate how often the brakes are being applied and the magnitude of the deceleration that the brakes are providing to the truck. With this information, the maximum deceleration that the brakes can provide to the truck is determined, and each deceleration during a duty cycle is defined as a percentage of the maximum deceleration. From suppliers' data, the maximum stroke and air displacement of the brake is found, along with an estimate of the corresponding energy for displacing the volume of air at this pressure shown in Eq. (8).

$$\text{Energy} = \text{Pressure} \times \text{Volume} \tag{8}$$

TABLE II. MAXIMUM STROKE AND AIR DISPLACEMENT OF AIR COMPRESSOR

Name	Amount
Pressure (kPa)	689
Volume Displaced (m^3)	0.00145
Energy (kJ)	0.997

The energy for each deceleration during a duty cycle is calculated and normalized to the miles driven as shown in Table 3.

F. *SimaPro*

As a broadly accepted program for LCA, SimaPro is a specialized program that allows to model products and systems [27]. SimaPro models these systems from a life cycle perspective for the user's analysis. The program has the ability to build complex models of multiple processes and subassemblies as well. SimaPro has several different environmental databases and is used for a variety of applications in more than 80 countries worldwide. As an intuitive life cycle model, SimaPro enabled to easily model the drum brake life cycle with multiple tools and inventory databases.

TABLE III. COMPRESSOR ENERGY PER MILE FOR EACH DUTY CYCLE

Duty Cycle	$E_{Compressor}$ per Mile (J)
HHDDT Cruise	4.19
HHDDT Transient	110.54
New York City	1,268.78
City Suburban	585.02
UDDS	623.49
HHDDT65 Cruise	82.82

IV. BRAKE SYSTEM

A. *Brake System of Class 8 Trucks*

Within the commercial vehicle industry, trucks are divided into different classes based on their Gross Vehicle Weight Rating (GVWR). The significant portion of the US market consists of class 8 line-haul vehicles of which the GVWR is above 33,000 lbs. A typical class 8 truck, a tractor-trailer combination truck, uses a total of ten brakes in order to retard the motion of the vehicle. Most class 8 line-haul trucks utilize drum brakes rather than disc brakes. This lead to the selection of a traditionally designed drum brake, as the line-haul brake system to model.

B. *Components of Brake System*

There are three major manufacturers in US whom all offer similar brake systems with little difference in performance and technology; government and performance regulations are usually met by all three manufacturers. Figure 2 shows that the system consists of drum and drum brake which includes two shoes, springs and so on.

C. *Drum Brake*

Figure 3 shows the appearance of a traditionally designed drum brake which uses the abrasion of friction pads on the brake drum to retard the motion of the vehicle. Over the course of the life cycle of a drum brake, the friction pads are replaced several times as they wear from use. A typical class truck (tractor-trailer combination) uses a total of ten brakes in order to retard the motion of the vehicle. The drum brake is a highly adaptable brake that can be customized for multiple OEMs' tractors and trailers. The brake can be configured for different commercial and line-haul applications as well ranging from long-range freeway distribution to waste management and city transit. Due to this flexibility, the product's specifications can vary on a unit-to-unit basis to satisfy customer requirements and packaging constraints. The brake size is defined as the diameter of the brake by the width of the friction pad, and can range from 15 in by 4 in to 16.5 in by 8.625 in. In addition, several different types of friction pads are available depending on the truck vocation.

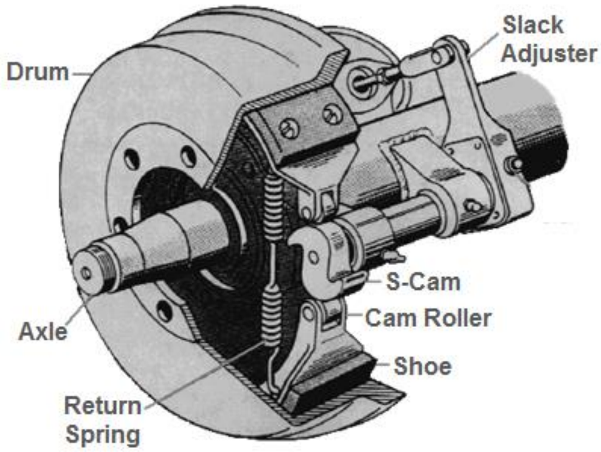

Fig. 2. *Typical brake system*

While multiple friction pads are available in the brake aftermarket, the size of brake selected for analysis is the size paired with most popular friction pads, 16.5 in by 8.625 in for the new reduced stopping distance (RSD) requirements of Federal Motor Vehicle Safety Standard (FMVSS) No. 121 [28].

