Factors that Affect Fuel Consumption and Harvesting Cost

By

Jonathan Tye Kenney

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Approved by

Thomas V. Gallagher, Chair, Associate Professor, AU School of Forestry and Wildlife Sciences
Dana Mitchell, Project Leader, United States Forest Service
Mathew Smidt, Associate Professor, AU School of Forestry and Wildlife Sciences
Tim McDonald, Associate Professor, AU Dept. of Biosystems Engineering

Abstract

Fuel consumption in logging is an important component of harvesting costs. There has been an increased interest in the carbon budget associated with timber harvesting as well as an industrial need for updated fuel consumption information. Since loggers are paid by the tons of wood they produce, it is important to note how many gallons of fuel it takes to produce one ton of wood. An extensive literature review was conducted to evaluate different harvesting systems and the amount of fuel they consumed per unit of wood they produced. Research has shown that variability in fuel consumption could be attributed to various harvesting conditions. A study was developed and completed to evaluate fuel consumption that involved surveying loggers about slope, tree size, soil moisture, type of cut, types of machines, gallons of fuel consumed, and weight (in tons) of wood produced while harvesting. Data were collected over two years from six logging crews who worked with harvesting operations that supplied ~486,000 tons of wood. Altogether, these crews averaged 0.51 gal/ton for their in-woods operations. The lowest fuel consumption reported was 0.42 gal/ton, and the highest fuel consumption reported was 0.60 gal/ton. The study indicated that for treelength ground based logging systems, factors such as harvest type, average tree size, machine types, and crew differences have effects on fuel consumption. This new data will enable timber harvesters and mills to have a better grasp of modern in-woods harvesting systems and show what factors can lead to variability in fuel consumption.

Acknowledgements

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I. Introduction and Objectives

On a global scale, it is becoming increasingly important to quantify and measure energy inputs and costs to produce renewable resources. Fuel has been found to make up 22.8% of the in-woods logging cost that a logger incurs (Baker 2013). Research has identified several important factors which could influence fuel consumption such as tree size, slope, soil moisture, and harvest type. A study was developed to quantify fuel consumption and its variability. Literature from the 1980's to today were analyzed to find fuel consumption estimates across a variety of different logging systems, but fuel consumption of more modern logging equipment was also needed for the study.

The first objective for this study was to quantify fuel consumption of logging crews. The analysis was conducted by focusing on fuel consumption for each machine in the logging crew, then combining the machines' fuel consumption to form the average fuel consumption for the harvesting system. The second objective for the study was to analyze harvesting factors such as tree size, slope, soil moisture, and harvest type (clearcut vs. thinning) to determine the effects in fuel consumption among different harvesting machines and harvesting systems.

II. Literature Review

2.1 Fuel Consumption in the Modern Era and its Importance

2.1.1 Fuel Consumption and Its Overall Importance in Emerging Markets

Fuel consumption in logging has been studied to measure how much it influences costs and to determine the role it plays in the overall wood supply system. One emerging market that has expressed an increased interest in fuel consumption for logging systems is bioenergy. One major goal of the bioenergy industry is to offset the use of fossil fuel energy with renewable energy. In the pellet industry, feedstocks of the raw material, pellet production, and pellet distribution costs together form the aggregated fuel costs of pellet supply to energy plants in energy per ton of pellet delivered (Sikkema et al. 2010). The pellet production life cycle activities include biofiber harvesting, forest renewal, forest road construction, biofiber transportation to a pellet facility, pelletization, and pellet delivery to the mills where it is utilized (Zhang et al. 2009). Fossil fuel is a major component that fits under the category of biomass harvesting and must be measured as part of the wood pellet life cycle analysis.

2.1.2 Fuel Costs over Time

Figure 1 shows the price fluctuation of on-road diesel prices from the years 2008 to 2014. Note that off-road diesel is used in logging and can be found by subtracting federal and state taxes from the price shown. The figure shows an increase in price in 2008 and a steady increase from the years 2008 until 2011 where fuel prices have remained steady until 2014 (United States Energy Information Administration).

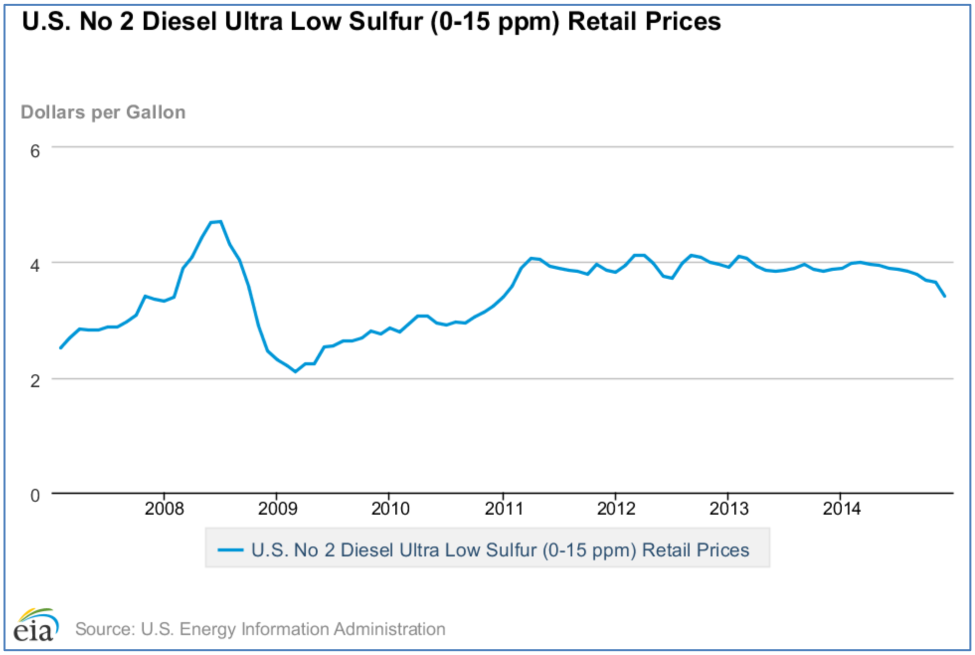

Figure 1: United States Average On-Road Diesel Fuel Prices from 2008-2014

2.1.3 Logging Costs and Fuel Consumption

In order to obtain accurate estimates of fuel consumption, research must first start at the local level where the wood is being harvested. Moldenhauer and Bolding (2009) found that 36 percent of participants reported that fuel prices have resulted in a diminishing workforce of logging contractors. It was also reported that rising fuel costs led to minimized haul distances, reduced work weeks, reduced skid distances, cutting of only high value timber, hauling loads over legal weight limits, and cutting family forests.

When breaking down fuel costs as a part of the total cost, Miyata (1980) found that the fuel consumption rate of a piece of equipment depends on the engine size, load factor, condition of the equipment, operator’s driving habits, environmental conditions, and the basic design of the equipment. According to Miyata et al. (1981), it becomes increasingly difficult to plan logging operations in order to minimize costs and maximize profits due to a variety of factors. These factors that contribute to variability include new harvesting equipment, smaller timber, scattered logging areas, lighter volumes per acre, inflation, and rising production and labor costs which contribute to planning difficulties.

2.1.4 Delivered Costs and "Cut and Haul"

Timber harvesting and transport costs are significantly affected by the cost of fuel. Fuel costs can be dependent upon haul distances, type of logging conditions, and market fuel prices (Baker et al. 2014a). In an attempt to evaluate shifts in cut and haul rates, a costing index was created to show the rapid changes in logging costs. A study completed to track average cut and haul rates in the southeast United States showed a dramatic increase in 2008 when diesel fuel prices rose (Baker et al. 2014b).

2.2 Evaluating Fuel Consumption

2.2.1 Fuel Consumption in Relation to Engine Power

Machine size and horsepower have a significant impact on fuel consumption in timber harvesting equipment. Klvac and Skoupy (2009) found that larger machines with greater horsepower consumed greater amounts of fuel than smaller machines on a gallon per hour basis. This is a common way to interpret fuel usage regarding machine size; however, it is also important to evaluate fuel consumption for each ton of wood produced regarding machine size. Athanassiadis et al. (1999) found that larger machines generally consumed less fuel per cubic meter of wood produced than smaller machines.

"Work-Load Factor (WLF)" is a ratio of the power demanded by machine to the power available from the machine (Silversides and Sundberg 1989).WLF consists of three main measures: fuel consumption per unit of productivity, fuel consumption of the machine at maximum power, and horsepower rating of the machine. According to Silversides and Sundberg (1989), fuel consumption depends on engine power and load factor. Load factor is a term used to express actual fuel consumption as a percentage of the maximum capacity of the engine to burn fuel. For example, the highest fuel consumption possible for a machine would operate at a load factor of 100 percent. Silversides and Sundberg (1989) used an equation to determine average fuel consumption that involved multiplying WLF by the actual fuel consumed by the engine at maximum power and the horsepower rating of the engine. When load size is known, WLF can be useful in determining expected fuel consumption of a machine.

Klvac and Skoupy (2009) found that engine output power had a significant relationship with fuel consumption in that increased engine output power can lead to increased fuel consumption among machines. As a result of these findings, they used a similar model for WLF to quantify fuel consumption in logging equipment through the following equation:

Fuel Consumption = Effective Work Time *(Amount of Fuel Consumed/Engine Output Power).

2.2.2 Fuel Consumption by Specific Machine Types

Plummer and Stokes (1983) stated that fuel consumption is a function of horsepower rating, transmission rate, machine type, and machine use. Similarly, Miyata (1980) indicated that fuel consumption is a function of overall horsepower per hour, where approximately 0.40 pounds of diesel fuel is consumed per horsepower hour. It is important to note that Miyata's calculations were from research conducted in the middle 1970's.

Brinker et al. (2002) provided estimated fuel consumption rates by specific machine types, makes, models, and transmission types. Fuel consumption was estimated for 104 different timber harvesting machines. Transmission type and machine type were used to calculate a fuel consumption rate of gallons per horsepower hour (gal/hp-hr).

2.3 Logging Productivity and its Effect on Fuel Consumption

Since fuel consumption is determined by fuel input and production output, productivity has a large effect on the rate in which fuel is consumed. Hence, Klvac and Skoupy (2009) found that fuel consumption depends on factors such as machine productivity, engine design, and operator's experience. Sambo (2002) compared fuel consumption among different types of logging machinery and found that more productive systems typically have lower costs overall as well as less fuel consumption per unit of wood harvested.

Adebayo et al. (2007) compared logging costs and productivity between treelength systems and cut-to-length (CTL) systems in mixed conifer stands. It was found that treelength systems had higher hourly machine costs than CTL systems. However, treelength systems had lower overall harvesting costs per unit because of higher productivity levels. These increased productivity levels per unit could be due to the ability of treelength logging systems to harvest greater amounts of wood in a shorter amount of time.

Other factors found to impact overall harvesting productivity are slope and soil moisture. When these conditions are extreme, they can impact the productivity of the machines (Silversides and Sundberg 1989).

2.3.1 Cost of Fuel/Hour

2.3.2 Fuel Consumption as a Unit of Production (Gallons/Ton and Liters/Cubic Meter)

While evaluating fuel consumption and other variable costs per hour provides valuable information, measuring fuel consumption per unit of wood produced accounts for productivity and its effect on fuel consumption. One way that is particularly useful involves studying fuel consumption by measuring the gallons of fuel it takes to produce a volume of wood (gal/ton). This ratio allows logging crews and industry foresters alike to know how much fuel is used to produce one ton of wood. In the United States, quantifying fuel consumption in gallons per ton (gal/ton) accounts for productivity within logging systems and provides a beneficial way to evaluate fuel consumption in logging. In other parts of the world, fuel consumption is measured as liters per cubic meter (l/m^3) of wood. Generally speaking, a cubic meter of wood weighs approximately one ton, so a direct comparison between systems can be made by converting liters to gallons.

2.3.2 Evaluating Productivity among Treelength Harvesting Systems

When evaluating productivity among treelength harvesting machines, many factors can contribute to changes in productivity for each machine. Typically, productivity of feller-bunchers increases when cutting larger diameter trees, which results in producing a greater volume of wood per productive machine hour (PMH) (Akay et al. 2004).

Skidding also involves a number of variables that can affect production. Factors that affect skidder productivity are ground slope, greater load weights, and load size (Akay et al. 2004). It was also found that the capacity of the skidder is highly dependent on horsepower, weight, and traction obtainable under the ground conditions during operation. Klepac et al. (2001) found that different tire sizes among skidders can have an effect on productivity.

In a study determining hydraulic tracked loader productivity, it was found that productivity is usually influenced by loader capacity and average tree volume (Akay et al. 2004). Other processing equipment can also contribute to overall fuel consumption.

2.4 Factors Affecting the Efficiency of Machine Use

2.4.1 Different Logging Systems Use Different Rates of Fuel

Certain differences in logging systems can contribute to variation in fuel consumption. It is important to note the different types of logging systems that occur while providing estimates on how to evaluate fuel consumption in each system and what type of equipment consumes fuel in each system. In this section, different systems are presented as well as various theories about fuel consumption and energy output in each system. The fundamental reasons that logging systems differ are mostly due to machine type and processes in which they operate. Klvac and Skoupy (2009) found that fuel consumption can also be affected by operational engine load, working speed, fuel composition, and technical conditions. However, all of these factors vary greatly across different harvesting systems.

It has been found that for each of the three major harvesting processes (felling, loading, and skidding), cost decreases with an increase in average tree size (Silversides and Sundberg 1989). When evaluating harvest type as a possible effect on system fuel consumption, results have varied as to whether thinning or clearcut uses more fuel. Baker et al. (2010) showed similar fuel consumption between thinning and clearcut operations. The only difference noticed was a chipper used on the clearcut site added slightly more fuel consumption per unit ton of wood produced. However, Sambo (2002) studied energy use, measured in mega joule per cubic meter (MJ/m^3), in treelength and CTL harvesting systems for both clearcut and thinning operations. It was found that treelength thinning operations used 126 MJ/m^3, while full tree clearcut operations used only 80 MJ/m^3. This difference was less dramatic for CTL operations: CTL thinning operations used 78 MJ/m^3, while CTL clearcut operations used 73 MJ/m^3.

2.4.1.1 Comparing Cut-to-Length and Treelength Harvesting

One common system used in timber harvesting is the CTL system. CTL systems usually consist of two machines: a harvester and a forwarder. The function of the harvester is to cut and merchandise stems, while the function of the forwarder is to grab trees and transport them to the roadside or to a landing. Another system in which timber is harvested is called a treelength system. A treelength system is one in which trees are felled and transported with the branches and tops intact to a loading mechanism that processes and prepares them for transportation to the mill. A typical treelength system consists of a felling machine, a skidding machine, and some form of loader/processor. CTL systems have been found to use 17 to 19 percent less energy than treelength systems because skidding logs to roadsides consumes more energy. This is due to excess material causing increased friction when skidded across the landscape (Sambo 2002).

2.4.2 Felling Machines

Feller-bunchers usually consist of a rubber tire or track mounted machine that have either a circular saw head or a shear head attached in order to fell trees and bunch them accordingly. As previously mentioned, tree size can effect feller-buncher productivity which could lead to decreased fuel consumption per unit of wood produced. Typically, chainsaws are often used in areas of steep slopes and consume small amounts of fuel. A study conducted by Popovici (2013) showed that chainsaw fuel consumption was 0.43 l/m^3 of wood harvested (0.11 gal/ton).

2.4.3 Skidding Machines

Phillips (1983) found that maximum payloads would help reduce costs per unit of wood skidded. Factors such as slope of the skid trail, skidder weight, and skid distances were used to determine the amount of fuel used per turn. When evaluating tree size as a possible effect on skidding processes, a great deal of variation in fuel consumption was found because harvesting increased amounts of smaller stems can create higher costs per cubic meter of wood harvested (Silversides and Sundberg 1989). This is suspected to be because increased branches and stems with larger trees results in more work to be done when skidding the trees across the landscape.

2.4.4 Loading/ Processing Machines

Research has shown that tree size has an effect on fuel consumption, logging productivity, and loggings costs. Silversides and Sundberg (1989) found that a range of tree sizes has had an important effect on operational efficiency and production cost. Productivity and cost tend to vary directly with tree size in that larger trees usually have higher man-day productivity, resulting in decreased fuel consumption per unit of wood produced. In loading, it is thought that tree size and harvest type could have an impact on productivity. This is possibly due to increased work done with the merchandising of higher value products, which would result in increased fuel consumption. Baker et al. (2009) evaluated knuckle-boom loader processing time in five different merchantability classes and found that chip-n-saw size material took the most time to load while pulpwood took the least amount of loading time. The study found that loading super pulpwood was the most productive with an average of 161 tons/PMH, while pre-cut sawtimber was the least productive with an average of 35 tons/PMH.

III. Methods

3.1 Evaluating and Estimating Fuel Consumption from Surveyed Literature

A literature review was conducted to evaluate research that recorded fuel input, productivity, harvest type, slope, soil moisture conditions, and average tree size among different equipment types. Fuel consumption was then determined from each source that was evaluated.

Sources were excluded if they appeared to utilize “rule of thumb” fuel consumption estimates (Miyata 1980; Brinker et al. 2002) instead of actually measuring fuel consumption. Sources that had publication dates before 1980 were also excluded from consideration.

For each source, the following characteristics were noted: slope, specific gravity of major species harvested, average tree size in diameter, average tree volume in cubic feet, harvest type, machine class, horsepower of the machine, fuel consumption, and volume or weight of the wood that was harvested during the study. Volumes were reported in cubic feet as well as cubic meters, while weights were reported in tons. Conversions were needed because not all of the sources reported wood volumes. To convert wood weights into volumes, specific gravities of the wood and moisture contents were estimated for all of the major species harvested. Then, all of the production data was converted into cubic meters of wood harvested. Similarly, fuel consumption, which was recorded in gal/PMH, was converted to gallons per cubic meter (gal/m^3), so it could be further analyzed to determine average fuel consumption by each machine and logging system.

A study was undertaken in order to estimate more modern fuel consumption in logging systems. This project was launched to include multiple approaches of gathering fuel consumption data from logging crews across all regions of the United States.

A survey was developed to gather fuel consumption estimates from loggers on a per tract basis. Certain data fields were created to estimate the different components of the specific harvesting operations while noting the total amount of fuel consumed and the total weight of wood harvested in tons. (See Logger Survey, Chart 1, appendix)

Loggers were contacted in a variety of different ways. One contact method was using already existing relationships between Auburn University and different logging crews. Another method was distributing surveys across different parts of the country by visiting logging expos to present the study to logging crews and meeting with local loggers face to face. This was accomplished in order to evaluate fuel consumption across a broad variety of geographical regions.

To obtain a measure of fuel consumption, each crew was asked to submit the total amount of gallons of fuel used in each machine per week and how much total wood (in tons) was delivered to the mill that week. The study relied on loggers to provide accurate fuel consumption records. It is assumed that when evaluating the weekly data that all fuel consumed and wood weights obtained from the mill were recorded daily then totaled for the week. To improve participation, data was also collected for the total system on a per track basis. This data was helpful, but little statistics could be used to evaluate it. While the study was originally designed to estimate fuel consumption over the course of harvesting one tract, weekly fuel consumption and harvesting records also provided an accurate means of accounting for overall fuel consumption.

3.2 Data Entry

A survey form was structured to accept fuel consumption by tract and by week. Since many logging crews record their fuel information on a weekly basis, the study sought to gather their weekly fuel consumption, which included both fuel consumed in gallons and total wood harvested in tons.

The data was organized both by crew and chronologically by the date of harvest. The fuel consumption of each harvesting process was kept separate for each logging crew. All wood weights were reported in tons, while all fuel consumption was reported in gallons.

3.3 Data Processing and Statistical Analysis

Statistical analysis began by combining and organizing the data to prepare it to be evaluated. R Statistical Software (R Core Team, 2013) was used to analyze the survey data. Based on survey response, specific factors were chosen for evaluation. The factors were average slope of the tract, average tree size harvested (merchantability class), harvest type (clearcut or thinning), crew differences, and soil moisture level of the tract. Interaction terms were also evaluated to test if two factors' interaction had a significant effect on the rate of fuel consumption.

An exploratory analysis using boxplots was performed on the data to show the levels of fuel consumption in gal/ton for each factor, separated by machine type. The boxplots showed each factor on the "X-axis" and fuel consumption (gal/ton) on the "Y-axis". All analysis was conducted by separating each forest operation class (felling, skidding, and loading) and evaluating each machine's fuel consumption differences among crew, harvest type, slope, soil moisture, machine class, and merchantability class. Upon evaluating the boxplots, relationships were identified to determine what type of function to use to test for significance. A statistical model containing all of the possible factors was then developed to provide a way to estimate fuel consumption (Y) given the tested variables (X). The statistical model as originally tested was:

$$Y= \beta_0X_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+ \beta_4X_4+ \beta_5X_5 + \beta_6(X_1*X_2) + \beta_7(X_1*X_3) + \beta_8(X_1*X_4) + \beta_9(X_1*X_5) + \beta_{10}(X_2*X_3)$$

where,

Y= Fuel consumption (Gal/Ton)

X_1= Crew

X_2= Average Merchantability Class of Stand (Based on DBH)

X_3= Harvest Type (Clearcut or Thinning)

X_4= Slope (Average slope class of the Tract)

X_5= Soil Moisture (Survey response moisture class)

When factors were found to be insignificant due to high p-values, they were deleted from the statistical model. These statistically insignificant factors will still be displayed on boxplots to show the data distribution among the various categories.