Fig. 3. *Typical drum brake*

The individual brake is chosen over the system of ~~as~~ the functional unit in order to simplify modeling in the use phase – the brake pads are replaced and discarded separately as they wear. This method would allow focusing on the effects of a single brake and scaling the information gathered and conclusions to the whole braking system.

The drum brake consists of four major assemblies as follows:

- Bracket: Holds the camshaft and brake in place. Attaches to the spider and envelops the camshaft.
- Camshaft: Actuates the brake shoes when the driver engages the brake pedal. This consists of metal rod and S-shaped head called S-cam that turns when the brake pedal is engaged. The energy to perform the action comes from pressurized air in the attached air chamber.
- Shoe Assembly: Contains the table, webs, and friction pad. The shoe assembly is

the main part of the brake that could be remanufactured as the friction pad wears. Wears down due to the abrasive contact with a drum and must eventually be relined.

- Spider: Attaches the bracket and brake shoe assembly together, and can be cast iron or stamped steel so called fabricated steel. Depending on the type of spider used, the brake weight can vary by up to 5 lbs.

All other parts including common parts, dust shield and springs that make up less than 5% of the total brake weight are lumped together into one single process during the analysis. Furthermore, the brake assembly is produced and sold separately from a slack adjuster so this analysis does not consider the slack adjuster. The air chamber attached to the brake is also not included in this analysis; this is a discrete and separate product as well.

D. Drum

Most brake system suppliers produce two kinds of drums for use with the drum brake. Drums are discrete and separate products, however, so they are modeled separately from the drum brake. The drums can be either of these two, distinct types:

- Lightweight drum: As a premium brake drum, achieves a weight reduction of about 20 lbs compared to a competing cast iron drum.

- Cast iron Drum – As shown in Figure 4, this drum is used in the industry as a standard drum and produced by machining and welding a piece of cast iron.

Fig. 4. *Typical drum*

The functional unit is defined to be one drum though the entire brake system is defined as a set of ten drums to complement ten brakes. This method allows focusing on the effects of a single drum and applying the information gathered and conclusions to the brake system. Also, the drums are replaced and discarded separately as they wear like the brake friction pads.

E. End Users of Brake System

For class 8 trucks, the main end-users are fleets. Based on the frequency of stops and delivery distance, these fleets are divided into three different vocations as follows:

- National: National fleets are going to be the fleets that are going to be traveling long distances with a low frequency of stops. These vehicles will contain trucks similar to generic line-haul vehicles, and is the baseline fleet used throughout most of the papers. National fleets as well are the majority of the class 8 trucks on the market.

- Regional: Fleets that operate somewhere in between Severe and National fleets. These fleets contain vehicles similar to food delivery, general freight, and heavy hauling.

- Severe: Vehicles that operate in severe fleets have a high frequency of stops such as refuse and construction vehicles and occupied a relatively small market share.

In order to simulate and calculate environmental impact during use-phase from each three kinds of end-users, their drive cycles are assumed with interviews. By using the calculated duty cycle unit miles from acceleration, constant velocity and decollation mode, 3 drive modes based on the different vocations are assumed and established from end-user interviews by aggregating the calculated duty cycle unit miles. With an Excel based tool for the calculations, the assumptions could be easily checked during the interviews. For example, in this paper, the regional drive cycle is assumed the combination of the 80% HHDDT cruise and 20% HHDDT transient and confirmed as a generic case from interviews with end-users.

V. APPLICATION OF LCA

This comparative LCA is conducted in order to determine the relative effects of six major impacts associated with the drum brakes: energy usage, GHG emissions-specifically CO_2 emission, recycling, volatile organic compound (VOC) emission, waste generation, and water usage.

A. Goal and Scope

The LCA of a 16.5 in by 8.625 in drum brake system for class 8 trucks in US is conducted to quantify the relative environmental impact. The scope of LCA is selected due to its wide use in the commercial vehicle industry.

The relative impacts of two types of each product, the drum brake with the cast spider or stamped-fabricated spider and the cast iron drum or lightweight drum are compared. In addition, the brakes with new shoes and remanufactured shoes are also compared. Furthermore, those comparative assessments are applied to three usage simulations based on three types of fleets. The comparative LCA of multiple drum brake systems is performed in order to identify high environmental impact areas and provide recommendations on possibilities for current and future reduction. Moreover, the results of this LCA are intended for providing the guideline of new brake system development. For this specific LCA, it is defined that the brake system is the set of ten drum brakes and drums that operate in conjunction to retard the motion of the vehicle when actuated. The functional unit, however, is one brake and one drum because the brake shoes and drum are discarded separately as they wear. The system is looked at from raw material acquisition to final disposal, but does not include the manufacturing, maintenance, and decommissioning information of the capital goods such as stamping machines for manufacturing the drum brakes.

During the LCA, the weights of material going through each process and the number of parts are used to allocate the environmental effects of the drum brake. Six impact categories are selected: energy usage, GHG emissions, recycling, VOC emissions, waste generation, and water usage. SimaPro is used as an environmental modeling tool and the IMPACT 2002+ Impact Assessment Method is used to assist in determining the relative environmental impact [29].

The initial data used during the assessment are SimaPro data. These data are used to determine the areas of the product life cycle on which to focus the most time and energy. During this initial analysis, the drum brake and drum weights are used to compare the different processes that occur during the product manufacturing by using US SimaPro unit processes data. The relatively small parts such as stainless steel common parts and nylon bushings do not impact the manufacturing process at more than a two percent threshold. Therefore, noncast iron or wrought steel is excluded from the LCA. In addition, while friction pads are judged to have a large environmental impact during the use phase, they are excluded from further assessment because friction pad material suppliers are secretive about the manufacturing process and material composition of their products.

Through analysis of the drum brake life cycle, the raw materials, waste, energy, and emissions associated with each step of the life cycle process has been quantified. This information is used in order to create specific recommendations for two separate goals as follows:

1. Identification of environmental impact in the drum brake life cycle
2. Recommendation for a more sustainable brake system development based on the LCA results

Again, several key findings are presented on the following critical components of the brake, as these items represent the greatest opportunity for contributing to overall reduced environmental impact.

- Drum brakes equipped with cast spider and stamped-fabricated spider
- Lightweight drum and cast iron drums
- Drum brakes equipped with new shoes and remanufactured shoes

B. *Life Cycle Impact Analysis*

As shown in Figure 5, six key areas of the value chain through the drum brake life cycle are identified for the initial data analysis:

- Manufacturing: This area of focus includes all steps throughout manufacturing, including raw material extraction, material processing, manufacturing, and assembly. This is associated with the life cycle “cradle to gate” of the drum brake.
- Supply Chain: This focus area is given as the energy required for moving each brake component and the brake itself from supplier to supplier and finally to customer.
- Use: This stage is defined as the environmental impacts associated with using the class 8 truck, including fuel combustion and brake shoe and drum replacement.
- Maintenance: This stage of the life cycle includes any scheduled repairs and maintenance for the brake systems on the vehicle.
- Re-manufacturing: This area of focus consists of the procedures followed for remanufactured brake assemblies, which are disassembling the brake assembly, transporting the shoe sub-assembly, disassembling the shoe sub-assembly, disposing of the friction pad, repainting, and replacing the friction pad.
- Disposal: This stage is the final disposal or recycling of the drum brake and its associated materials. This is associated with the life cycle “grave” of the brake.

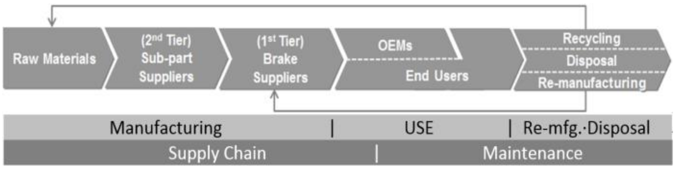

Fig. 5. *High-level drum brake value chain*

After the initial modeling as shown in Figure 6, the re-manufacturing, manufacturing, use, and supply chain phases are focused on due to hypotheses formed during the initial analysis. To collect these data, the following three methods are used:

- Documentary survey: Several different types of drum brakes and drums data are utilized throughout the assessment. These data include material, weight, production and engineering specifications. Data regarding all the various product stages of the drum brake are also collected.

- SimaPro: General data from SimaPro and SimaPro's ecoinvent databases are used for both the initial data analysis and the more focused data analysis.

- Interviews: These data including duty cycle information are collected through in-person and phone interviews with knowledgeable subjects. The data are collected from several external sources including suppliers, operators, and customers.

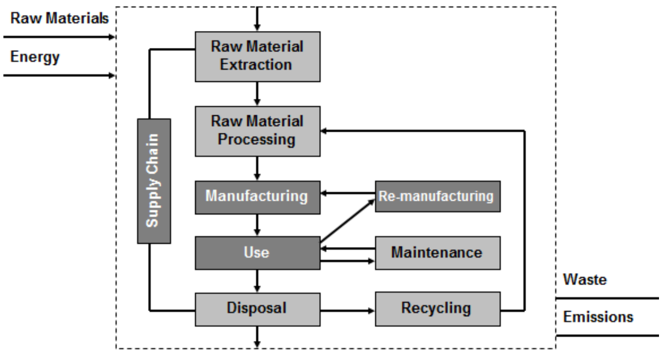

Fig. 6. *Initial LCA model of drum brake with focus areas*

With the information collected, the use phase would dominate the energy use and GHG emissions, and there would be a manufacturing-usage tradeoff between the cast and stamped spiders. The disposal and maintenance phases have negligible environmental impact.