3.4 Finalizing the Data and Presenting

After the statistical analysis was completed, the factors that were determined to have a significant effect on fuel consumption were studied in detail by evaluating differences in fuel consumption among the categories within each independent factor. In order to accomplish the further evaluation, pairwise comparisons were used to determine the specific differences in fuel consumption among these categories.

IV. Results and Discussion

4.1 Literature Review

From the literature, it was found that a ground based harvesting system consisting of a feller-buncher, skidder, and a loader averaged 2.41 l/m^3. When evaluating felling machines, it was noticed that feller-bunchers yielded an average fuel consumption of 26.3 liters/productive machine hour (l/PMH) while yielding a l/m^3 fuel consumption of 1.10. Harvesters consumed 21.1 l/PMH while using 1.59 l/m^3. Evaluation of primary transport machines showed that skidders used an average of 23.6 l/PMH and 0.93 l/m^3. Forwarders used 11.09 l/PMH and 0.61 l/m^3. Other harvesting systems such as loading, delimbing, and processing were also evaluated in order to determine average fuel consumption. Loaders used an average of 26.3 l/PMH while consuming 0.38 l/m^3. Delimbers were found to use 17.3 l/PMH while consuming 0.49 l/m^3. Systems that operated processing heads for merchandising used 22.6 l/PMH and 0.69 l/m^3. All literature review fuel consumption information can be found in Table 1.

When evaluating the amount of data reported in each machine type, it is important to note that only seven delimbers were evaluated making it the machine type with the least amount of evaluations. On the opposite end of the spectrum the most evaluated machine type was grapple skidders, in which 43 different machines were evaluated for fuel consumption (Table 1).

Table 1: Literature Review- Comprehensive Data Analysis Table with Fuel Use Estimates

System	Machine Type	Average L/Hr.	Total Sources of Data	Std Dev L/Hr	Average L/m^3	Std. Dev L/m^3
Treelength (Ground Based)	Feller Buncher	26.27	33	9.54	1.10	1.67
Treelength (Ground Based)	Grapple Skidder	23.62	43	23.09	0.93	1.34
Treelength (Ground Based)	Loader	26.31	9	2.69	0.38	0.11
CTL (Ground Based)	Harvester	21.08	20	7.72	1.59	0.76
CTL (Ground Based)	Forwarder	11.09	9	1.67	0.61	0.15
Processing Elements	Delimber	17.30	7	4.35	0.49	0.19
Processing Elements	Processor	22.56	14	4.13	0.69	0.34

A chart was created based on the literature review to display average fuel consumption estimates for the five different types of logging systems in liters per cubic meter (l/m$^{3)}$ that occurred throughout the research. The first two systems are a CTL (Hot) system and a CTL (Cold) system. These types of systems contain a harvester that cuts and merchandises stems and a forwarder that loads stems and transports them directly to the mill (Hot) or stores them at the roadside to be transported later (Cold). It was found that CTL (Hot) systems used an average of 0.81 l/m^3 while CTL (Cold) systems used 0.94 l/m^3 of fuel. It is assumed that the CTL (Cold) systems consumed more fuel because of the extra handling when loading the logs and transporting them twice. The next system is a whole tree system that produced shortwood. This system consists of a feller-buncher and a skidder that hauls to the landing where wood is then cut to certain lengths using a processor. These systems were found to consume approximately 1.08

l/m^3. Another system is a whole tree treelength system that harvested southern yellow pine, usually consisting of a feller-buncher, skidder, and a loader. These systems were found to consume approximately 0.79 l/m^3 of fuel. Finally, whole tree systems that harvested treelength material with heavy limbs also consist of a feller-buncher, skidder, and a loader while harvesting hardwood stems. These systems were found to consume an average of 1.10 l/m^3 of fuel (Table 2 and Figure 2).

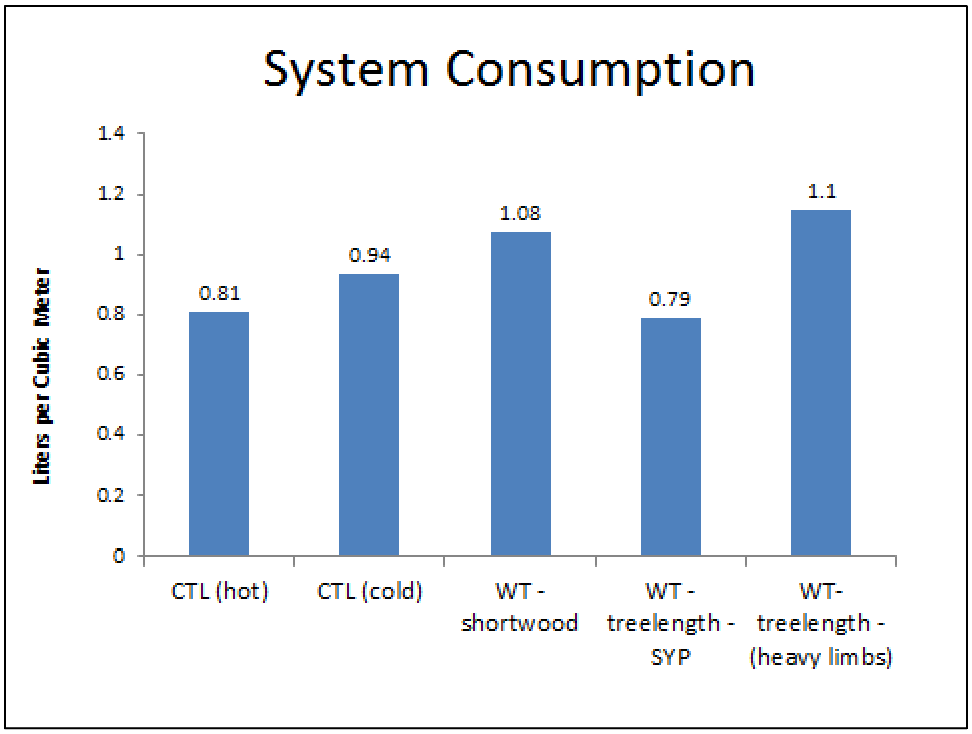

Figure 2: Estimated System Fuel Consumption- Literature Review

The following few figures indicate fuel consumption on a per hour and per unit of wood produced. The bar in the middle represents the average consumption, while the upper and lower

90% confidence interval are represented by the “O” and “X”, respectively. Figure 3 shows the fuel consumption for felling and harvesting found from the literature study. While harvesters used less fuel on a liter per productive machine hour (l/PMH) basis, they actually consumed more fuel than feller-bunchers on a liter per cubic meter (l/m^3) basis. This was because feller-bunchers did not conduct the merchandizing processes that the harvester accomplished. Also, they were able to produce more wood, leading to less fuel consumption per unit of wood produced (l/m^3).

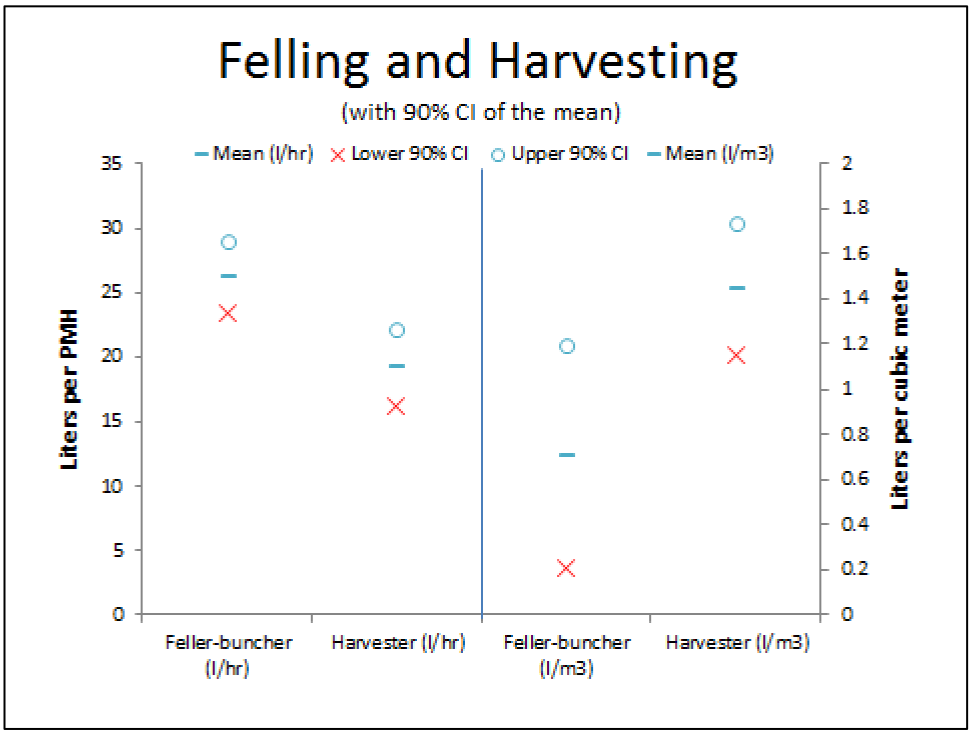

Figure 3: Estimated Felling and Harvesting Fuel Consumption- Literature Review

Similarly, Figure 4 shows the difference between l/PMH and l/m^3, now comparing a skidder and a forwarder. Based on the selected studies in the literature review, skidders used about 3.31 more liters of fuel per hour than forwarders, on average. Additionally, skidders only used 0.12 l/m^3 more fuel than forwarders, on average.

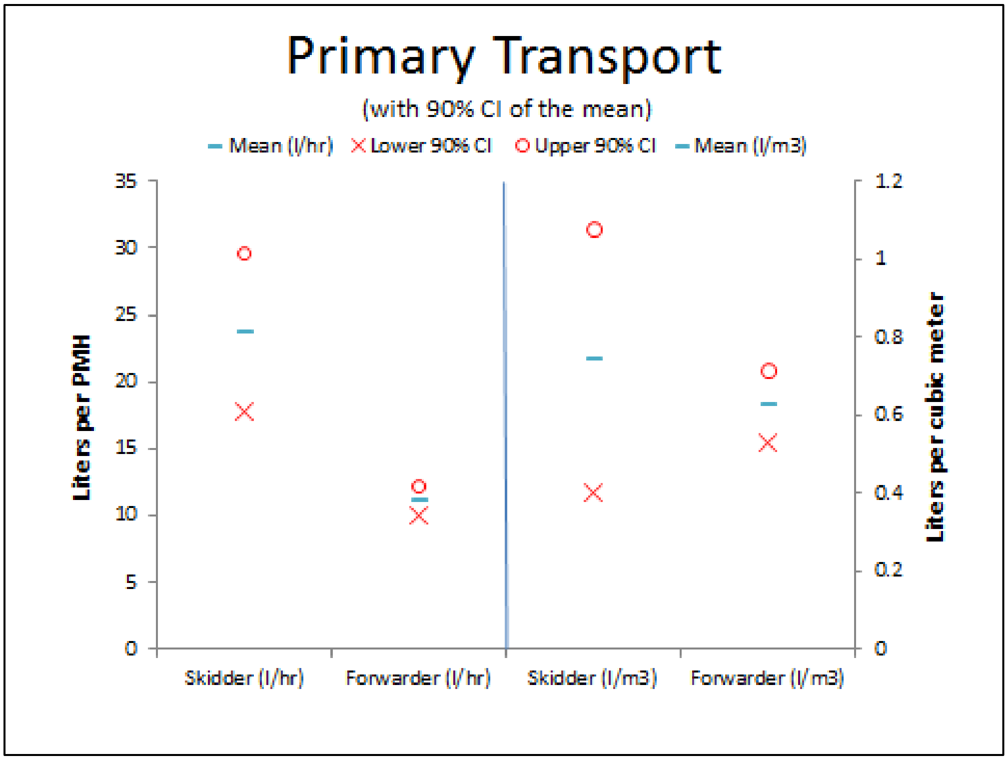

Figure 4: Estimated Primary Transport Fuel Consumption- Literature Review

Figure 5 shows that loading used more fuel than both delimbers and processors on a l/PMH basis. However, on a l/m^3 basis, loading used the least amount of fuel compared to delimbers and processors.

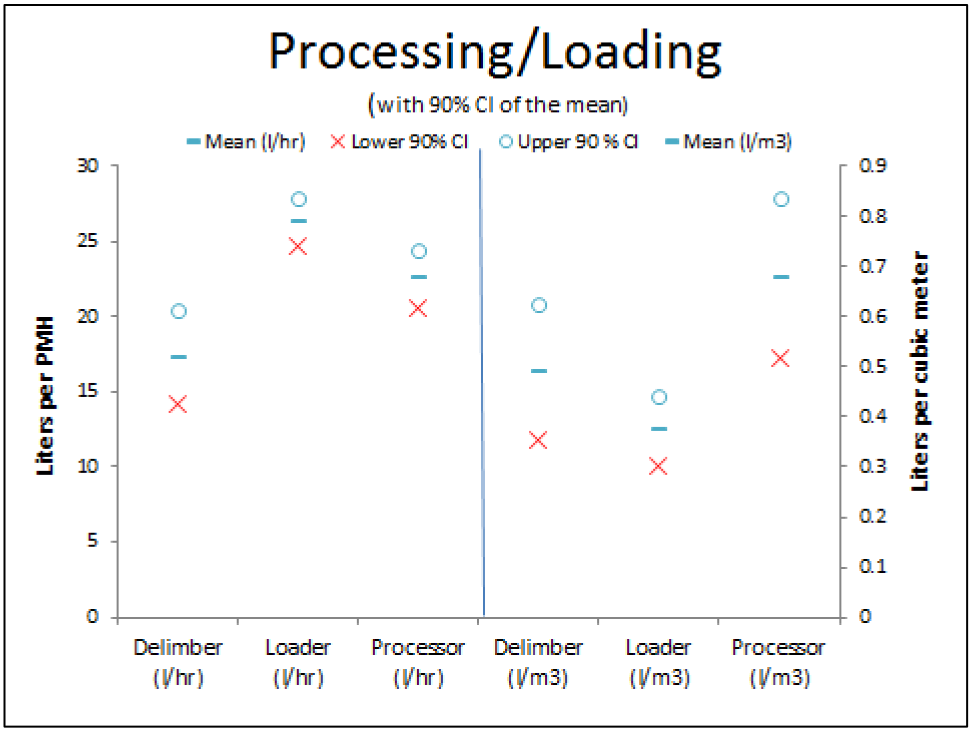

Figure 5: Estimated Processing/Loading Fuel Consumption- Literature Review

After evaluating the chart in Table 1 and analyzing the standard deviation of fuel consumption for each machine type, it was evident that there was a certain degree of variability, especially in the feller-buncher and skidder classes. Tree size data collected from the literature review also showed that larger trees typically use less fuel on a l/m^3 basis. This variability could be due to a difference in terrain of the harvested tracts, differences in harvest type (thinning or clearcut), and/or the age of the equipment. The distribution of the data over a thirty-year period could have also contributed to fuel consumption variability, where older machines were grouped in with newer models in the literature analysis.

4.2 Logger Survey Data

4.2.1 Tract Data

Fuel consumption records were received from 15 different logging crews. 9 of those crews reported fuel consumption by tract. In total, crews that produced tract data harvested over 48,000 tons of wood (Table 3).

Table 2: Total Tons by Logging Crew (Tract Data)

Crew	Total Tons Harvested
Crew 1	23,000
Crew 2	700
Crew 3	8,000
Crew 4	6,865
Crews 5-9	9,800
Tract Data Total Tons	**48,365**

The tract data gave regional variety to the study, while giving fuel consumption estimates for a variety of different logging machinery and systems. Systems varied from ground based treelength logging operations in the Southeastern United States (crews 1-4) to other ground based harvesting operations in the Lake States, which sometimes used chainsaw felling. The crews that reported tract data were denoted in tables and figures by the state abbreviation and the respective numbers of crews reported in the study.

Logging crews that submitted tract data had a variety of different harvesting conditions and machine types. The crews from the Southeastern United States had typical ground based logging operations that contained one or more of the following machines: a feller-buncher, a skidder, and a loader. Crews 5-9 harvested on slopes greater than 35% grade and also operated using log loaders with processing attachments needed to merchandize hardwood stems. While

Crew 5 cut trees with a tracked feller-buncher, Crews 6-9 did not report felling data since they felled with chainsaws. Crew 5 and Crew 8 operated cable skidders as well as grapple skidders, while Crew 7 operated only one cable skidder. The machines used by each crew that submitted fuel consumption on a per tract basis can be found in Table 4.

Table 3: Tract Data (Crew Machine Information)

Crew Name	Machine Class	Machine Year	Machine Model
Crew 1	FB	2009	Tigercat 720 E
	SK	2011	CAT 525C
	LD	2008	John Deere 437 C
Crew 2	FB	2001	Tigercat 726 B
	SK	1995	Timberjack 380 C
	LD	1995	Barko 160 B
Crew 3	FB	2003	Tigercat 724 D
	FB	2012	Tigercat 726 E
	SK	2005	Tigercat 630 C
	SK	2006	Tigercat 630 C
	SK	2012	Tigercat 630 D
	LD	2005	Tigercat 244
	LD	2010	Tigercat 250 B
	LD	2013	CAT 320 D
	Dozer	2001	CAT D6R XL
Crew 4	FB	2010	Tigercat 724 E
	SK	2008	CAT 525 C
	LD	2006	Prentice 384
Crew 5	Tracked FB	1997	Timbco w/ bar saw
	Cable SK	1997	Timberjack 240
	Grapple SK	1992	Timberjack 450
	LD	2001	Prentice 384
	Dozer	2004	John Deere 650 H
Crew 6	Chainsaws	NA	NA
	SK	NA	John Deere 648 E
	LD	NA	Timberjack
	Dozer	2007	John Deere 650
Crew 7	Chainsaws	NA	NA
	Cable SK	NA	CAT
	LD	NA	Barko w/ sawbuck
	Dozer	NA	CAT D5
Crew 8	Chainsaws	NA	NA
	Grapple SK	2008	John Deere 650 H
	Cable SK	2008	John Deere 648 H
	LD	2008	Prentice 2210
	Dozer	2007	John Deere 650 H
Crew 9	Chainsaws	NA	NA
	SK	1989	John Deere 640 D
	LD	2003	Barko 160 D
	Dozer	1993	John Deere 450 G
Chart Abbreviations		FB= Feller-Buncher Tracked FB= Tracked Feller-Buncher SK=Skidder LD=Loader	

Total system fuel consumption was calculated for each harvested tract. The average fuel consumption of all nine crews that reported tract data was approximately 0.65 gal/ton. The minimum fuel consumption for the tract data crews was 0.37 gal/ton. This was the average fuel consumption for Crew 8, who did not report felling fuel consumption. The maximum fuel consumption from the tract data was 0.94 gal/ton, reported by Crew 7 (Table 5 and Figure 6).

Crew 1 was the only crew to report fuel consumption on more than one tract. They reported data for 8 tracts (Table 5). This multi-tract crew yielded an overall fuel consumption of 0.69 gal/ton with a standard deviation of 0.12. An average fuel consumption of 0.65 gal/ton for all crews that submitted tract data provided a broad look into treelength ground based logging systems, which had a variety of machine age ranging from the years 1992 to 2013. (Figure 6).