For the Impact Assessment stage of the LCA, the environmental effects of multiple different metrics have to be compared. Some of these metrics, such as VOC emissions and GHG emissions, have extremely different values for the inventory analysis. For example, total VOC emissions for the cast spider are 0.079 kg but total GHG emissions for the cast spider are 1,130 kg. In order to compare the relative impact of one kg VOC to one kg GHG, judgments on the relative impact of each of these emissions have to be made. Among the multiple impact assessment method calculations for the value judgments, the IMPACT 2002+ Impact Assessment Method is chose to use. This method combines the information from the inventory analysis into four primary damage categories – human health, ecosystem quality, climate change, and resources. Also, the method is broken down into its fifteen sub-categories during the analysis so the impact of the different brake phases is better understood.

C. *Life Cycle Interpretation*

Life Cycle Interpretation is based on a relative approach – it should be noted that these are potential environmental impacts, and not the actual endpoints of the environmental impacts.

The major findings are briefly listed as follows:

- Drum brake has the greatest environmental impact with energy use, GHG emissions, and waste; these primarily occur during the use phase

- Stamped-fabricated spider is a 5% reduction in environmental impact for line-haul vehicles

- Lightweight drum is a 15% reduction in environmental impact for line-haul vehicles

- Environmental impact reduction varies by fleets and vocations; smaller market severe fleets represent higher impact reduction per vehicle than larger market national fleets.

Before discussing the details of the major findings, the 4 comparative assessments are presented, as a foundation for understanding the potential improvements to the drum brake life cycle.

D. *Relative Environmental Impact of Brake Life Cycle Phases*

A comparative LCA of the drum brake is conducted in order to determine the relative impact of each phase of the brake life cycle. As mentioned before, 6 main environmental metrics for the LCA are focused: energy usage, GHG Emissions, Recycling, VOC emissions, waste generation, and water usage. The use phase has a large energy and GHG emissions which are mainly CO_2 emissions due to burning diesel fuel. Figure 7 shows that the manufacturing, re-manufacturing, and supply chain phases also have smaller impacts in several metrics, while the maintenance and disposal phases have negligible impacts in most metrics. The use phase has the largest environmental impact due to the large amount of energy needed to accelerate the brake and overcome the weight-dependent natural retarding force of rolling resistance. Following the metrics, the recycling, VOC emissions, waste generation, and water usage for each phase are determined.

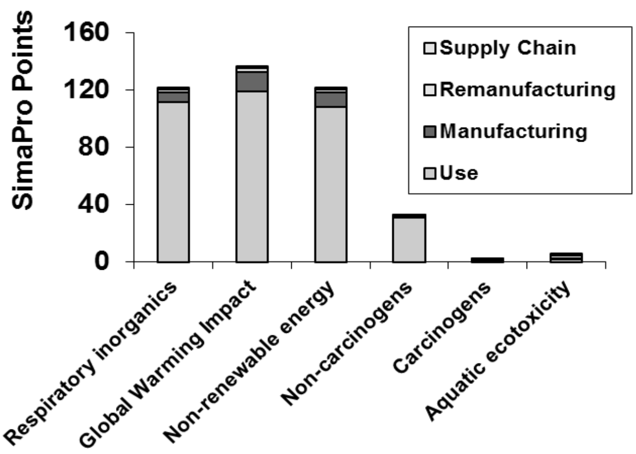

Fig. 7. *Drum brake environmental comparison by phases*

To compare all 6 metrics across each phase, the IMPACT 2002+ Impact Assessment Method is applied. Using this method, the relative environmental impacts of each metric of the drum brake in several categories is weighted and each category is given a score to compare it to the other categories. These scores are based on the number and degree of environmental impact of all inflows and outflows. Figure 7 shows that the most significant categories for the drum brake are Global Warming, Nonrenewable Energy and Respiratory Inorganics due to the impact of the use phase. The energy and GHG emissions are the most important metrics for the environmental impact of the drum brake due to the high level of impact for the use phase.

The use phase dominates the environmental impacts due to the effects of burning diesel fuel; the nonrenewable energy effects are from burning a fossil fuel, the global warming impact derives from the CO_2 released during fuel use, and the noncarcinogens and respiratory inorganics are from the sulfur oxides, nitrogen oxides, and VOCs released during the burning of diesel fuel.

Energy usage and GHG emissions are two influential metrics throughout the life cycle of the drum brake. This is a direct result of the use phase and the energy required during the manufacturing phase. Based on the generic line-haul test case along with a cast iron spider, the drum brake will consume 14,400 MJ of energy (143 MJ of energy is roughly 1 gallon of diesel fuel) and will emit 1,130 kg of GHGs over the course of its life cycle. Figures 8 and 9 illustrate the breakdown of the energy and GHG emissions associated with the life cycle of the drum brake by phase.