Table 4: Tract Data Average Fuel Consumption

Crew	Gal/Ton	Harvest System	State
Crew 1	0.69	treelength	Alabama
Crew 2	0.64	treelength	Georgia
Crew 3	0.63	treelength	Louisiana
Crew 4	0.47	treelength	North Carolina
Crew 5	0.75	treelength	Ohio
Crew 6	0.41	treelength	Ohio
Crew 7	0.94	treelength	Ohio
Crew 8	0.37	treelength	Ohio
Crew 9	0.92	treelength	Ohio
Average Fuel Consumption	0.65		

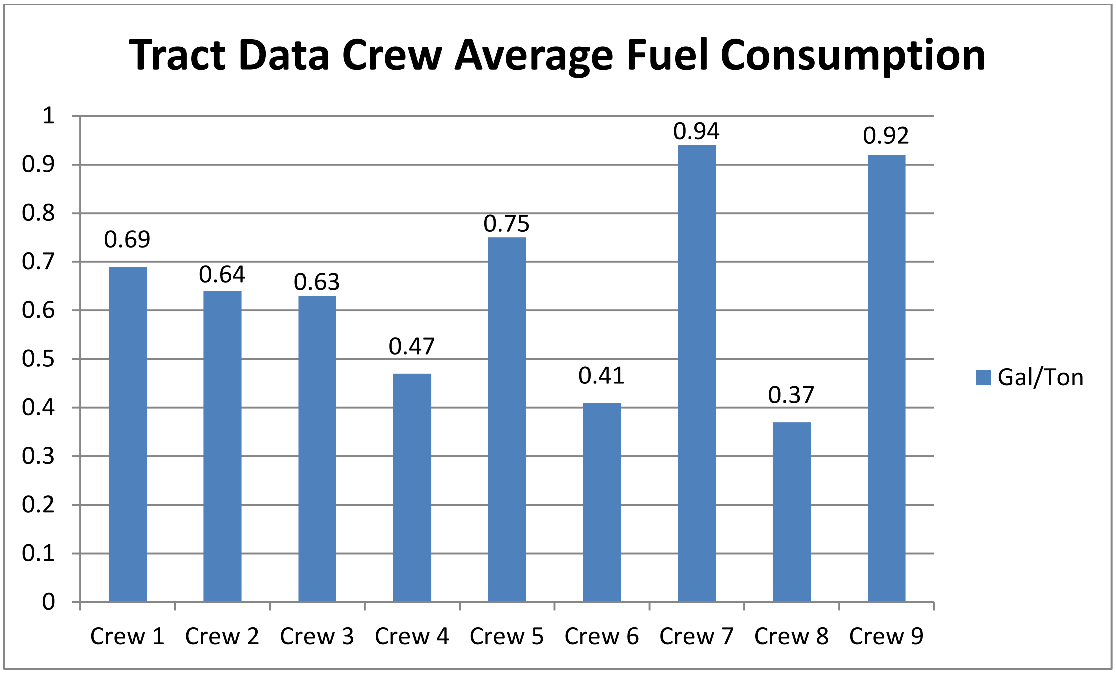

Figure 6: Tract Data Fuel Consumption by Crew

4.2.2 Weekly Data

The remainder of the fuel consumption data was provided by six logging crews on a per week basis. The six crews were located in South Alabama and Northeast Florida. The total amount of wood harvested by the six crews totaled approximately 486,000 tons (Table 6). All crews operated in slope conditions with less than a 35% grade. The majority of the terrain represented in the study had a slope of less than 15%. Crews operated in both thinnings and clearcuts and harvested diameters ranging from 5-18 inches diameter at breast height (DBH). Soil moisture was divided into three classes: dry, moist, and wet. However, only 22% of the crews reported soil moisture.

Table 5: Total Tons by Logging Crew (Weekly Data)

Crew	Total Tons	Average Weekly Tons
Crew A	119,000	1505
Crew B	91,000	1129
Crew C	111,000	1439
Crew D	19,000	843
Crew E	94,000	1810
Crew F	52,000	1246
Weekly Data Total Tons	**486,000**	

Figure 7 shows the weekly productivity in tons/week for each crew and the total weeks submitted by each crew. The most productive crew was Crew E, which averaged 1810 tons/week (49 weeks), while the least productive crew was Crew D, averaging 843 tons/week (23 weeks). Crew B submitted the most weeks with 81 weeks, while Crew D submitted the least amount of weeks with 23 weeks.

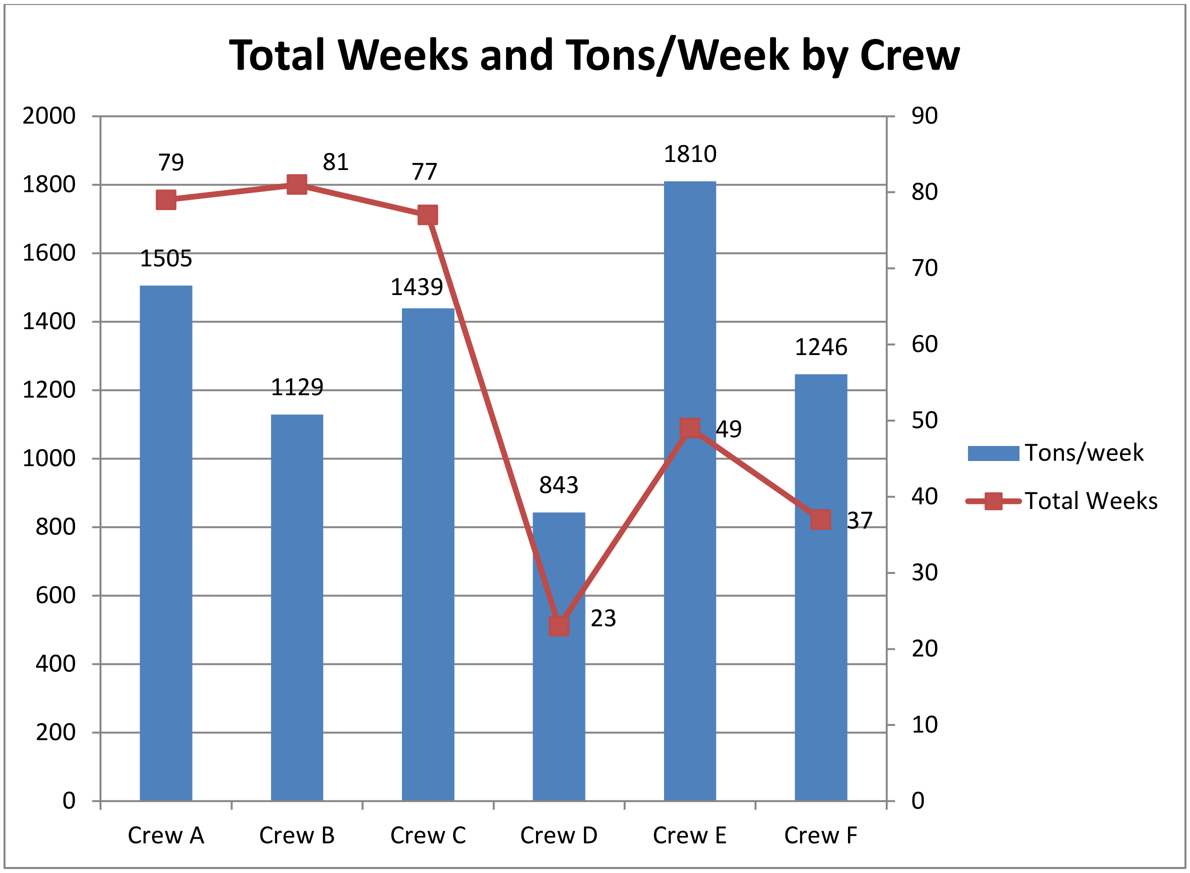

Figure 7: Weekly Productivity and Total Harvesting Weeks by Crew

Logging crews that submitted weekly data were all ground based treelength logging operations that had one or more of the following machine types: feller-buncher, skidder, and loader. Some of the logging crews had other machinery such as bulldozers, in-woods trucks, chain flail de-limbers, and processing heads. A machine information table for all crews that submitted weekly fuel data can be found in Table 7**.**

Table 6: Weekly Data (Crew Machine Information)

Crew Name	Machine Class	Machine Year	Machine Model	HP
Crew A	FB	2010	2010 Tigercat 720 E	173
	SK	2011	2011 John Deere 848 H	224
	LD	2012	2012 John Deere 437 D	173
	Miscellaneous equipment	1988	1988 in woods army truck	NA
Crew B	FB	2013	2013 Tigercat 720 E	190
	SK	2007	2007 John Deere 848 H	200
	LD	2011	2011 Caterpillar 529	156
Crew C	FB	2010	2010 Tigercat 720 E	173
	SK	2006	2006 John Deere 648 G	171
	SK	2002	2002 John Deere 648 G	185
	LD	2012	2012 John Deere 437 D	173
	Miscellaneous Equipment	2005	2005 Timberjack 608 S	205
Crew D	FB	2006	2006 John Deere 643 J	174
	SK	2008	2008 John Deere 848 H	224
	LD	2014	2014 John Deere 437 D	173
Crew E	FB	2014	2014 Tigercat 720 E	190
	SK	2014	2014 Tigercat 630 E	260
	LD	2010	2010 Tigercat 234	173
	Miscellaneous Equipment	1981	1981 Mack Truck	NA
	Miscellaneous Equipment	1987	1987 Mack Truck	NA
Crew F	FB	2009	2009 Tigercat 720 B	190
	SK	2004	2004 Tigercat 630 B	180
	LD	2013	2013 Tigercat 234	173
	Miscellaneous Equipment	NA	Army Truck	NA
Chart Abbreviations	FB= Feller-Buncher Tracked FB= Tracked Feller-Buncher SK=Skidder LD=Loader			

The weekly data had low variability among machine type and had an average fuel consumption of 0.509 (±0.013, 90% CI) gal/ton. The minimum fuel consumption came from Crew E with 0.42 gal/ton. The maximum fuel consumption came from Crew F, which used 0.60 gal/ton of fuel while harvesting (Figure 8). The standard deviation of fuel consumption showed some variability across the weeks that were submitted. Crew E showed the lowest variability with a standard deviation of 0.11, while Crew D showed the greatest variability with a standard deviation of 0.18.

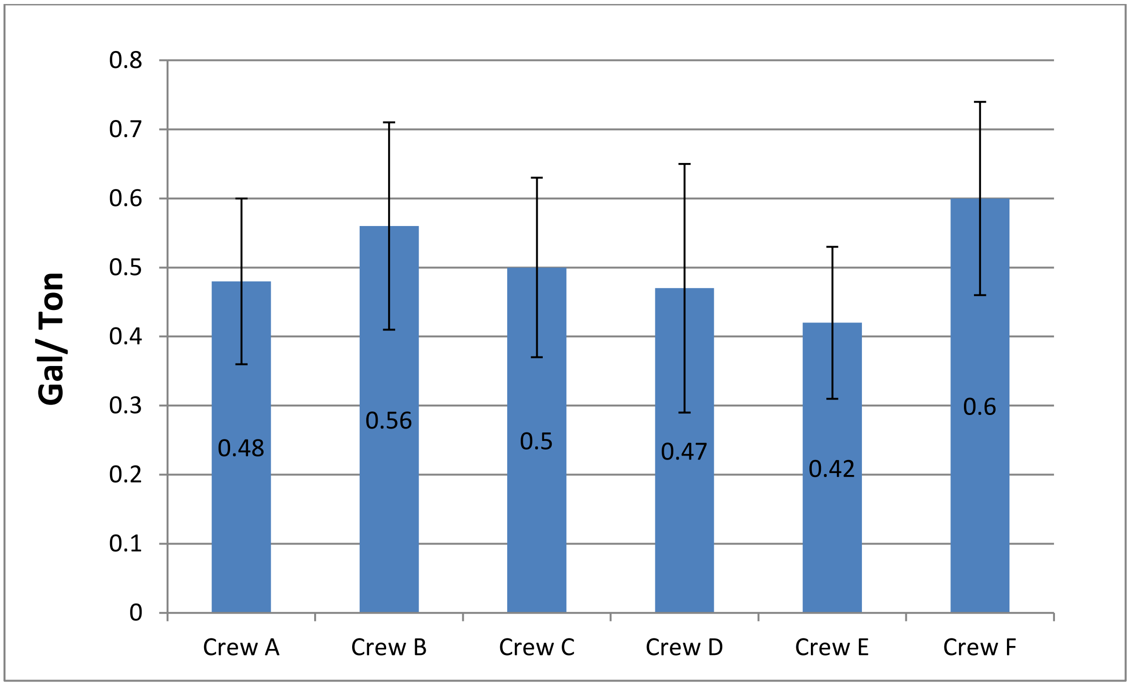

Figure 8: Average Weekly Fuel Consumption by Crew

Further evaluation of the weekly data was conducted by calculating the average fuel consumption for each machine type. For felling, the average amount of fuel consumption was 0.175 (±0.006, 90% CI) gal/ton. The minimum amount of fuel consumption recorded was 0.12 gal/ton by the Crew C, and the maximum amount of fuel consumption recorded for the felling class was 0.24 gal/ton by Crew F. Figure 9 indicates the fuel consumption for felling. The average fuel consumption is represented by the dark horizontal bar; the bottom of the box represents the 25th percentile while the top of the box represents the 75th percentile of all data. Data within the dashed line represents 95 % of all data. Circular spheres represent extreme data points that lie outside 95 % of all data.

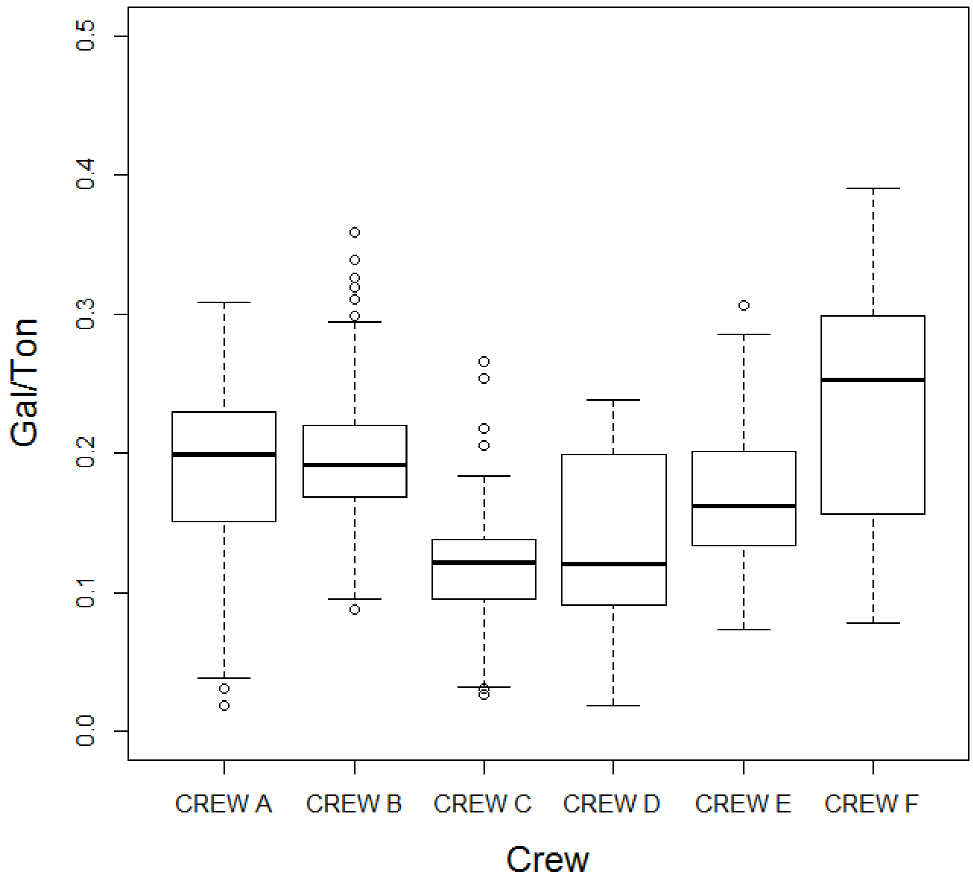

Figure 9: Average Weekly Felling Fuel Consumption by Crew

For skidding, the overall average fuel consumption was 0.177 (±0.005, 90% CI) gal/ton. The minimum amount of skidding fuel consumption came from Crew A, which used an average of 0.15 gal/ton. The maximum amount of fuel consumption came from Crew F, which used 0.24 gal/ton (Figure 10).

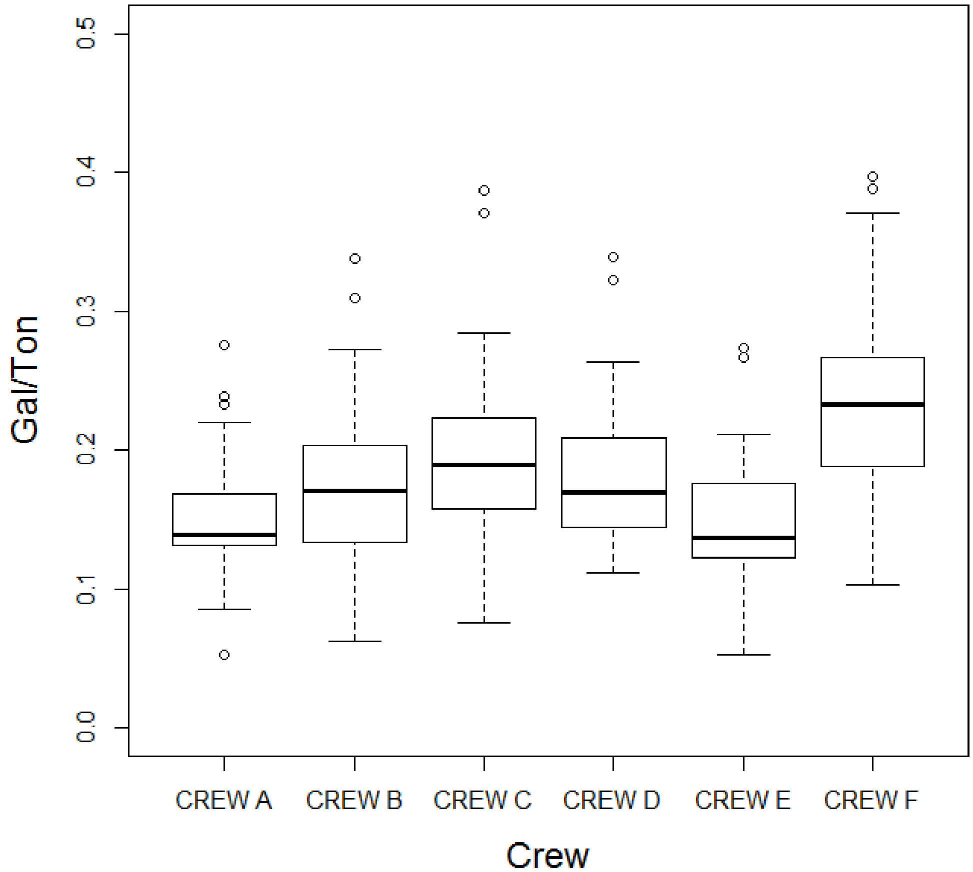

Figure 10: Average Weekly Skidding Fuel Consumption by Crew

For loading, the overall average fuel consumption was 0.103 (±0.004, 90% CI) gal/ton. The minimum amount of fuel consumption came from both Crew C and Crew E. These crews used an average of 0.07 gal/ton. The maximum amount of fuel consumption came from Crew B, which used an average of 0.15 gal/ton (Figure 11).

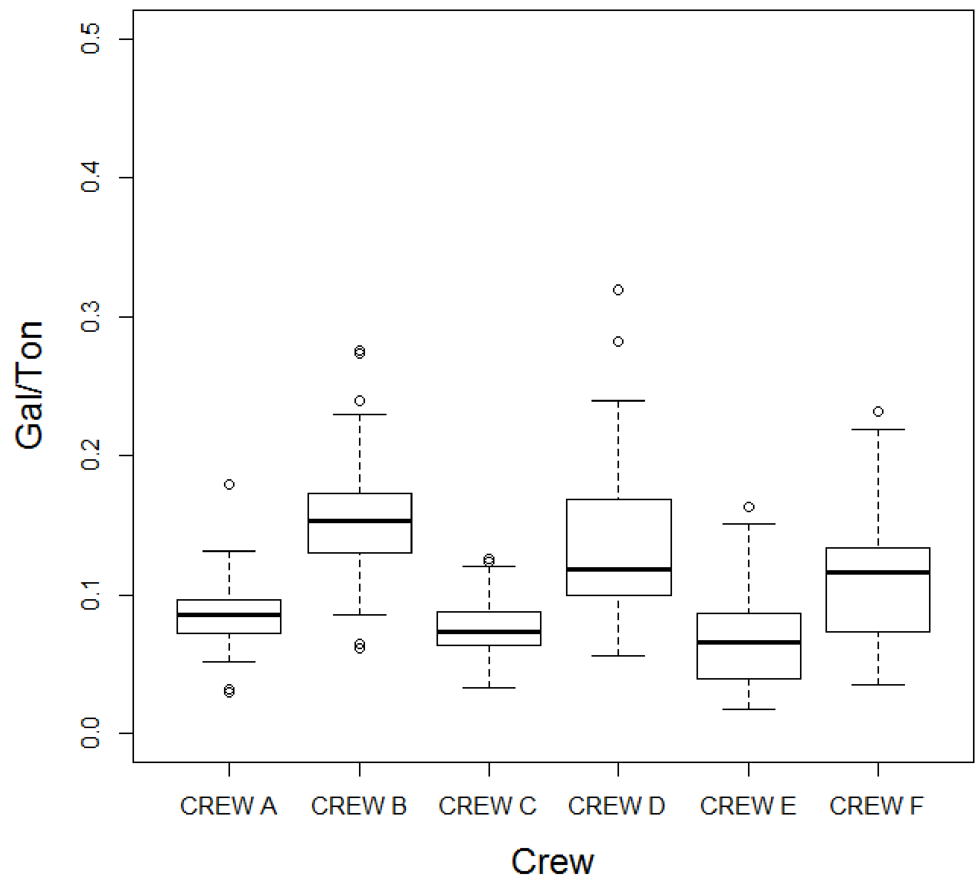

Figure 11: Average Weekly Loading/Processing Fuel Consumption by Crew

4.3 Evaluating the Collected Data

All of the survey study machine analysis was completed on a weekly basis. One challenge of using weekly data was that loaded log trailers are sometimes left in the woods for an extended period of time. Recording weekly fuel consumption would be most accurate when all wood that was harvested was taken to the mill by the end of the week. Larger sample sizes of multiple weeks by the same crew should account for any possible inaccuracies in the data. In the graphs displaying average fuel consumption for each week, the dips and spikes are assumed to be due to delays in wood being brought to the mill. These graphs are included in the appendix (pages 61-80).

4.4 Statistical Analysis

4.4.1 The Exploratory Analysis

In preparation for statistical analysis, an exploratory analysis was performed to evaluate each independent variable's effect on fuel consumption. This was accomplished by creating boxplots to show the relationship between each categorical factor and the average fuel consumption for each category. Once each independent variable was evaluated, an analysis of variance (ANOVA) test was used to determine potentially significant factors' effect on fuel consumption.

When evaluating the surveys, only 22% of the weeks contained a response for soil moisture. An exploratory data analysis was conducted by evaluating boxplots for the different soil moisture classes in relation to fuel consumption. The predetermined soil moisture classes were dry, moist, and wet. Loading was not tested when considering soil moisture because it is mostly a stationary machine and was assumed to not be affected by soil moisture. For both felling and skidding operations, it was noticed that there was little to no significant difference in fuel consumption among the different soil moisture classes (Figures 12 and 13). Similarly, when evaluating a possible effect of soil moisture on crew fuel consumption, no significance was found (p-value= 0.672). Due to these circumstances, attempts were made to evaluate weekly precipitation for the counties where each logging crew operated. The precipitation data was included in the model but did not a yield a significant effect on the rate of fuel consumption for any of the machine types. Due to a lack of significance, soil moisture was removed from the model.

While no scientific literature was found citing a significant relationship between soil moisture and fuel consumption, there could be many reasons for this. The various logging crews could have recorded soil moisture differently. For example, determining whether the soil for a whole property is dry, moist, or wet could be subjective. Another reason soil moisture could be hard to determine is the possible existence of topological variability within the tract. This could lead to some areas of the property being wetter than others. Only an assessment of the entire tract in determining an average soil moisture level would be an accurate way to determine a statistical relationship with soil moisture and fuel consumption. Lastly, few sites were categorized as "wet" because most crews do not work on sites during high moisture because of best management practice (BMP) implications.

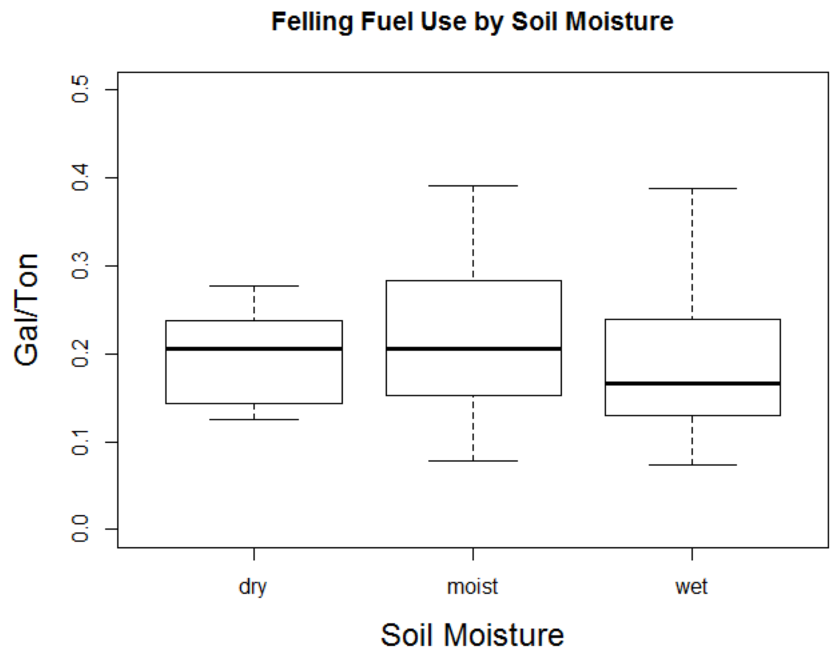

Figure 12: Soil Moisture Effect on Fuel Consumption-Felling

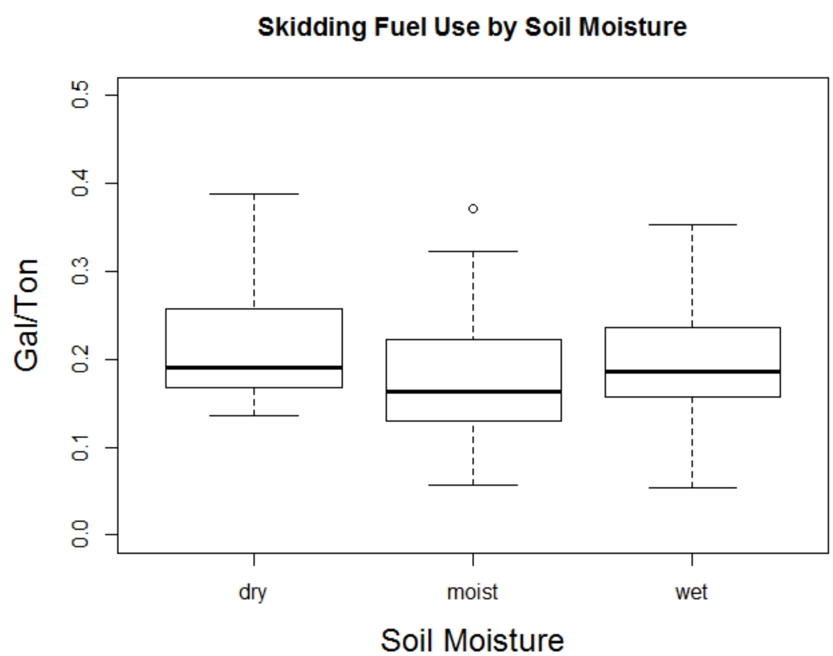

Figure 13: Soil Moisture Effect on Fuel Consumption- Skidding

Slope was also considered for its effect on fuel consumption. Again, loading was not considered when evaluating slope because it is mostly a stationary machine assumed to not be affected by slope. There was no significant difference in fuel consumption among slope classes (0%, 1-15%, 16-35%, and >35%) for either the felling or skidding machines (Figures 14 and 15). Interactions such as machine and slope interactions, slope and crew interactions, as well as slope and harvest type interactions were tested. Slope was not found to have any statistically significant effect on the rate of fuel consumption of the logging system (p-value= 0.217). Because of this, slope was moved from the statistical model (Figures 14 and 15).

No sources from scientific literature were found to validate a significant relationship between slope and fuel consumption in logging machines. Similarly, no significance was found between slope and fuel consumption in the survey study analysis. Some assumptions can be made for why slope has not shown a statistically significant relationship with fuel consumption. Similar to soil moisture, the way average slope class was measured could have been subjective. Also, like soil moisture, a topological variety within the tract could have made it difficult to determine an average slope of an entire property. It would require an assessment of the entire tract to accurately determine if there is a significant relationship between slope and fuel consumption.

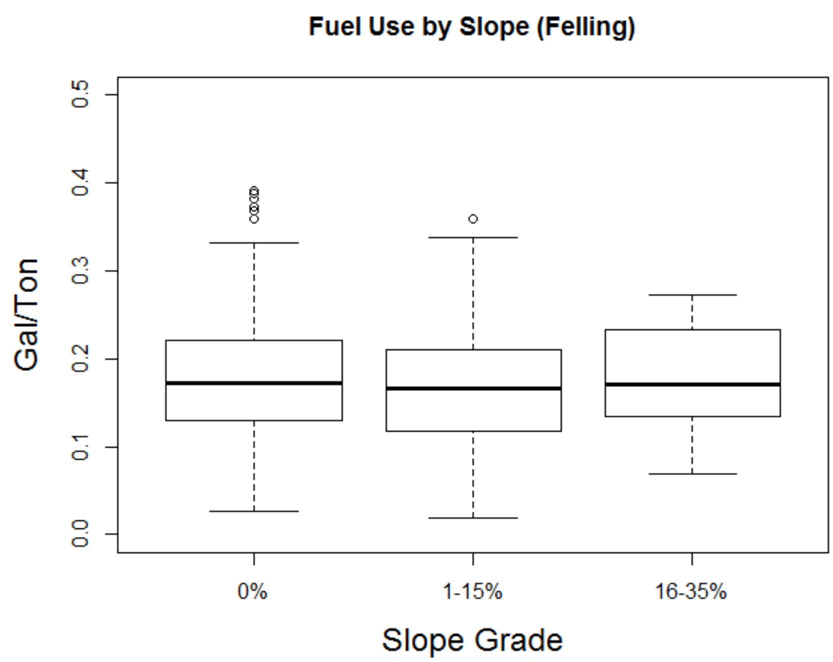

Figure 14: Slope Effect on Fuel Consumption-Felling

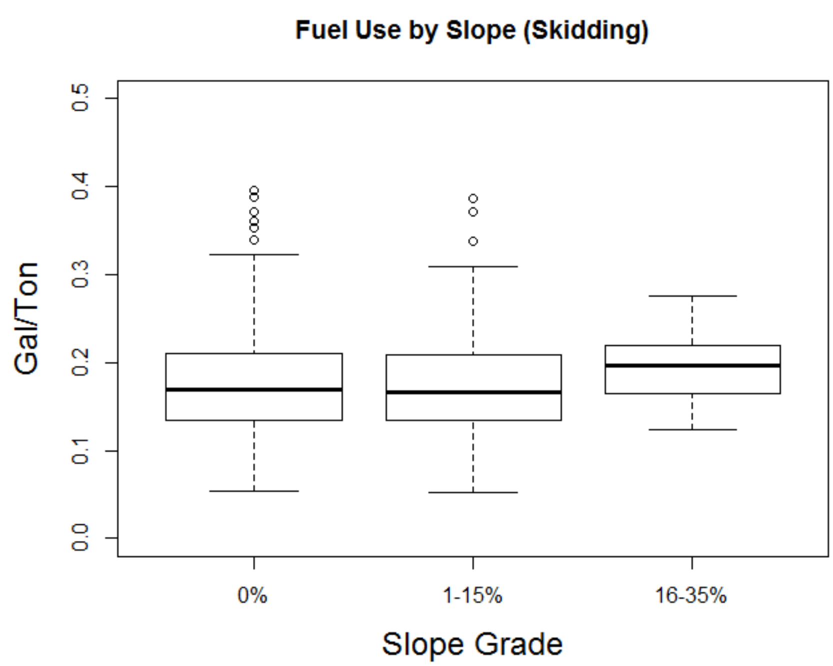

Figure 15: Slope Effect on Fuel Consumption-Skidding

Average tree size was later changed to merchantability class based on the merchantability classes listed in Timber Mart South (2014): “pulpwood” DBH – 6 to 7 inches, “chip-n-saw” DBH - 8 to 11 inches, and “sawtimber” DBH - 12 inches and greater. All machines (felling, skidding, and loading) were tested. Differences in fuel consumption can be noticed across machine operation types (Figures 16-18). For felling operations, harvesting pulpwood trees yielded the highest rate of fuel consumption. However, for skidding and loading, sawtimber size trees yielded the highest rate of fuel consumption.

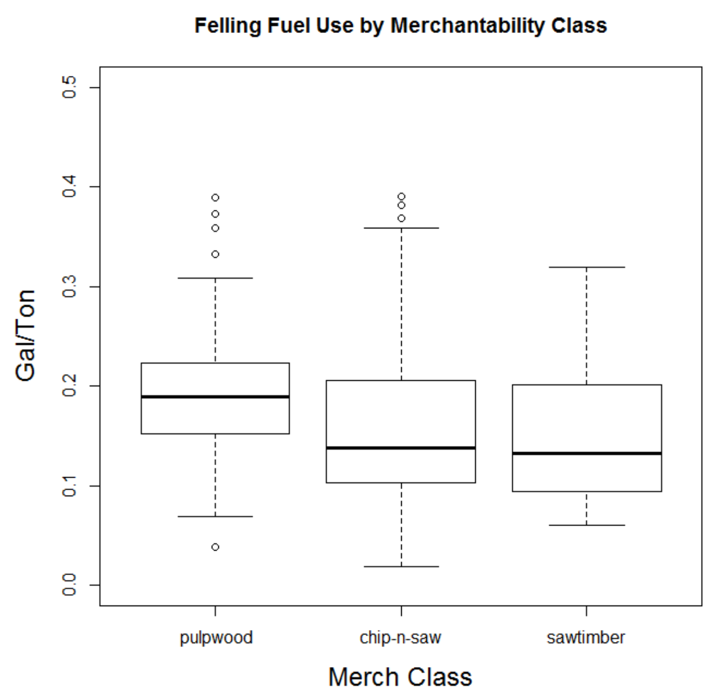

Figure 16: Average Felling Fuel Use by Merchantability Class

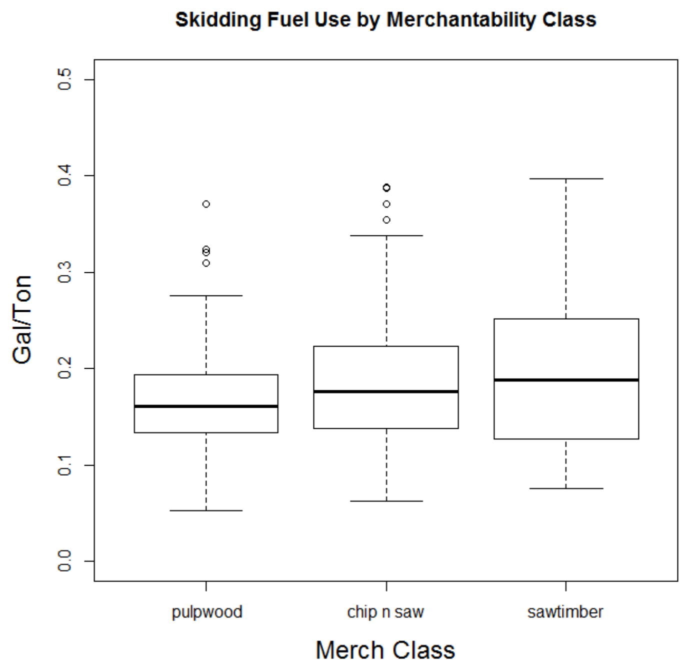

Figure 17: Average Skidding Fuel Use by Merchantability Class

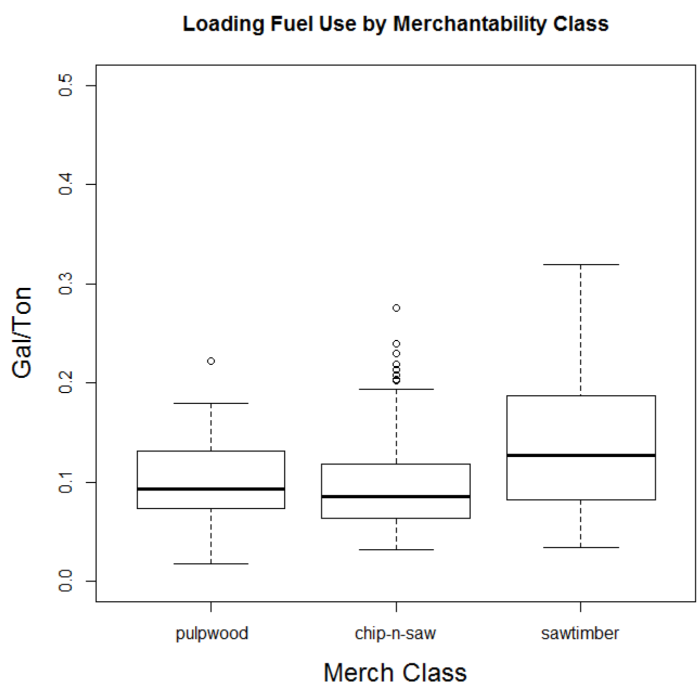

Figure 18: Average Loading Fuel Consumption by Merchantability Class

Table 12 shows the number of weeks and the amount of tons harvested for each harvest type (clearcut or thinning) by each crew. Four of the crews (Crew A, Crew B, Crew C, and Crew D) had over 75% of production in one harvest type. However, for Crew E and Crew F, activity in two harvesting types was more balanced. Crew E harvested 59% of their production in thinnings, while the remaining 41% was harvested from clearcuts. Crew F harvested 57% of their material from thinnings, while harvesting 43% of their material in clearcuts. Overall, 53% of production was harvested from thinnings, while harvesting the remaining 47% from clearcuts.

Table 7: Harvest Type Tons Harvested by Crew

Crew	% Tons TH	% Tons CC	Total Tons	Total Weeks TH	Total Weeks CC	Total tons TH	Total Tons CC
Crew A	78%	22%	118,920	63	16	92,370	26,550
Crew B	78%	22%	91,465	63	18	71,524	19,941
Crew C	5%	95%	110,800	6	71	5,784	105,016
Crew D	18%	82%	19,399	5	18	3,567	15,832
Crew E	59%	41%	88,693	29	20	52,571	36,122
Crew F	57%	43%	46,114	21	16	26,314	19,800
All Crews	**53%**	**47%**	**475,391**			**252,130**	**223,261**

When evaluating the total crew fuel consumption (sum of all harvesting machines' fuel in each crew), it was found that five crews showed greater fuel consumption in thinnings while one crew averaged the same fuel consumption in both harvest types (Figure 19). An analysis of variance (AOV) test was done that showed harvest type had a significant effect on crew fuel consumption (p-value=0.011). A Tukey's pairwise comparison showed that thinnings used 0.03 gal/ton more fuel than clearcuts (p-value=0.04).

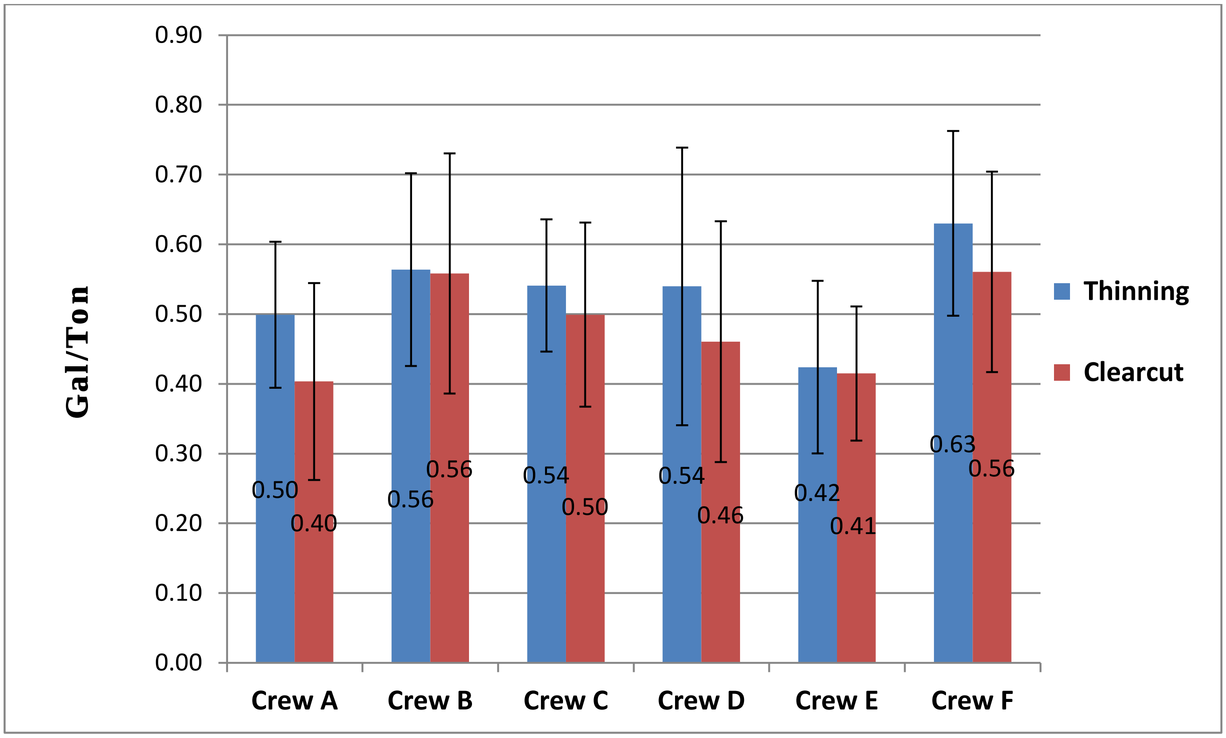

Figure 19: Average Crew Fuel Consumption by Harvest Type

The average fuel consumption for each harvest type by felling machines can be found in Figure 20. An AOV test found a significant relationship between harvest type and felling fuel consumption (p-value<0.001). A Tukey's pairwise comparison then showed felling in thinning harvest types consumed 0.014 gal/ton more fuel when compared to felling in clearcut harvest types (p-value=0.03).

The model also tested for a significant relationship between harvest type and fuel consumption for skidding (p-value=0.568) and loading (p-value=0.235). In both cases, there was no statistical significance, thus showing that harvest type only had a statistically significant relationship with fuel consumption in the felling class and in the total logging crew.