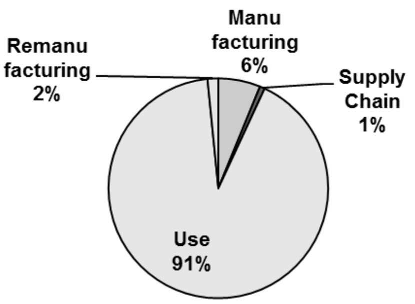

Fig. 8. *Drum brake energy usage by phases*

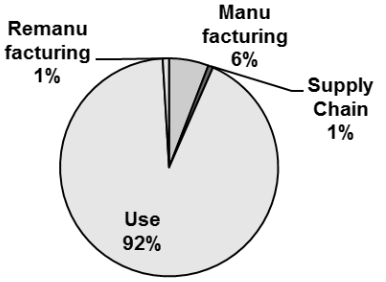

Fig. 9. *Drum brake GHG emissions by phases*

While performing this analysis, no performance difference between stamped–fabricated spiders and cast spiders is assumed. If a significant performance difference exists between the two spiders, however, it would not affect the final results unless the stamped-fabricated spider is considered unsafe and more likely to break than the cast spider. Weight is the main factor in determining the environmental impact for the spiders because of the effects of creating and burning diesel fuel; lightweight spiders will usually have a smaller environmental impact.

Overall the drum brake has 41 kg of waste, while about half of that, 25 kg, is friction pad waste during use. The friction pad is required in order to use the drum brake, and the amount of friction pad waste changes based on the truck duty cycle. Even if the friction pad waste specifically can have a large potential impact on the environment, this LCA assessment did not include its environmental impact because it is too hard to get any detail material information about it.

Water consumption is 31 kg for the cast spider drum brake, but usually treated within the suppliers' plants before being sent to the city municipality for additional treatment and reuse. In this manner, it is decided that the water used by the manufacturing processes did not have a significant environmental effect. Recycling is additionally another tracked metric, but mainly tracked as a positive metric to compare suppliers' facilities. The drum brake manufacturing process recycles many materials including scrap metals from stampings, coolant, waste oil, and casting sand. In addition, the drum brake itself is designed for easy recycling – most of the materials used are cast iron or wrought steel and all other materials used are less than 5% by weight and negligible. In total, 72 kg is recycled during the life cycle of the cast spider drum brake.

After the overall analysis, the product impact is use-intensive. The use phase is the source of more than 90% of GHG Emissions and energy use occurs, and it also produces more than 50% of the waste. The IMPACT 2002+ Impact Assessment Method confirms this hypothesis. While the drum brake can contain plastic bushings, it is mostly made of cast iron and wrought steel. If the drum brake has been made of different, more hazardous materials, rather than cast iron and wrought steel, then the use phase may not have been as dominant.

Since the product is found to be use-dominant due to the burning of diesel fuel during the use phase, energy consumption is a strong indication of environmental impact as can be seen from Figures 7 and 8. In the following sections the energy consumption is shown as the environmental impact for the stamped-fabricated and cast spider drum brakes along with the lightweight and cast iron drums.

E. Stamped-fabricated and Cast Spider Drum Brakes

Along with the overall impact of the drum brake, the environmental differences between the two types of spiders for the drum brake. While the spiders are fairly similar, they have two major differences. The cast spider drum brake uses cast iron rather than stamped-fabricated steel for the spider subassembly and weighs about 5 lbs more. During manufacturing, there are several metrics that can contrast the stamped-fabricated and cast spider drum brakes. The overall impact of each of these metrics can vary based on the total amount of material used during each process. While the cast and stamped-fabricated spider drum brakes vary during manufacturing, they both have fairly similar supply chains. The difference is that stamped-fabricated spiders have a North American supply chain that is fairly simple while cast spiders have a complex Brazilian supply chain. This leads to the cast spiders having an environmental impact from their supply chain of about 3 times the environmental impact of the stamped-fabricated spider due to the differences of additional weight and the distance.

To compare the stamped-fabricated and cast spider drum brakes in terms of the energy used throughout the life cycle, the environmental impact of each type of drum brake is inspected as shown in Figure 10. The stamped-fabricated spider drum brake has a smaller impact overall than the cast spider drum brake. The major difference between the two types of brake occurs during the use phase. Most of the energy allocated to the drum brake during the use phase is due to the weight of the brake – transporting the brake around on the truck requires a lot of energy. Therefore, by reducing the weight of the brake by switching from a cast spider to a stamped-fabricated spider, customers would be able to save energy and reduce GHG emissions during the use phase. For the general line-haul test case, using a stamped-fabricated spider instead of a cast spider would save 4.91 gallons of diesel fuel. This also corresponds to a savings of 55 kg of GHGs per brake at the given MPG. Table 5 illustrates the savings achieved per wheel in energy and GHG emissions.