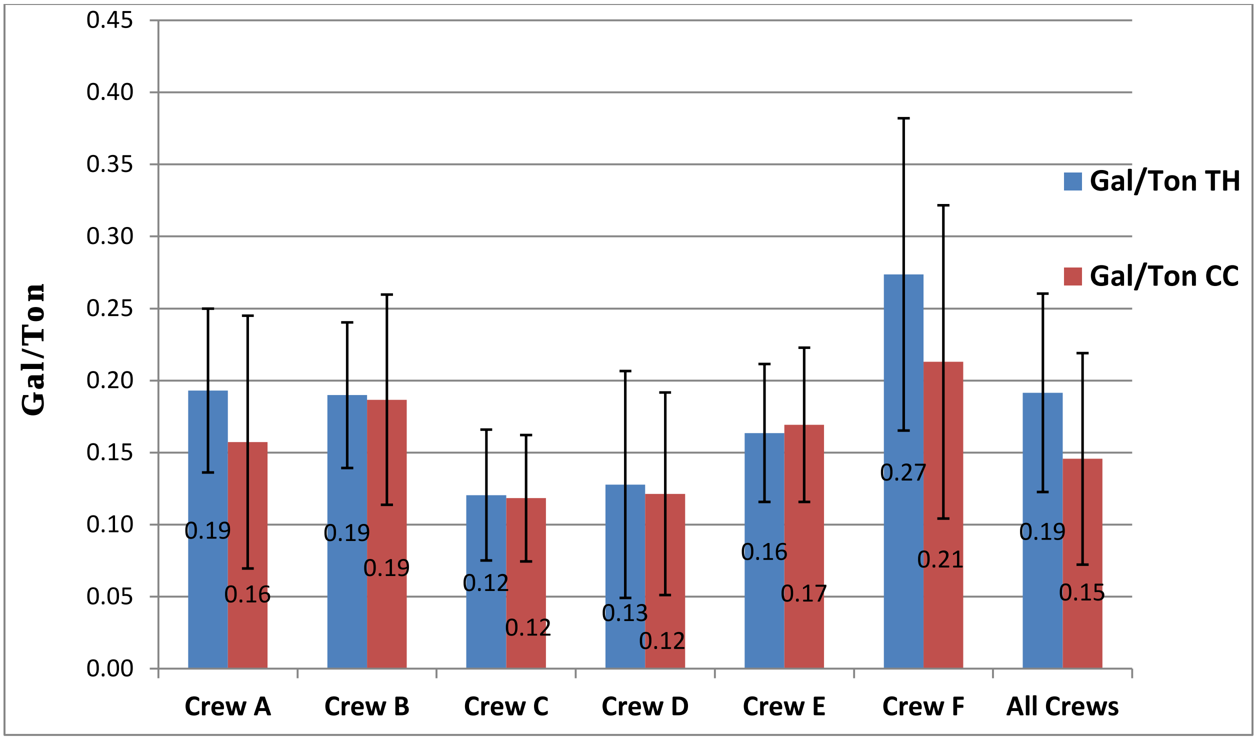

Figure 20: Average Crew Felling Fuel Consumption for Thinning and Clearcut

4.4.2 The Statistical Analysis Output

An analysis of variance (AOV) test was conducted on each harvesting operation class (felling, skidding, and loading) to evaluate possible factors that could affect fuel consumption (merchantability class, harvest type, and crew differences). Output tables were created to show only the terms that had a statistically significant relationship with fuel consumption (Tables 13-15).

4.4.2.1 Felling Machines Analysis

Table 8 shows the AOV model of weekly data for fuel consumption for felling. The mean fuel consumption for felling machines was 0.175 (±0.006, 90% CI) gal/ton. Harvest type was found to have a significant effect on the rate of fuel consumption in felling machines (p-value <0.001). When evaluating thinning versus clearcut, a Tukey's pairwise comparison showed that thinning used 0.014 gal/ton more fuel than clearcut operations (p-value=0.03). Akay et al. (2004) found that feller-buncher productivity decreases when the amount of trees per unit area increases, so the increased fuel consumption levels of feller-bunchers in thinnings in this study could be due to decreased productivity levels.

Merchantability class was also found to have a significant effect on the rate of fuel consumption in felling machines (p-value <0.001) When evaluating the merchantability class categorical factors, a Tukey's pairwise comparison showed that felling pulpwood consumed 0.038 gal/ton more fuel than felling chip-n-saw wood (p-value <0.001). Reduced productivity in felling smaller diameter stems could be the reason for increased fuel consumption in felling pulpwood. However, there was no significant difference found between pulpwood and sawtimber classes. This could be because only four percent of the total weeks submitted fell in the sawtimber category.

Table 8: Felling Statistical Significance Chart

Felling Full Model Statistics					
Significance: Pr(>F) <0.05					
	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
merch class	**2**	**0.128**	**0.064**	**17.0**	**< .001**
harvest type	**1**	**0.039**	**0.039**	**10.4**	**< .001**
crew	**5**	**0.375**	**0.075**	**19.9**	**< .001**
merch class*crew	**8**	**0.136**	**0.017**	**4.52**	**< .001**
Tukey's pairwise comparison					
	diff	**lwr**	**upr**	**p adj**	
pulpwood-chip n saw	**0.038**	**0.022**	**0.054**	**< .001**	
Thinning-Clearcut	**0.014**	**0.001**	**0.027**	**0.029**	

Table 8 also shows that the crew factor had a significant effect on average fuel consumption (p-value <0.001). A Tukey's pairwise comparison showed a significant difference among the different crews. For felling, seven of the possible fifteen crew comparisons yielded a significant difference in the rate of fuel consumption, shown in Table 9. The table also displays the machine year, make, and model used by each crew and notes the manufactured horsepower rating of each machine engine. In some cases, two crews' machine and model type were the same. While some of the crew differences might be attributed to equipment differences, no trends could be identified. Certain differences in fuel consumption could be due to operator effect or engine fine tuning by equipment mechanics.

Table 9: Felling Crew Machine Differences- Tukey's Pairwise Comparisons

Crew Differences in Felling							
	Diff (Gal/Ton)	lwr	upr	p adj	Significance	Felling Machine Comp. with (HP)	
CREW B-CREW A	0.014	-0.014	0.042	0.726	No	2013 Tigercat 720 E (190)	2010 Tigercat 720E (173)
CREW C-CREW A	-0.031	-0.059	-0.002	0.025	Yes	2010 Tigercat 720 E (173)	2010 Tigercat 720E (173)
CREW D-CREW A	-0.024	-0.067	0.017	0.547	No	2006 John Deere 643 J (174)	2010 Tigercat 720E (173)
CREW E-CREW A	-0.006	-0.037	0.026	0.996	No	2014 Tigercat 720 E (190)	2010 Tigercat 720E (173)
CREW F-CREW A	0.074	0.040	0.108	< .001	Yes	2009 Tigercat 720 B (190)	2010 Tigercat 720E (173)
CREW C-CREW B	-0.044	-0.072	-0.016	< .001	Yes	2010 Tigercat 720 E (173)	2013 Tigercat 720 E (190)
CREW D-CREW B	-0.038	-0.080	0.003	0.094	No	2006 John Deere 643 J (174)	2013 Tigercat 720 E (190)
CREW E-CREW B	-0.019	-0.050	0.012	0.484	No	2014 Tigercat 720 E (190)	2013 Tigercat 720 E (190)
CREW F-CREW B	0.061	0.036	0.094	< .001	Yes	2009 Tigercat 720 B (190)	2013 Tigercat 720 E (190)
CREW D-CREW C	0.006	-0.036	0.048	0.998	No	2006 John Deere 643 J (174)	2010 Tigercat 720 E (173)
CREW E-CREW C	0.025	-0.006	0.056	0.204	No	2014 Tigercat 720 E (190)	2010 Tigercat 720 E (173)
CREW F-CREW C	0.105	0.071	0.139	< .001	Yes	2009 Tigercat 720 B (190)	2010 Tigercat 720 E (173)
CREW E-CREW D	0.019	-0.025	0.063	0.822	No	2014 Tigercat 720 E (190)	2006 John Deere 643 J (174)
CREW F-CREW D	0.099	0.053	0.145	< .001	Yes	2013 Tigercat 720 E (190)	2006 John Deere 643 J (174)
CREW F-CREW E	0.080	0.043	0.117	< .001	Yes	2013 Tigercat 720 E (190)	2013 Tigercat 720 E (190)

Table 8 shows where a statistically significant interaction was also found between merchantability class and crew (p-value <0.001). The merchantability class differences within crew could possibly be attributed to certain crews harvesting predominantly in one merchantability class compared to another. Table 10 shows the number of weeks each crew harvested in the three merchantability classes, while noting the harvest type in which they were operating.

Table 10: Crews' Weekly Data Distribution for Merchantability Class and Harvest Type

Merchantability Class Distribution of Weeks Among Harvest Type- (Cells Represent Weeks)							
	Thinning			Clearcut			
	Pulpwood	Chip-n-saw	Sawtimber	Pulpwood	Chip-n-saw	Sawtimber	Total Weeks
Crew A	61	2	0	1	8	7	79
Crew B	47	16	0	0	14	4	81
Crew C	0	6	0	8	59	4	77
Crew D	0	4	0	0	12	6	22
Crew E	27	2	0	6	14	0	49
Crew F	17	1	3	0	11	5	37
Total Weeks	152	31	3	15	118	26	345

4.4.2.2 Skidding Machines Analysis

Merchantability class yielded a significant effect on fuel consumption (p-value=0.01). The Tukey's pairwise comparison showed that skidding sawtimber size trees consumed 0.03 gal/ton more fuel than pulpwood **(**p-value=0.026). Other comparisons were tested among merchantability class, but they did not yield statistical significance.

Matthes et al. (1988) found that the optimal strategy with regard to fuel consumption would be to operate the skidder at the fastest safe speed to carry as large a load as possible. It might be expected that when skidding sawtimber, the larger load weights resulted in optimal engine output at slower speeds. The smaller load weights for pulpwood could result in faster speeds at optimal engine output. Due to speed limitations for comfort and safety during the loaded portion of the cycle there would be only slight reductions in cycle time for pulpwood. Time in unloaded cycle elements and delay would be similar for both sawtimber and pulpwood cycles with no difference in engine demand. Thus the higher production per cycle for sawtimber would logically have the greatest effect on fuel consumption per unit.

Table 11: Skidding Statistical Significance Chart

Skidding Full Model Statistics					
Significance: Pr(>F) <0.05					
	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
merch class	**2**	**0.031**	**0.015**	**4.64**	**0.01**
crew	**5**	**0.214**	**0.043**	**12.9**	**< .001**
merch class*crew	**8**	**0.057**	**0.007**	**2.14**	**0.032**
Residuals	**340**	**1.126**	**0.003**		
Tukey's pairwise comparison					
	diff	**lwr**	**upr**	**p adj**	
saw-pulpwood	**0.030**	**0.003**	**0.027**	**0.026**	

Similarly to the felling analysis, the crew factor was found significant in the skidding model. (p-value <0.001). A Tukey's pairwise comparison showed that six of the possible fifteen crew comparisons showed significantly different rates of fuel consumption in skidding. Table 12 shows these significant differences. The table also shows machine year, make, and model and notes the manufactured horsepower rating of each engine. Similar to the felling crew differences analysis, little can be said as to what contributes to variation in fuel consumption across the six crews' skidding machines. Possible equipment differences and operator effect are thought to contribute to this variability among crew fuel consumption. However, some noteworthy observations can be made as to the specific machines in the study which influenced the model. Table 12 shows that Crew F operated a skidder that consumed more fuel than any other crew's skidding operations.

Table 12: Skidding Crew Differences- Tukey's Pairwise Comparisons

Skidding Crew Machine Differences							
	Diff (Gal/Ton)	lwr	upr	p adj	Significance	Skidding Machine Comp. with (HP)	
CREW B-CREW A	0.015	-0.011	0.041	0.544	No	2007 John Deere 848 H (200)	2011 John Deere 848H (224)
CREW C-CREW A	0.029	0.002	0.055	0.025	Yes	2002 John Deere 648 G (185)	2011 John Deere 848H (224)
						2006 John Deere 648 G (171)	
CREW D-CREW A	0.019	-0.019	0.059	0.702	No	2008 John Deere 848 H (224)	2011 John Deere 848H (224)
CREW E-CREW A	0.005	-0.024	0.035	0.995	No	2014 Tigercat 630 E (260)	2011 John Deere 848H (224)
CREW F-CREW A	0.078	0.047	0.109	<.001	Yes	2004 Tigercat 630 B (180)	2011 John Deere 848H (224)
CREW C-CREW B	0.013	-0.013	0.040	0.692	No	2002 John Deere 648 G (185)	2007 John Deere 848 H (200)
						2006 John Deere 648 G (171)	
CREW D-CREW B	0.004	-0.035	0.043	1.00	No	2008 John Deere 848 H (224)	2007 John Deere 848 H (200)
CREW E-CREW B	-0.010	-0.040	0.019	0.925	No	2014 Tigercat 630 E (260)	2007 John Deere 848 H (200)
CREW F-CREW B	0.063	0.032	0.094	<.001	Yes	2004 Tigercat 630 B (180)	2007 John Deere 848 H (200)
CREW D-CREW C	-0.009	-0.048	0.030	0.986	No	2008 John Deere 848 H (224)	2002 John Deere 648 G (185)
							2006 John Deere 648 G (171)
CREW E-CREW C	-0.023	-0.053	0.006	0.211	No	2014 Tigercat 630 E (260)	2002 John Deere 648 G (185)
							2006 John Deere 648 G (171)
CREW F-CREW C	0.049	0.018	0.081	<.001	Yes	2004 Tigercat 630 B (180)	2002 John Deere 648 G (185)
							2006 John Deere 648 G (171)
CREW E-CREW D	-0.014	-0.055	0.027	0.921	No	2014 Tigercat 630 E (260)	2008 John Deere 848 H (224)
CREW F-CREW D	0.058	0.016	0.101	0.001	Yes	2004 Tigercat 630 B (180)	2008 John Deere 848 H (224)
CREW F-CREW E	0.073	0.039	0.107	<.001	Yes	2004 Tigercat 630 B (180)	2014 Tigercat 630 E (260)

Similar to the felling model, Table 11 shows where skidding yielded a significant interaction between merchantability class and crew (p-value=0.032). These merchantability class differences within crew could possibly be attributed to certain crews harvesting predominantly in one merchantability class compared to another. Table 10 shows the distribution of the amount of weeks harvested in each merchantability class by each crew while noting the harvest type.

4.4.2.3 Loading Machines Analysis

An AOV test for the loading operation class was also conducted and the statistical output can be found in Table 13. Average merchantability class yielded a statistically significant effect on fuel consumption (p-value<0.001). A Tukey's pairwise comparison showed that loading sawtimber size material consumed 0.04 gal/ton greater fuel than loading chip-n-saw material (p-value<0.001). Another pairwise comparison showed that loading sawtimber size material used 0.044 gal/ton greater fuel than loading pulpwood material (p-value<0.001). Fuel consumption is higher for the sawtimber class because more handling is needed when the trees are larger since more processing, bucking and product sorting is required.

Table 13: Loading Statistical Significance Chart

Loading Full Model Significance					
Significance: Pr(>F) <0.05					
	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
merch class	**2**	**0.051**	**0.025**	**25.4**	**< .001**
Crew	**5**	**0.374**	**0.075**	**74.8**	**< .001**
merch class*crew	**8**	**0.057**	**0.007**	**7.07**	**< .001**
Residuals	**338**	**0.338**	**0.001**		
Tukey's pairwise comparison					
	diff	**lwr**	**Upr**	**p adj**	
saw-chip n saw	**0.044**	**0.029**	**0.059**	**< .001**	
saw-pulpwood	**0.041**	**0.027**	**0.056**	**< .001**	

The crew factor was determined to have a statistically significant effect on fuel consumption (p-value <0.001). Table 18 shows Tukey's pairwise comparisons highlighting significant differences in crew fuel consumption among different crews' loaders. Of the fifteen possible comparisons among crews, twelve comparisons were determined to have significantly different rates of fuel consumption. The table notes the type, make, and model of loaders while also noting the manufactured horsepower rating of the machine’s engine.

Differences in engine technology could lead to some differences in fuel consumption. For example, Crew B's loader was the oldest of all the loaders in the study, and it was recorded that Crew B fuel consumption was significantly greater than that of the newer machines used by the five other crews. Technological advances are thought to have led to less fuel consumption for all other loaders in the study.

Table 14: Loading Crew Differences- Tukey's Pairwise Comparisons

Loading Crew Differences							
	Diff (Gal/Ton)	lwr	upr	p adj	Significance	Loading Machine Comp. with (HP)	
CREW B-CREW A	0.071	0.056	0.085	< .001	Yes	2011 CAT 529 (156)	2012 John Deere 437 D (173)
CREW C-CREW A	-0.008	-0.023	0.006	0.573	No	2012 John Deere 437 D (173)	2012 John Deere 437 D (173)
CREW D-CREW A	0.049	0.027	0.070	< .001	Yes	2014 John Deere 437 D (173)	2012 John Deere 437 D (173)
CREW E-CREW A	-0.012	-0.028	0.00	0.311	No	2010 Tigercat 234 (173)	2012 John Deere 437 D (173)
CREW F-CREW A	0.021	0.004	0.038	0.007	Yes	2013 Tigercat 234 (173)	2012 John Deere 437 D (173)
CREW C-CREW B	-0.079	-0.093	-0.065	< .001	Yes	2012 John Deere 437 D (173)	2011 CAT 529 (156)
CREW D-CREW B	-0.022	-0.044	-0.001	0.042	Yes	2014 John Deere 437 D (173)	2011 CAT 529 (156)
CREW E-CREW B	-0.082	-0.098	-0.067	< .001	Yes	2010 Tigercat 234 (173)	2011 CAT 529 (156)
CREW F-CREW B	-0.050	-0.067	-0.032	< .001	Yes	2013 Tigercat 234 (173)	2011 CAT 529 (156)
CREW D-CREW C	0.057	0.035	0.079	< .001	Yes	2014 John Deere 437 D (173)	2012 John Deere 437 D (173)
CREW E-CREW C	-0.003	-0.020	0.013	0.992	No	2010 Tigercat 234 (173)	2012 John Deere 437 D (173)
CREW F-CREW C	0.029	0.012	0.047	< .001	Yes	2013 Tigercat 234 (173)	2012 John Deere 437 D (173)
CREW E-CREW D	-0.060	-0.083	-0.037	< .001	Yes	2010 Tigercat 234 (173)	2014 John Deere 437 D (173)
CREW F-CREW D	-0.027	-0.051	-0.004	0.014	Yes	2013 Tigercat 234 (173)	2014 John Deere 437 D (173)
CREW F-CREW E	0.033	0.014	0.052	< .001	Yes	2013 Tigercat 234 (173)	2010 Tigercat 234 (173)

Table 13 shows where loading yielded a significant interaction between merchantability class and crew (p-value <0.001). These merchantability class differences within crew could possibly be attributed to certain crews harvesting predominantly in one merchantability class compared to another. Table 10 shows how a low sample of weeks spent harvesting in sawtimber size trees could have influenced the loading model.

4.5 Evaluating and Comparing Findings with Other Research

Figure 21 shows the differences in fuel consumption for the summarized literature review data and the survey data. The literature data was converted from l/m^3 to gal/ton using a conversion of 56 lb per cubic foot of solid wood for loblolly pine solid wood and bark (Dicke and Parker 2013) yielding 0.99 tons per cubic meter.

Differences in fuel consumption were noticed for the feller-buncher and grapple skidder, while loader fuel consumption was quite similar. The relationships can possibly be explained by the differences in equipment models and years. Most of the equipment from the literature review data contained equipment models from the 1980's and early 1990's year models, while the oldest machine in the weekly surveyed data was from 2004. Also, when evaluating the fuel consumption differences from the literature review and this study, it can be seen that some of the difference in skidders could be because the skidders in the survey study were larger than the skidders in the literature review study. Additionally, when evaluating feller-bunchers, it can be seen that the feller-bunchers in the survey study were more productive than those contained in the literature review study. This could be because newer harvesting machines are more productive than those from thirty years ago.

Loading machine comparison showed a similar rate of fuel consumption. However, loaders in the literature review mostly just loaded wood and did little delimbing and merchandising. In contrast, the loaders in this logger survey were loading as well as delimbing and merchandising. The fact that the studies showed similar fuel consumption shows that new loaders can do multiple functions that older loaders were not equipped to do while consuming similar amounts of fuel.