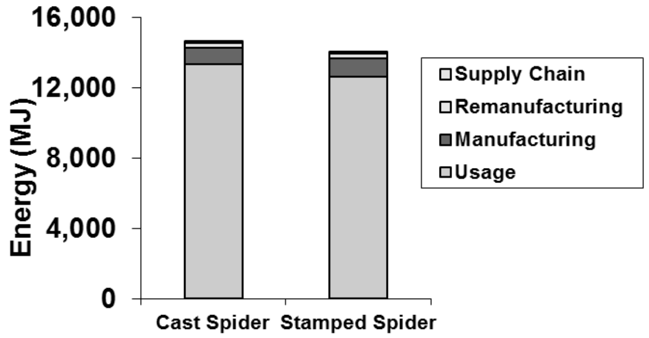

Fig. 10. *Cast and stamped-fabricated spider environmental impact comparison*

TABLE IV. LINE-HAUL CAST AND STAMPED-FABRICATED SPIDER COMPARISON

Spider Type	Use Phase Energy (Gallons Diesel)	GHGs (kg)
Cast Spider	93.3	1,040
Stamped Spider	88.4	988
Stamped Savings	4.9	55
Percent Savings	5.27%	5.27%

While performing this analysis, no performance difference between stamped–fabricated spiders and cast spiders is assumed. If a significant performance difference exists between the two spiders, however, it would not affect the final results unless the stamped-fabricated spider is considered unsafe and more likely to break than the cast spider. Weight is the main factor in determining the environmental impact for the spiders because of the effects of creating and burning diesel fuel; lightweight spiders will usually have a smaller environmental impact.

F. Cast Iron Drum and Lightweight Drum

The main environmental difference between the lightweight drum and a cast iron drum is due to their significant weight differences and different manufacturing processes. While the cast iron drum is 18.33 lbs heavier than the lightweight drum, it is formed entirely from cast iron; the lightweight drum is formed by casting iron onto a steel shell. Significant energy and GHG emission savings are associated with using the lightweight drum over a cast iron drum because of its benefits during use and manufacturing.

During manufacturing, there are several metrics that can contrast the cast iron drum and the lightweight drum. To compare the cast iron drum and the lightweight drum in terms of the energy used throughout the life cycle, the environmental impact of each type of drum is inspected as shown in Figure 11. The lightweight drum is better has a smaller impact overall than the cast iron drum. It is important to note that this comparison is only for one drum; usually a generic line-haul vehicle uses four drums over the course of its life cycle.

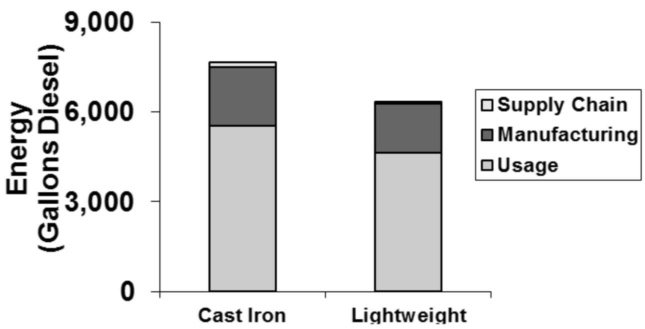

Fig. 11. *Drum environmental impact comparison*

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The major difference between the lightweight drum and the cast iron drum comes from the weight and moment of inertia. Since the drums can be roughly modeled as a thin, hollow shell, the moment of inertia is a function of the weight. This means that all of the energy allocated to the drums during the use phase is directly proportional to the weight of the drums. The difference due to weight is going to be even more significant with the drums than with the spiders because the drums will also be rotating, which will require additional energy, roughly equivalent with the translational energy. For the general line-haul test case, by using a lightweight drum instead of a cast iron drum the generic line-haul truck would save 25 gallons of diesel per wheel over the life cycle of the truck. This also corresponds to a savings of 280 kg of GHGs per wheel over the life cycle of the truck at the given MPG. Table 5 illustrates the savings achieved per wheel in energy and GHG emissions.

TABLE V. LINE-HAUL LIGHTWEIGHT AND CAST IRON DRUM COMPARISON

	Use Phase Energy (Gallons Diesel)	GHGs (kg)
Cast Iron Drum	155	1,730
Lightweight Drum	130	1,450
Lightweight Savings	25	280
Percent Savings	15.93%	15.93%

While performing this analysis, no performance difference between the lightweight drum and cast iron drum is assumed. If a significant performance difference exists between the two drums, however, it would not affect the final results unless the lightweight drum is considered unsafe and more likely to break than the cast iron drum.