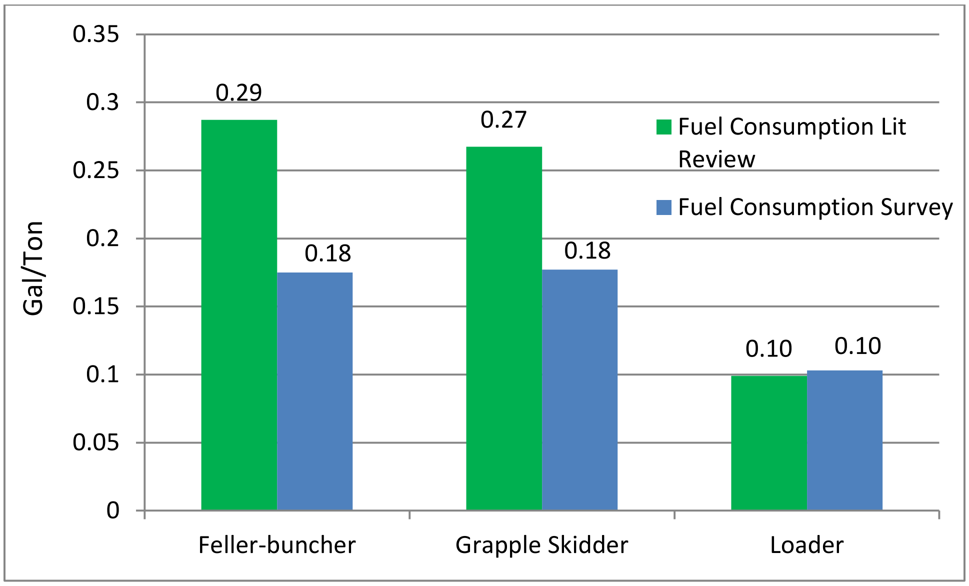

Figure 21: Literature Review vs. Survey Study- Machine Fuel Consumption Comparison

Compared to a study conducted by Baker et al. (2014b) that measured fuel consumption in feller-bunchers, skidders, and loaders, this study showed slightly greater fuel consumption in all three machine types (Figure 22). The Baker et al. study occurred in high production flat ground areas in the Coastal Plain. Baker et al.) also noted that the conditions of the harvests in the study were under "ideal logging conditions". The slightly higher fuel consumption numbers in this survey study could possibly be explained by operations in less than ideal conditions over a variety of tracts. This survey study allows for a look at fuel consumption in some of the more generalized logging conditions.

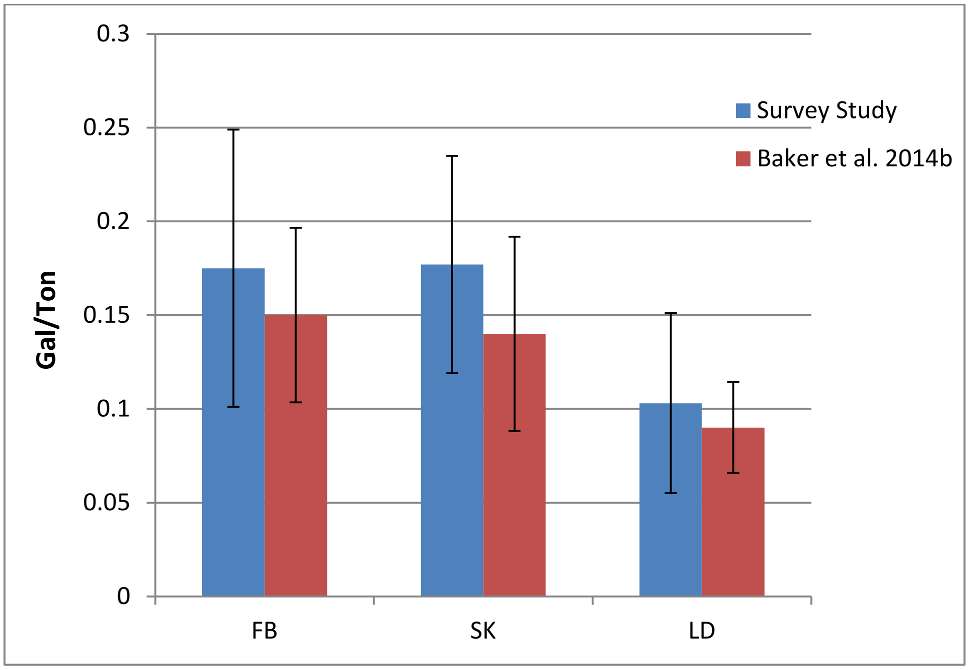

Figure 22: Comparing Two Study's Fuel Consumption between 3 Harvesting Machines

4.6 Evaluating the weekly fluctuations within the data

Fuel consumption was measured by using both gallons of fuel per week while noting the tons of wood harvested each week. Due to the way data was received on a weekly basis in the study, it can be noted that fuel consumption (in gal/ton) is greatly affected by the time that the wood arrives at the mill. For example, fuel is assumed to always be recorded for the day that it is used; however, the amount of wood harvested during that same time period is assumed to fluctuate in the time that it arrives at the mill. This could be because sometimes there are wood hold-overs at the mill. This could lead to an abundance of wood that has been harvested yet not accounted for in tons, which could portray misleading weekly fuel consumption. This occurrence is thought to lead to drastic dips and spikes in the overall weekly fuel consumption. Fuel reporting can show the same variability when an operator decides to fuel up at the beginning of the week rather than the end of the week. Graphs illustrating the weekly fuel consumption for each harvesting machine are provided in the appendix.

V. Conclusion

A literature review showed that ground based treelength logging systems can average 0.66 gal/ton fuel consumption where feller-bunchers consume 0.29 gal/ton, grapple skidders consume 0.27, and loaders use 0.10 gal/ton. These fuel consumption estimates are expected to be higher than normal, since a good portion of the machine models were from the 1980's and 1990's.

The tract data showed an average fuel consumption of 0.65 gal/ton for ground based treelength logging systems due to the presence of mainly older machines harvesting in somewhat different logging conditions than the weekly data crews. Crews in the tract data had relatively older machines from the 1990's to early 2000's year models. Crews also operated in a variety of different harvesting conditions. The tract data fuel consumption accounted for over 48,000 harvested tons of wood.

A fuel consumption study was completed by collecting weekly fuel consumption data across six logging crews operating with modern in-woods treelength logging systems within the Southeastern United States. The study found that they consumed approximately 0.509 (±0.013, 90% CI) gal/ton. Feller-bunchers consume approximately 0.175 (±0.006, 90% CI) gal/ton, while skidders use approximately 0.177 (±0.005, 90% CI) gal/ton, and loaders consume approximately 0.103 (±0.004, 90% CI) gal/ton. Additional fuel consumption can be accounted for by other miscellaneous equipment such as chain flail delimbers, in-woods transport trucks, and in-woods processing machines. Only in-woods fuel consumption was measured; this study did not account for fuel consumed during transportation of equipment and personnel to harvesting locations.

Due to a large sample of weeks and detailed survey response coming from the weekly fuel consumption study, a statistical analysis was completed to evaluate various factors' effect on fuel consumption. There was not enough data to determine the effect of slope and soil moisture on fuel consumption. In almost all harvesting equipment types (feller-buncher, skidder, and loader), there was found to be a significant difference in the rate of fuel consumption among different crews. From these findings, it could be that operator error, technical machine differences, system bottlenecks, or processing/sorting options led to different rates of fuel consumption. Of the three harvesting classes (felling, skidding, and loading) evaluated in the survey study, loading showed the most statistically significant difference in fuel consumption among crews. This was due to the technological advances in some of the newer loader compared to older loaders.

Average merchantability class of the harvested trees also showed statistical significance among felling, skidding, and loading. Using Tukey’s pairwise comparisons, it was found that harvesting pulpwood size trees with a feller-buncher used more fuel compared to harvesting chip-n-saw and sawtimber size trees. However, skidding larger diameter sawtimber trees used more fuel compared to skidding pulpwood size trees. Also, loading both chip-n-saw and sawtimber size trees used more fuel than loading pulpwood size trees.

When evaluating the logging crews' fuel consumption as a whole (felling, skidding, loading, and added miscellaneous equipment), harvest type showed statistical significance. It was seen that crew fuel consumption in thinnings was 0.03 gal/ton more than in clearcuts, which was statistically significant. Harvest type did not show any statistical significance in rate of fuel consumption in neither skidding nor loading, but did show some statistical significance in the more fuel than harvesting with a feller-buncher in clearcuts.

It is also important to note the possible confounding factors that occurred in the model among merchantability class and harvest type. As seen in Table 10, all crews did not operate in every merchantability class. Only 23 weeks submitted in the study occurred while harvesting in the sawtimber size category, with only 2 of those weeks occurring in thinnings. Only 14 weeks were spent operating in clearcuts with an average pulpwood size tree. It is also important to see that the majority of thinnings (152 weeks) were completed harvesting pulpwood size trees, while the majority of clearcuts (133 weeks) were done harvesting chip-n-saw size trees.

While data did not statistically show that slope or soil moisture have an effect on fuel consumption in logging, a future study that involves more detailed information about slope variation within a tract would be helpful. Also, evaluating skidder travel within a stand across or along slopes could be helpful in understanding more about the effects slope can have on fuel consumption. Soil moisture could also be measured in a more detailed manner to show variation along topographical sectors within a tract and how fuel consumption can differ between harvesting the wetter areas and dry areas. Due to the subjective manner of measuring both slope and soil moisture, it could also benefit to have one method or one person to evaluate each variable in order to remove some of that subjectivity.

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VII. Appendix

Crew name ____________________________ (will be kept confidential) State _______

Tract info: ______ acres **type cut:** _____partial _____clearcut

Please circle one **species**: mostly softwood mostly hardwood mix

on each of **slope**: 0% 0-15% 16-35% greater than 35%

these 3 lines: **moisture** : dry moist wet

Average diameter (inches) ______ Range of diameter___________ (such as 5" to 11")

Equipment info:

Type*		Year, Make and Model	Fuel Use**
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
____________	______	_____________________________________	_______
		System	_______

Total Volume __________ Product types (percentages must add up to 100%)

Circle one: tons Bolts______

MBF Chips_______

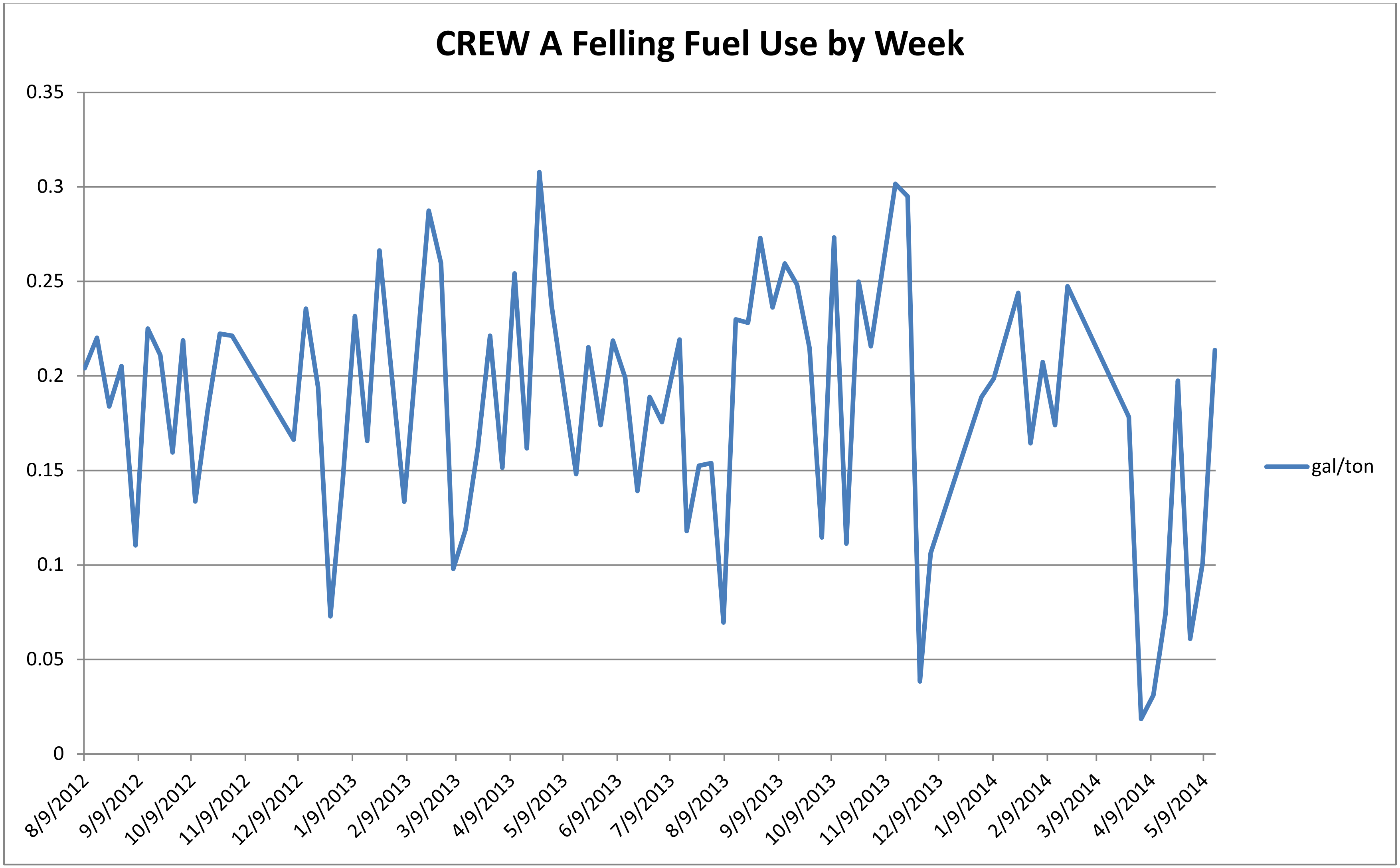
cords Pulpwood________

other ________ Sawtimber_________

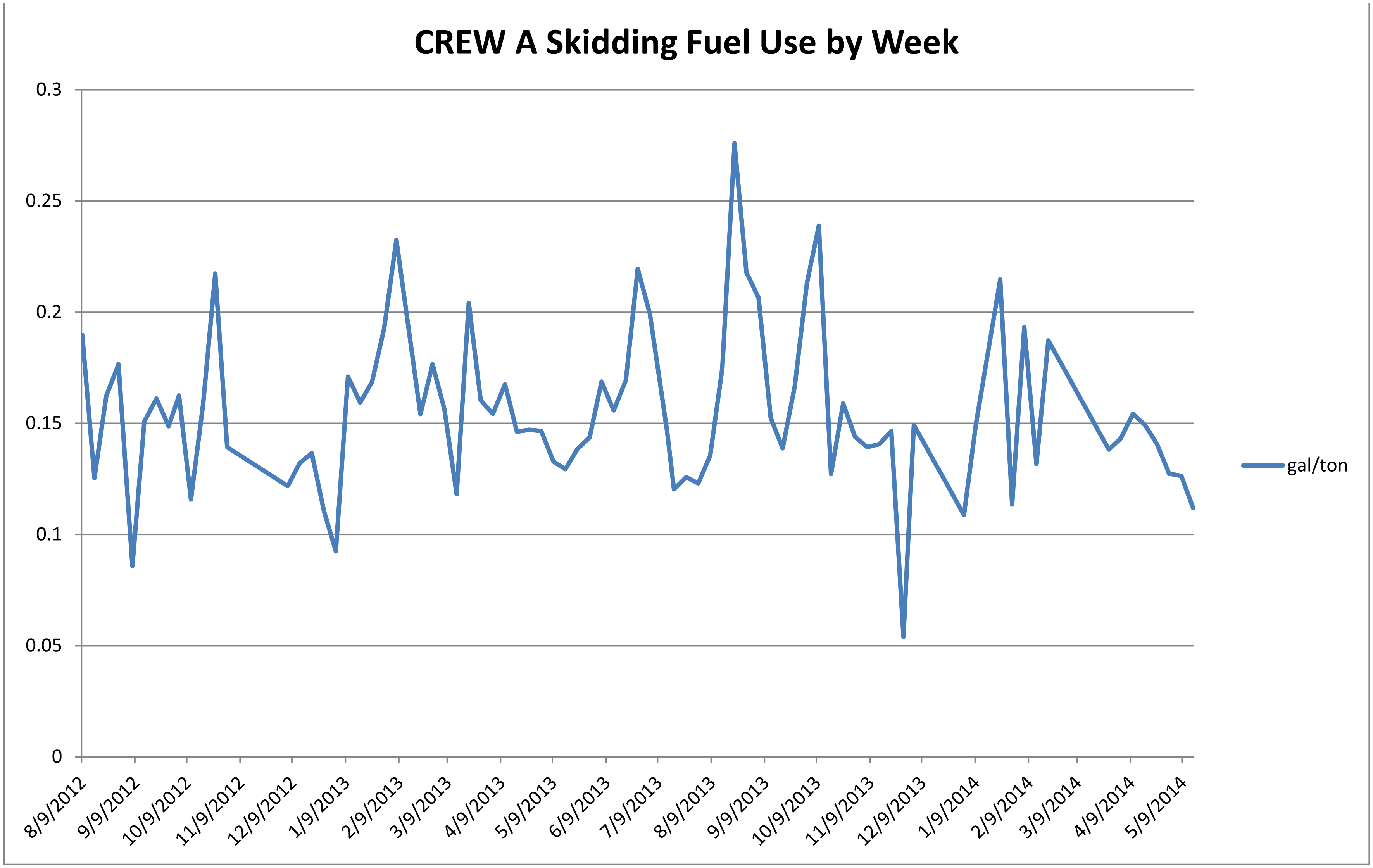
*type: list feller-buncher (FB), skidder (SK), knuckleboom loader (KL), processor (PR) ,chipper (CH), harvester (HA), forwarder (FW) or other (please give me a hint).

**fuel use: provide gallons consumed for individual machines if possible, or just list total system use on line at bottom

Chart 1: Logger Survey Form

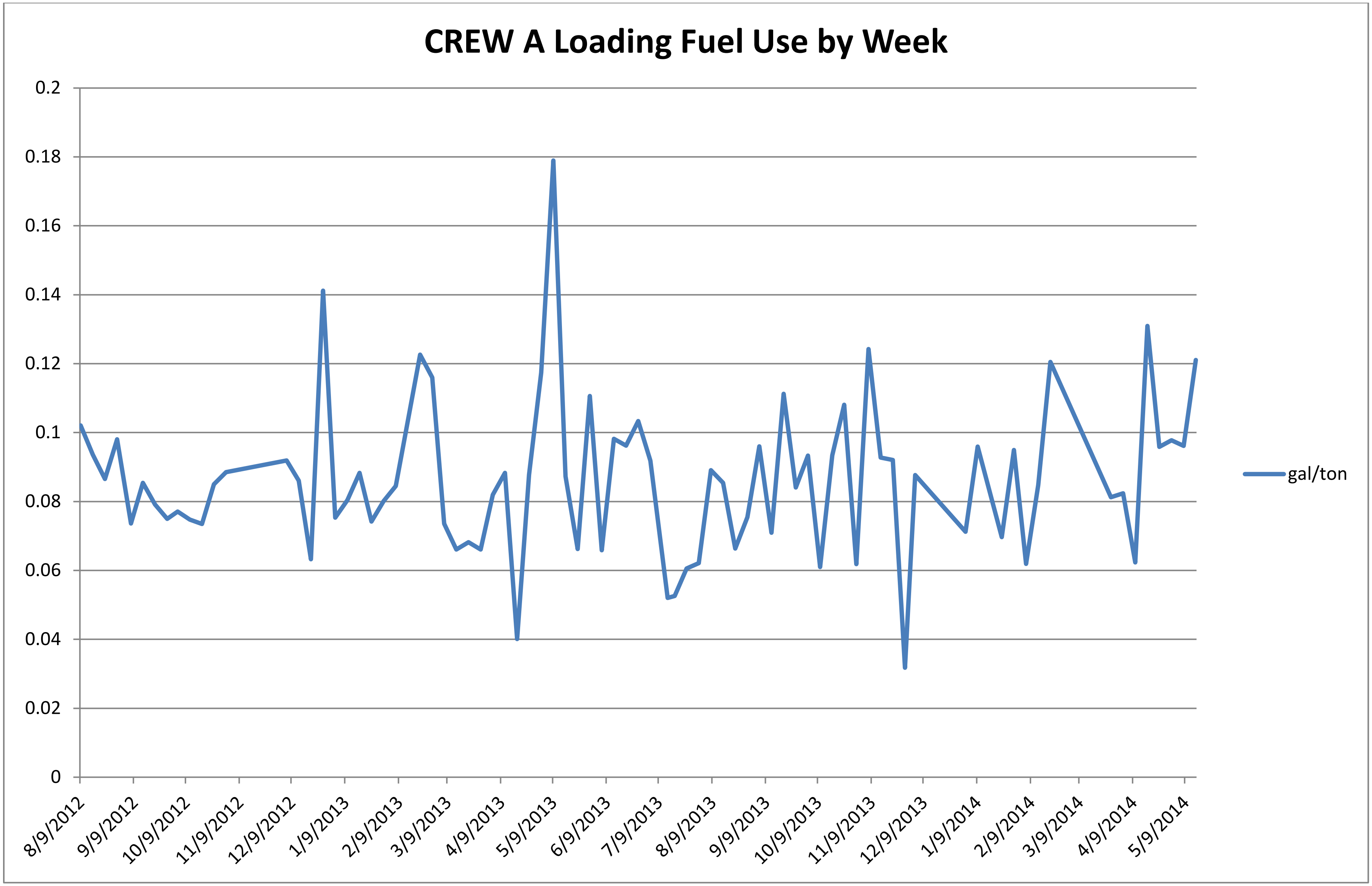


CREW A Felling Fuel Consumption by Week

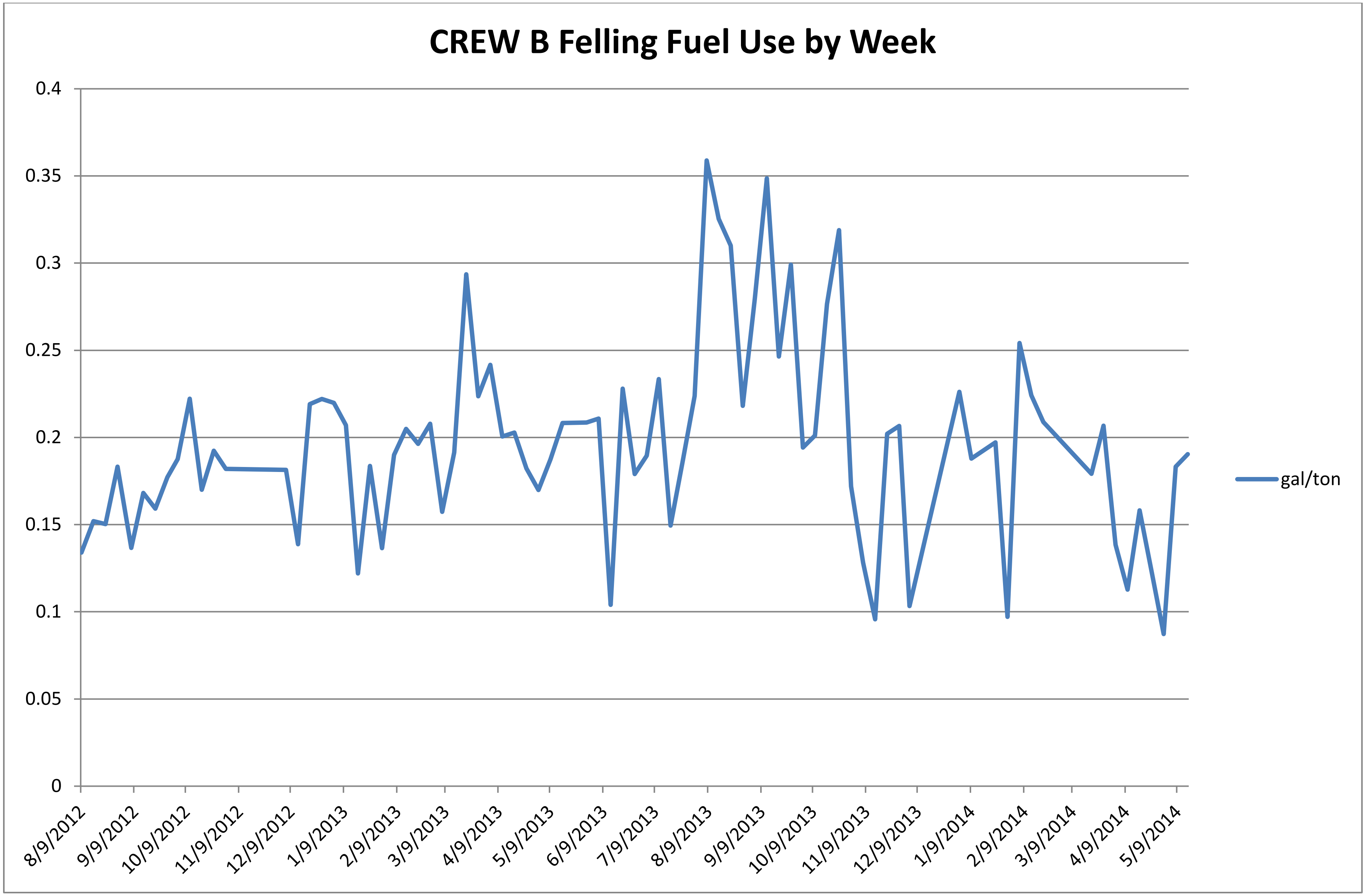


CREW A Skidding Fuel Consumption by Crew

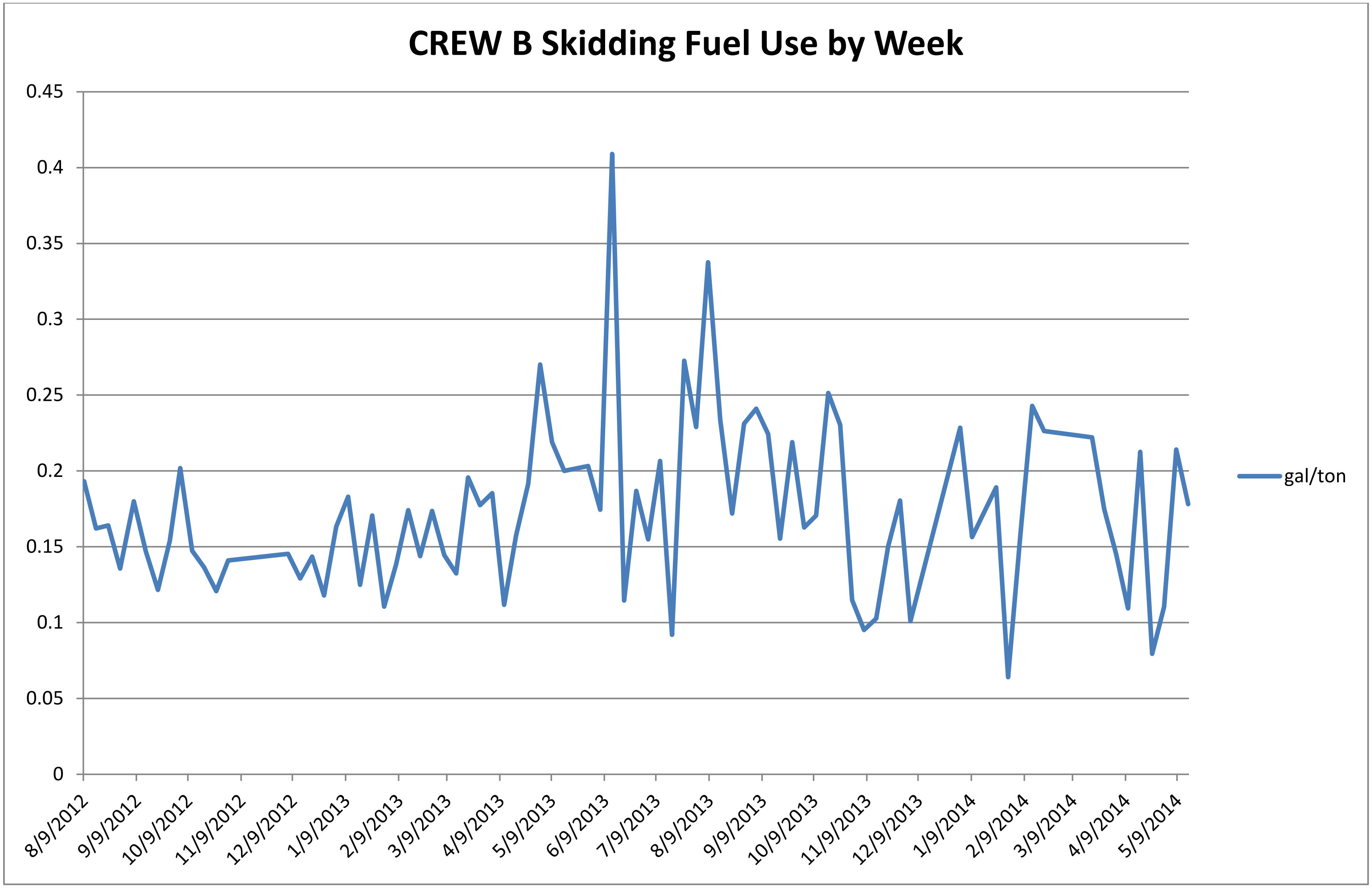
69



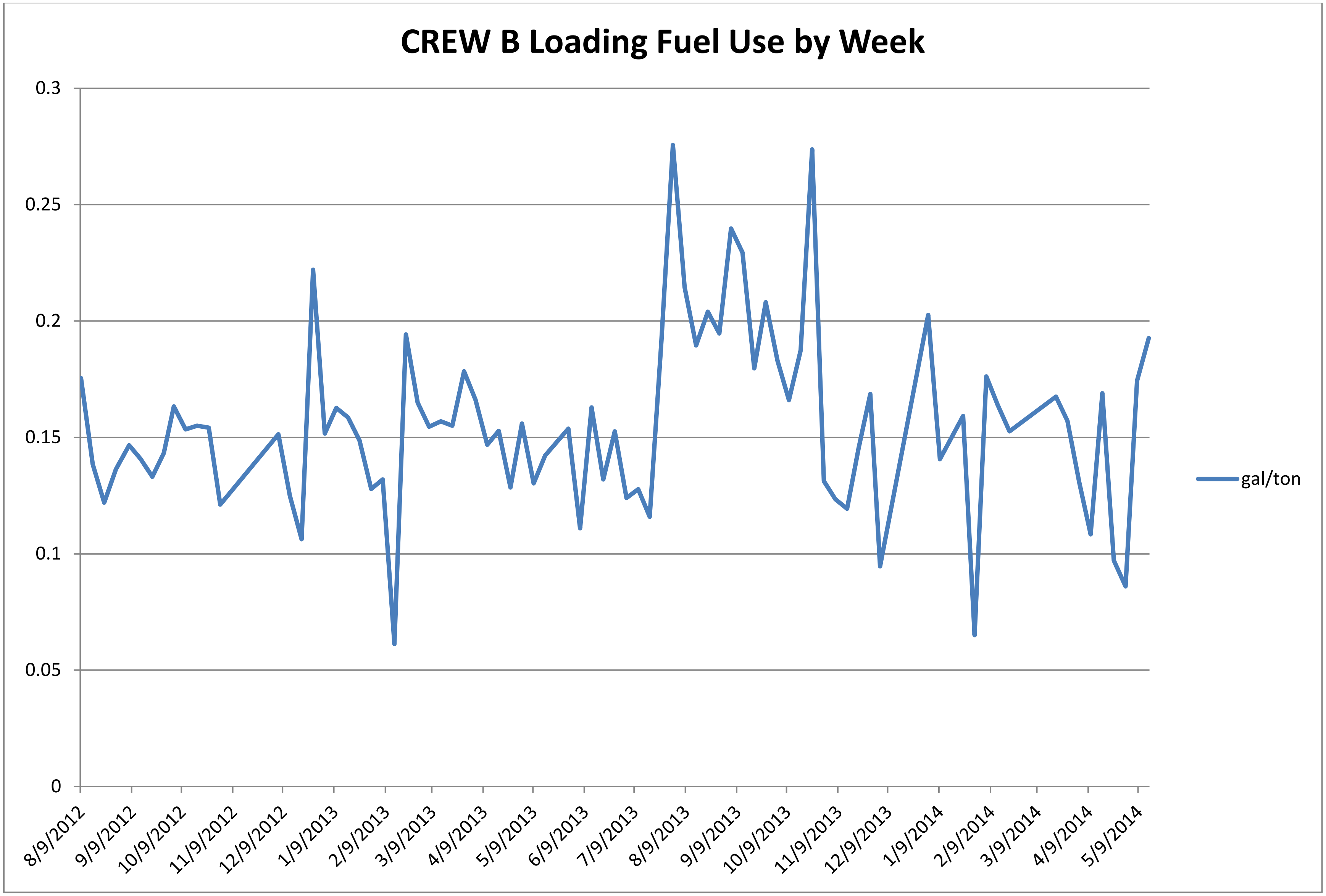
CREW A Loading Fuel Consumption by Week



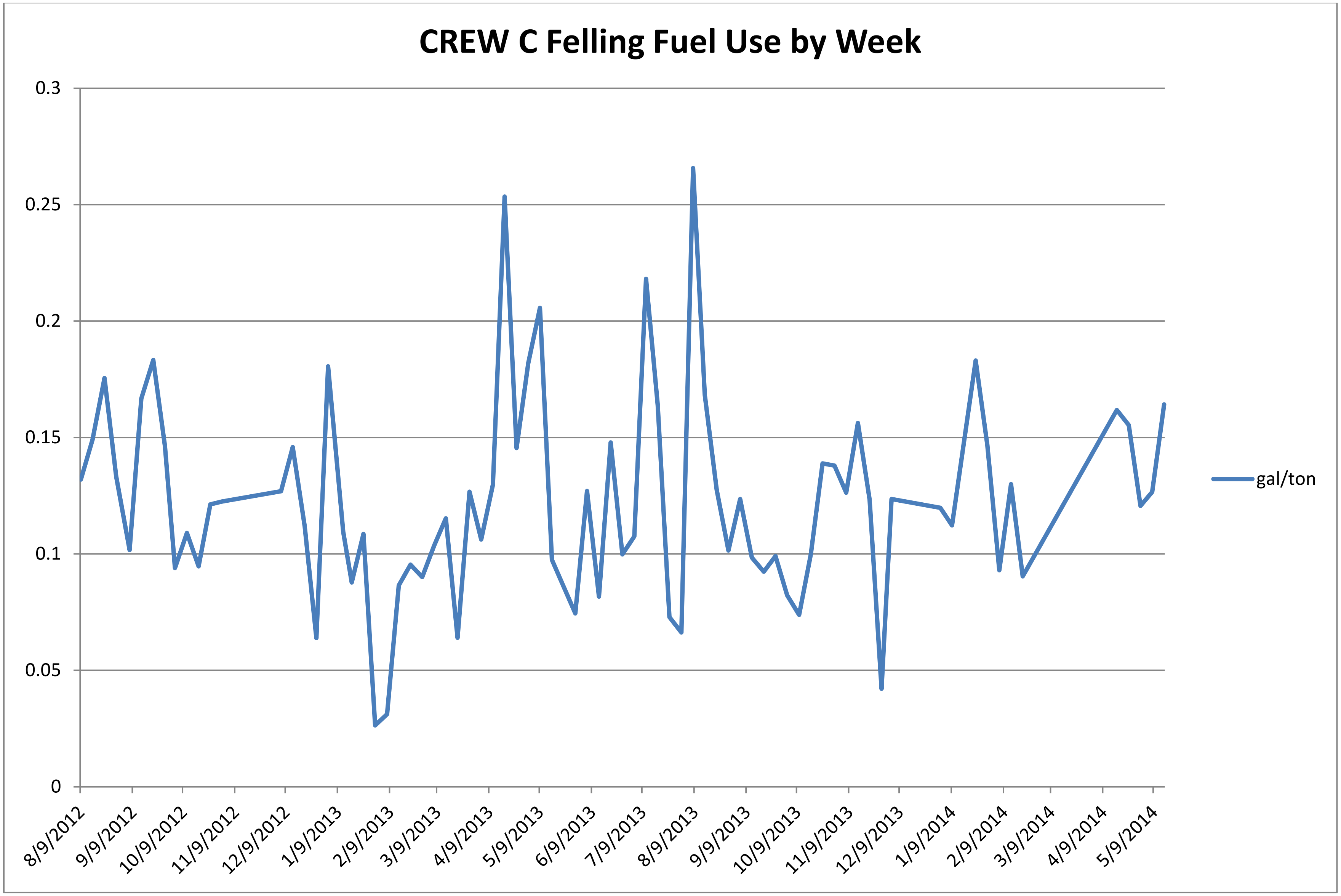
CREW B Felling Fuel Consumption by Week



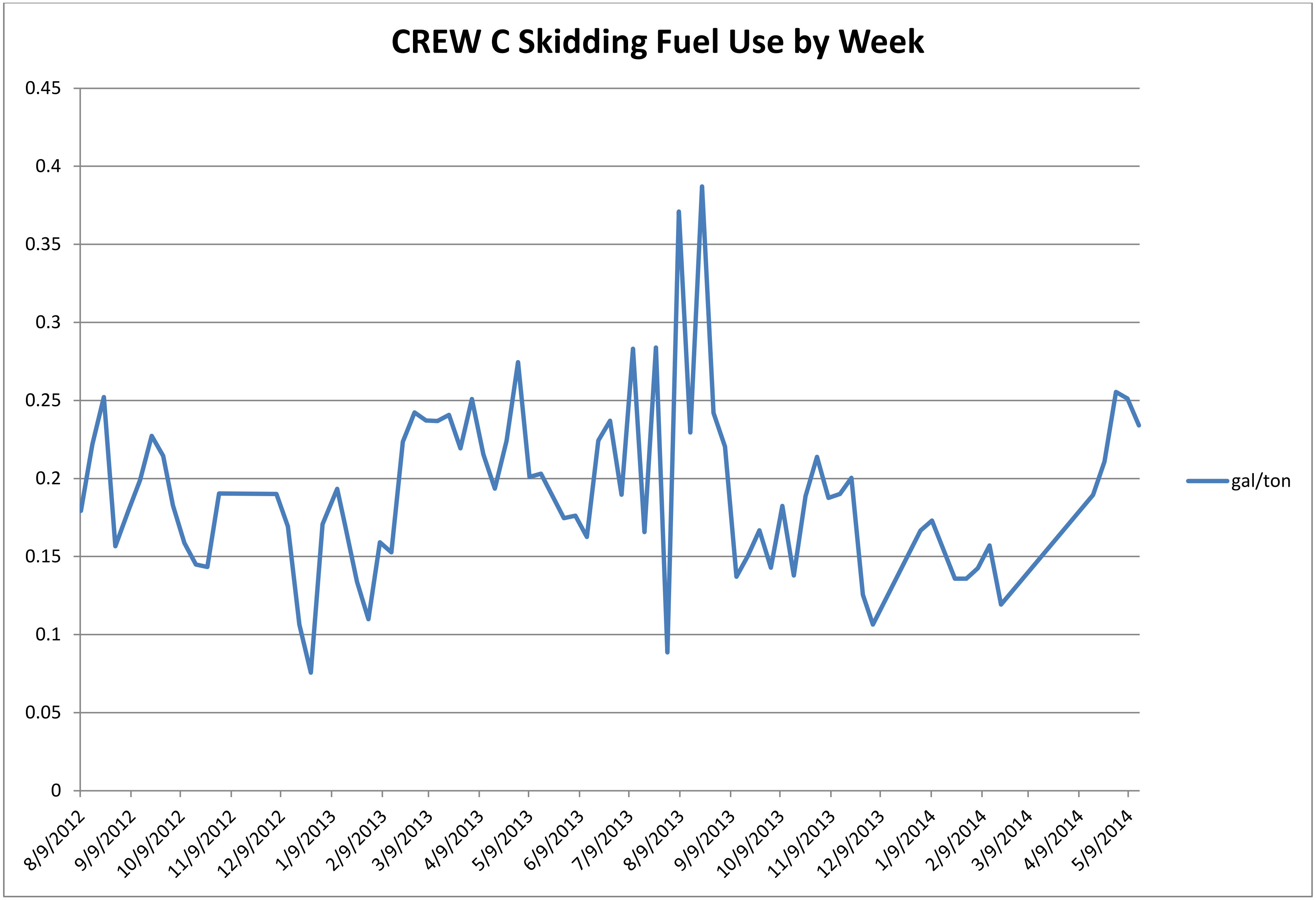
CREW B Skidding Fuel Consumption by Week