G. Vocational Differences

The final analysis is performed to compare the energy and environmental impact of three kinds of vocations; national, regional and severe fleets. With interviews, the data are collected from a total of 4 fleets which three regional fleets and one severe fleet. The information for the generic line-haul fleet[29] is used. After the data from each fleet are calculated, the relative impacts of each vocation against the others are depicted as Figure 12 where SSB and LWD stands for the stamped spider brake and the lightweight drum, respectively. Severe fleets will require the most energy during their life cycle due to their frequent replacement of shoes and drums. Most vocations will have a use dominant phase, but some (including severe and regional fleets close to severe) will be more dominated by the manufacturing phase. This is not a function of the energy of manufacturing, however, this is a function of the number of times drums and shoes are replaced during the use phase, which is a direct result of the fleet vocations. Fleets that stop and start more are more likely to be less dominated by the use phase because of their frequent shoe and drum replacements.

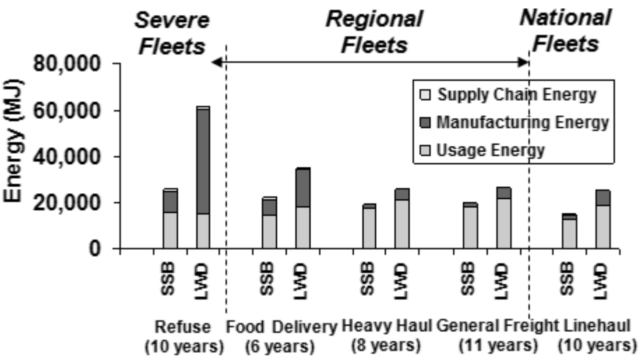

Fig. 12. *Energy consumptions of three types of fleets*

From Figure 12, it is clear that different choices during a fleets' life will affect the energy consumed, and thus the environmental impact. During the course of the fleet's life cycle, there are really three choices that they can make:

- Stamped (fabricated) or cast spider drum brake
- Remanufactured or new shoes
- Lightweight or cast iron drum

Dependent on each of these three choices, the fleets will be able to reduce their environmental impact by different amounts. The difference between each of these three choices is analyzed for the severe fleet, an average of the three regional fleets, and the national fleet, and is presented in Figure 13 where RS represents the reduction of impact by using the remanufactured shoes. The highest impact product on the total energy and thus environmental impact is the lightweight drum. By switching to this product, fleets can prevent the most environmental impacts over the life of the brake. The remanufactured shoes represent the next best environmental benefit, followed by the stamped-fabricated spider. As shown in Table 6, the new shoe requires more energy and is higher in every metric compared. This is mainly due to the effects of forming new steel for the brake shoe. The much higher recycling count for the new shoe is because the assumption is that the old shoe is then recycled if it is not remanufactured.

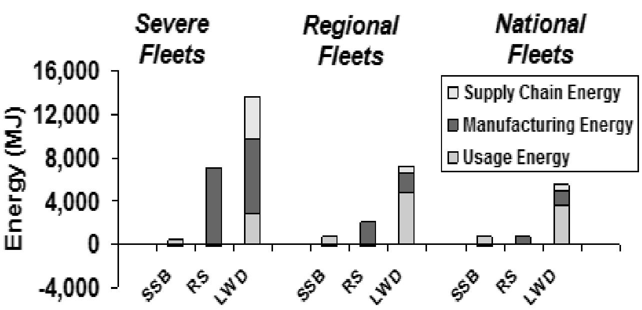

Fig. 13. *Delta energy impact for three product choices*

TABLE VI. NEW SHOES AND RE-MANUFACTURED SHOES METRICS

	New Shoes	Remanufactured Shoes
Energy (MJ)	333.98	76.79
VOC (g)	15.71	7.62
Waste (kg)	6.68	3.00
Recycle (kg)	14.70	1.18
GHG (kg)	28.47	3.55
Water (kg)	12.09	0.35

Moving forward, the use phase has been identified as the major environmental impact for all vocations. Even though severe appears to be manufacturing dominant, this is because it consumes many brake drums and shoes during the use phase. While line-haul trucks have a smaller difference in energy impact for the three options listed above, they are also the largest market and thus the largest potential for impact reduction. Since line-haul trucks are use dominant, lighter weight products such as the stamped-fabricated spider and lightweight drum can greatly reduce their impact. On the other hand, manufacturing dominant profiles such as severe fleets would benefit more from re-manufacturing programs such as the remanufactured shoes, and more durable brake linings and brake drums such as air disc brakes and ceramic friction pads.

VI. CONCLUSION

A. Results

Environmental sustainability encompasses more than simply designing to reduce environmental impact. Solutions must reduce environmental impact while maintaining the value provided to the customer. In order to synthesize the potential environmental impact with the actual business decisions, a cost and a benefit of each comparison point are performed for the various fleets. By inspecting choices from a variety of different stakeholders, a recommendation on how brake suppliers could best proceeds could be created in order to accomplish their goal of reducing their total environmental impact.

After examining the current situation and viewing which stakeholder will benefit from each decision, the top priority for developing new drum brake design for reducing environmental impact products are suggested as follows:

- Develop bipolarized premium products: Brake suppliers should consider some long-term approaches for a drum brake system development. As discussed above, severe fleets frequently change brake drums and brake shoes while national and regional fleets benefit more from lighter weight products. Since it would be expensive to develop a single product with both attributes, developing a durable and re-manufacturable product for severe vocations and a lightweight product for national and regional vocations would benefit most parties involved in the product development and use.

In this manner, drum brake suppliers could continue to analyze their new products in order to ensure that their products not only reduce environmental impact, but are environmentally sustainable.

B. Desinged New Tool for Brake LCA

For both drum brake and drum the use phase is dominant. In order to conduct the LCA, a use phase energy and environmental metrics calculator is created in Microsoft Excel as shown in Figure 14. This tool helps to compare two brake types and to determine the difference in energy and environmental metrics. The calculator contains several input slots such as the weight of the brake and drum, the truck's GVWR, lifetime miles, MPG, engine efficiency, number of brakes, kinds of fleet vocations such as line-haul, regional, severe, and mountainous and the percentage of miles spent in each vocation. The user can either select the current brake type from a drop down menu or from the built-in information on the weights of several brake or drum variations. The tool calculates total energy needed diesel fuel consumption, CO2 emissions, and VOC emissions of the truck in the use phase.

In a nutshell, those comparative LCA template focused on use phase can help suppliers and OEMs to get a sense about which area of components in an automotive should be improved in order to minimize an environmental impact based on their end-customers. Furthermore, the results can bring insights on the new component development and marketing strategies

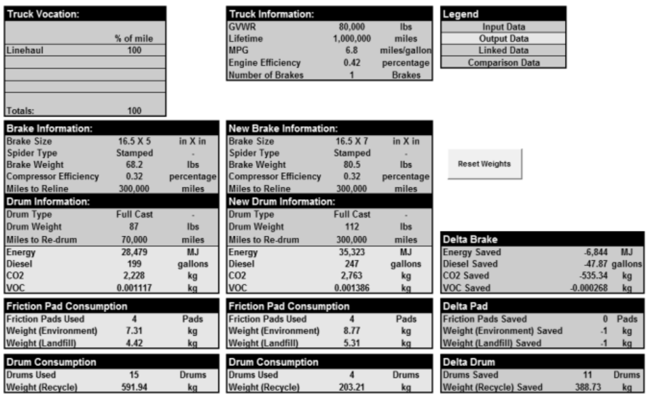

Fig. 14. *New tool for use phase energy and environmental metrics calculation*

C. Limitations

While the expectation is that some form of useful interpretation will derive from the LCA, there is no scientific reasoning to reduce the results from the LCA to a single overall score. This would require value choices in order to weight each different factor. Generally the information developed in an LCA study should be used as one part of a comprehensive decision process. LCA has some weaknesses when used for overall decisions; it usually doesn't address any social or economic product attributes. Social and economic product attributes, however, can be used when scientific basis does not exist for LCA decisions. Furthermore, SimaPro does have some limitations that can cause errors. A large amount of the environmental and process data within SimaPro was collected from European companies, and is not necessarily applicable to US companies. Another limitation of SimaPro is that the data collected are averages; unique plant information is not captured.

As mentioned before, many of the materials that are typically used in friction pads can endanger aquatic wildlife; it is important that the environmental effects of friction pads are further investigated. However, the assessment of the friction pad is not included because there is a small amount of information on the composition of the friction pads. In addition, most brake suppliers currently provide coated drum brakes in order to improve their durability and prevent a rust called rust jacking on shoes. However, those coated brakes are not investigated due to a lack of information as the friction pads are not.

During the course of the study, it is assumed that there would be no differences in durability between the cast and stamped-fabricated spiders, lightweight drum and cast iron drum, and remanufactured shoes and new shoes. Several of these products are relatively new, and field tests have not been assessed for multiple vocations. Further investigation can be made into the differences in durability between these products for multiple vocations.

The last limitation to the energy savings achievable by switching from cast to stamped-fabricated spiders is the weight of the truck. When fleets are able to save weight on truck vehicle components, the saved weight generally correlates to more cargo weight for the customer. The trucks will be running as heavy as they legally can in order to maximize earned revenue for each trip. Even if the total truck weight doesn't change because trucks are loading more cargo, eventually the environmental and cost savings will manifest though a reduction in the number of trips necessary to transport the same amount of cargo.

While these weaknesses may provide opportunities for improvement upon the study performed, they would change the overall recommendations and conclusions from the study.

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