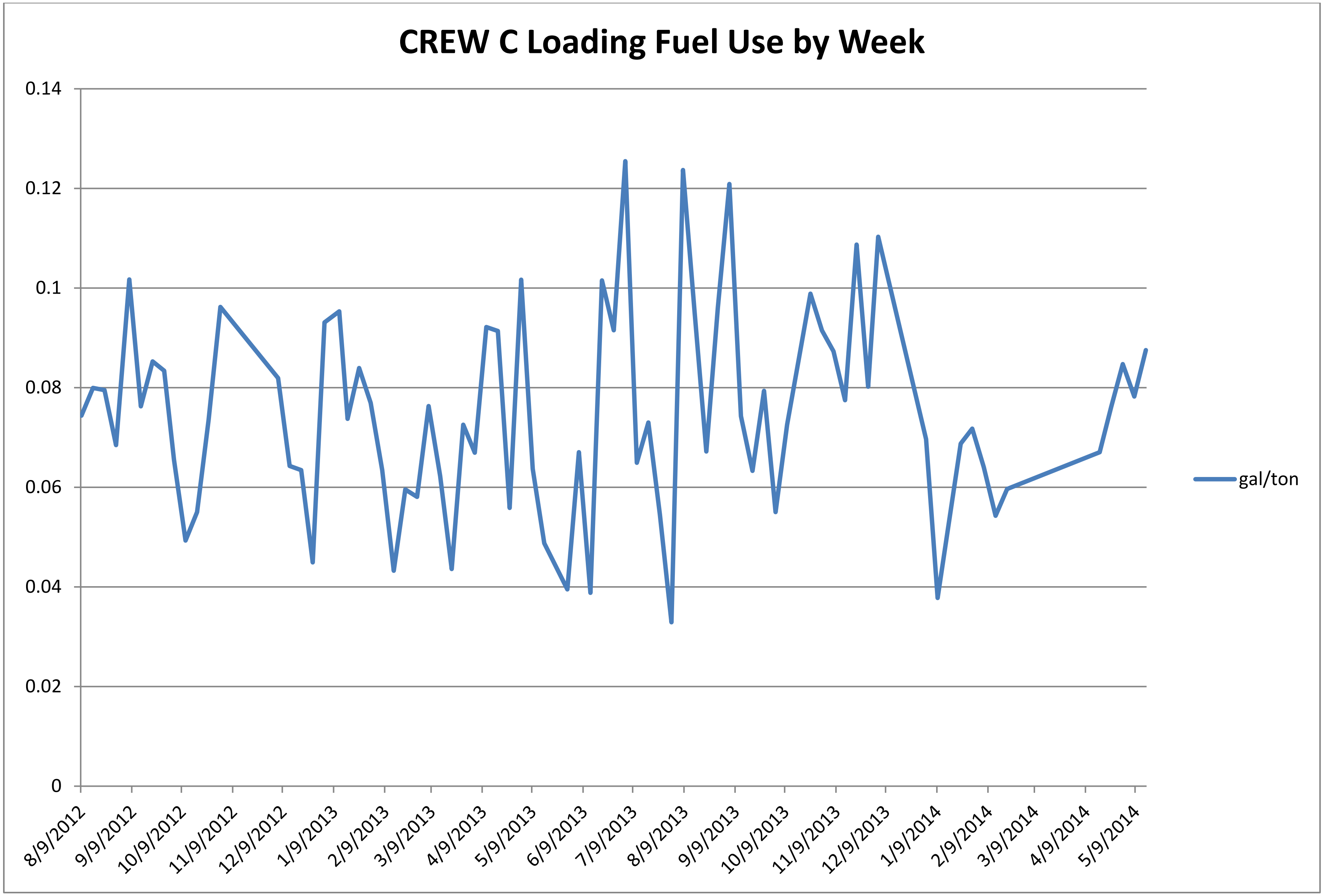
CREW B Loading Fuel Consumption by Week



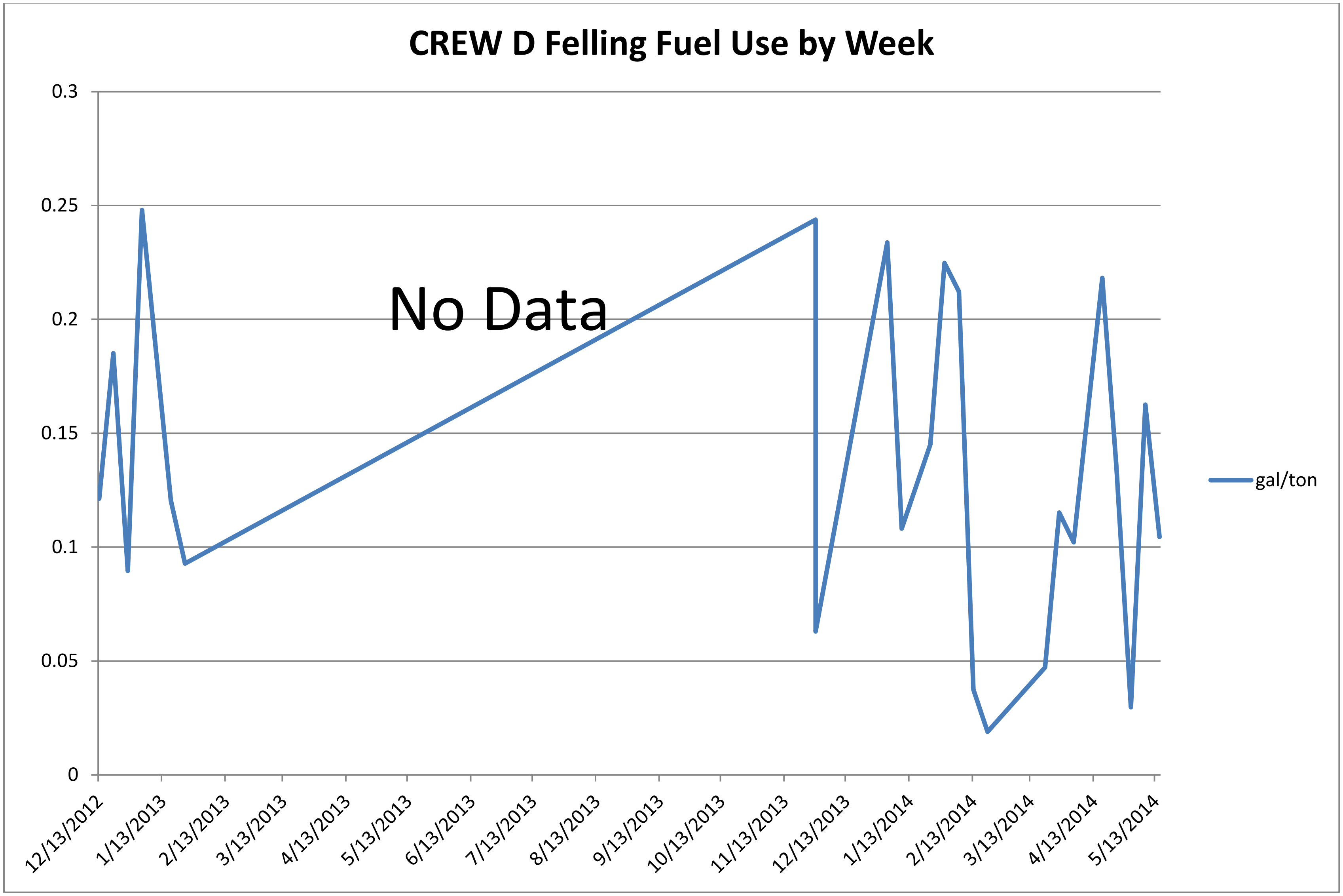
CREW C Felling Fuel Consumption by Week



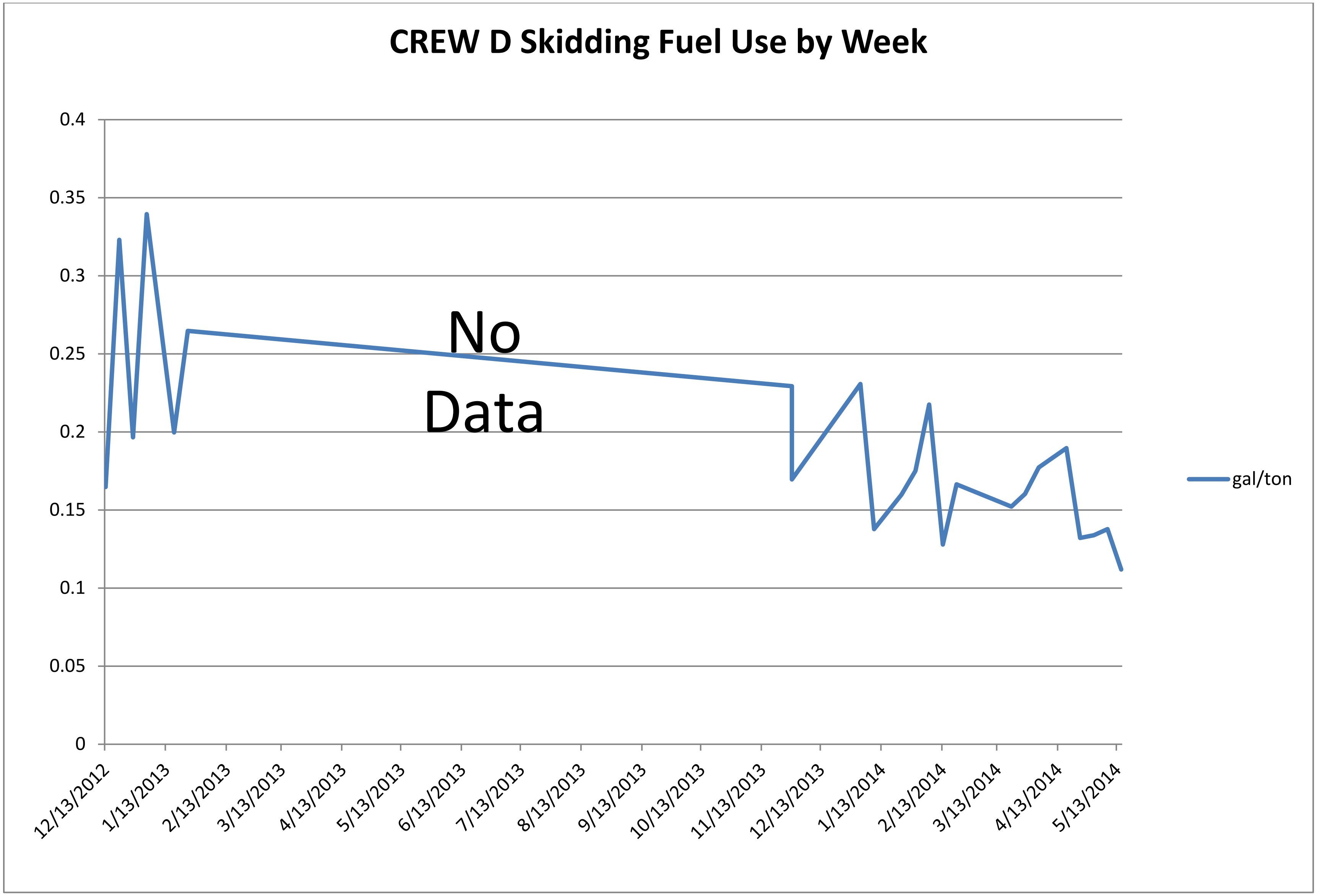
CREW C Skidding Fuel Consumption by Week



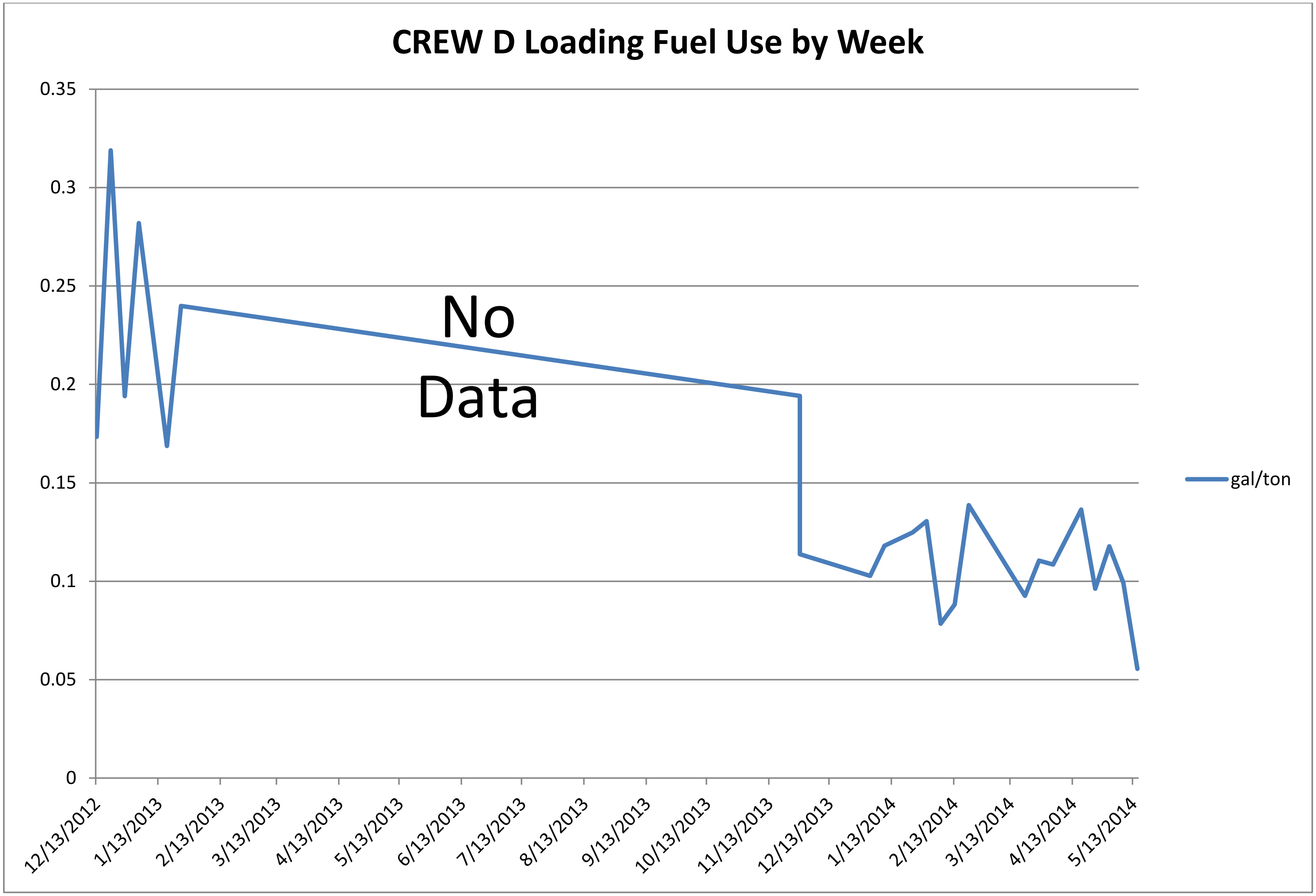
CREW C Loading Fuel Consumption by Week



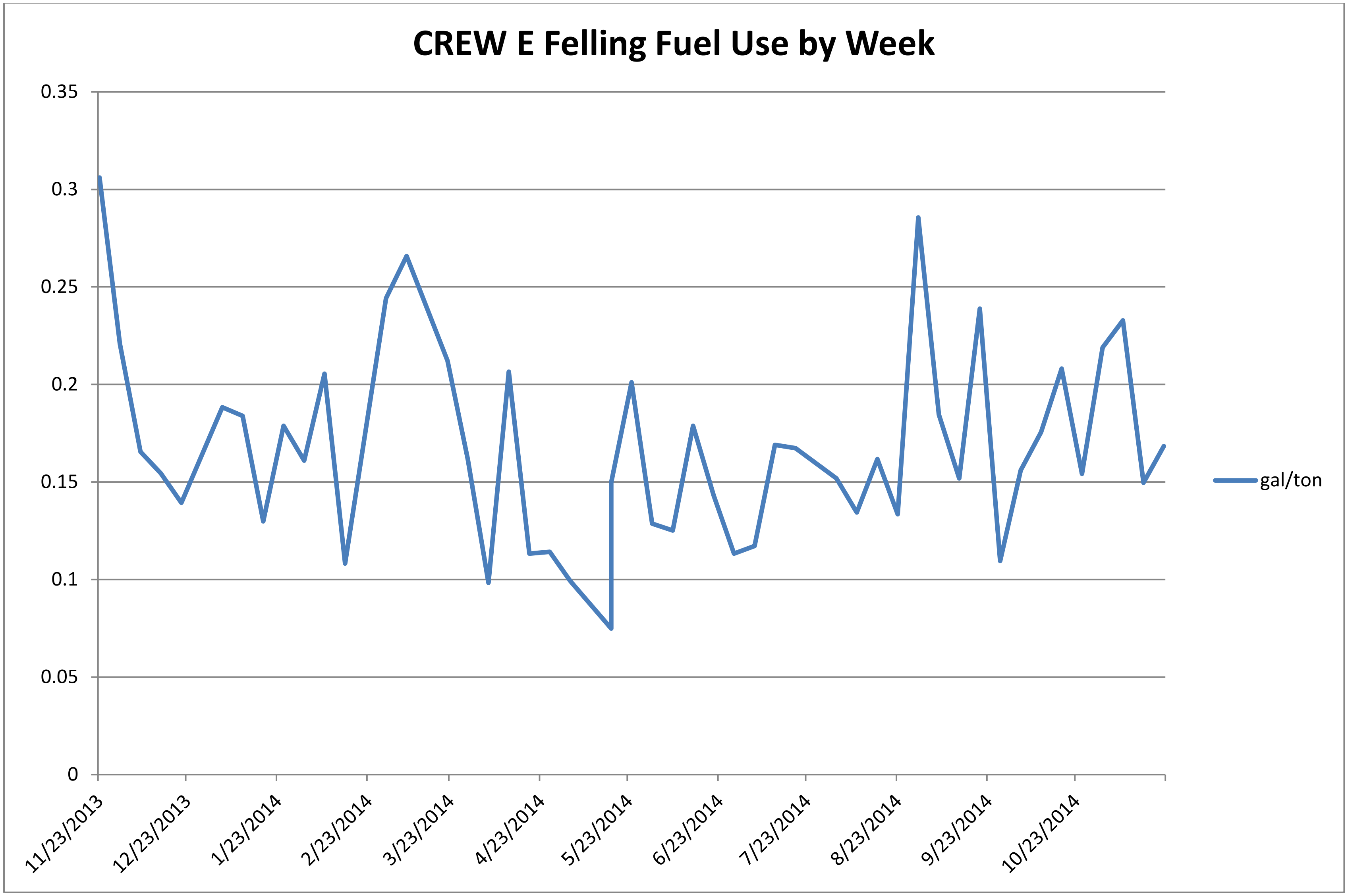
CREW D Felling Fuel Consumption by Week



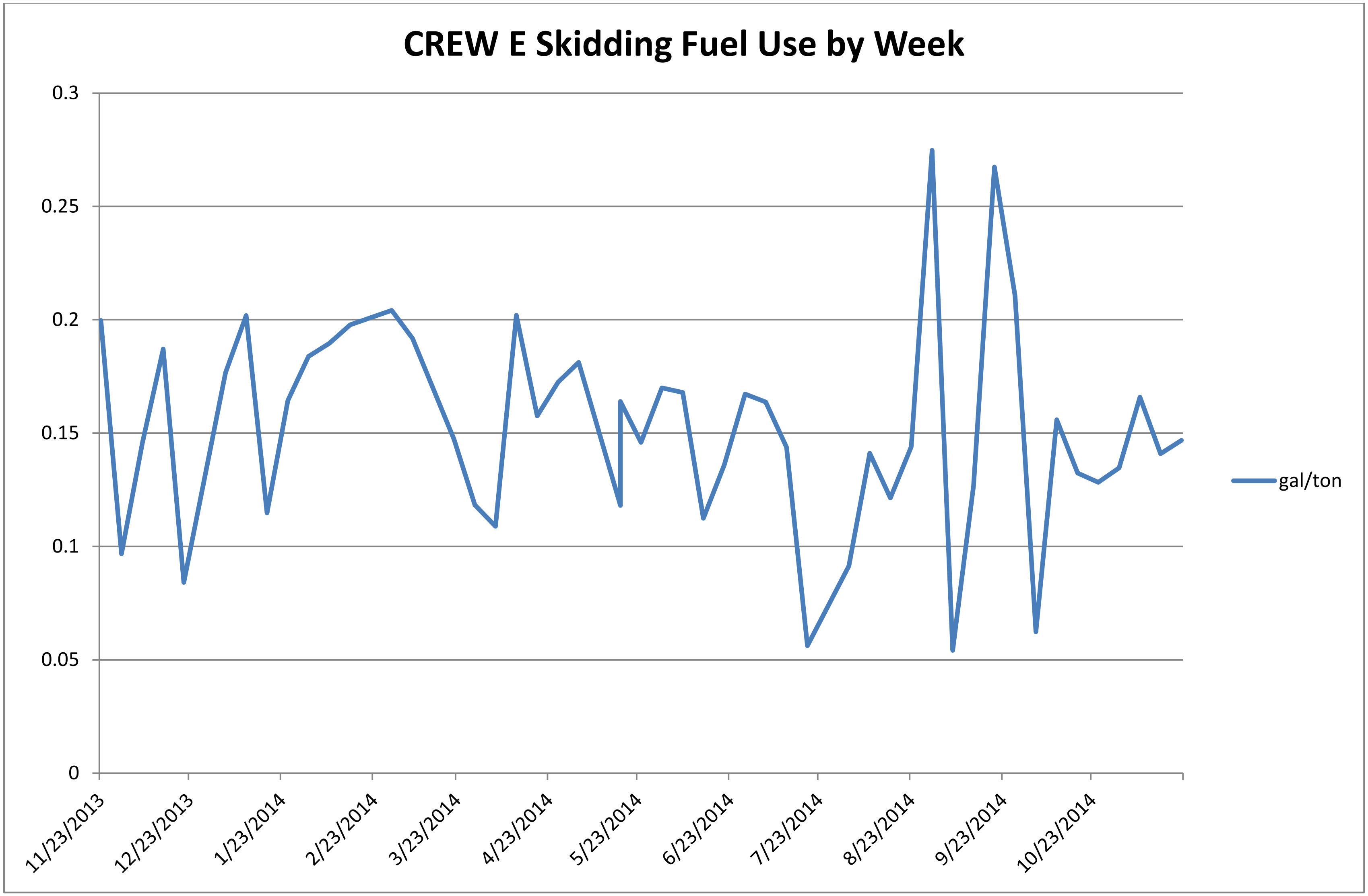
CREW D Skidding Fuel Consumption by Week



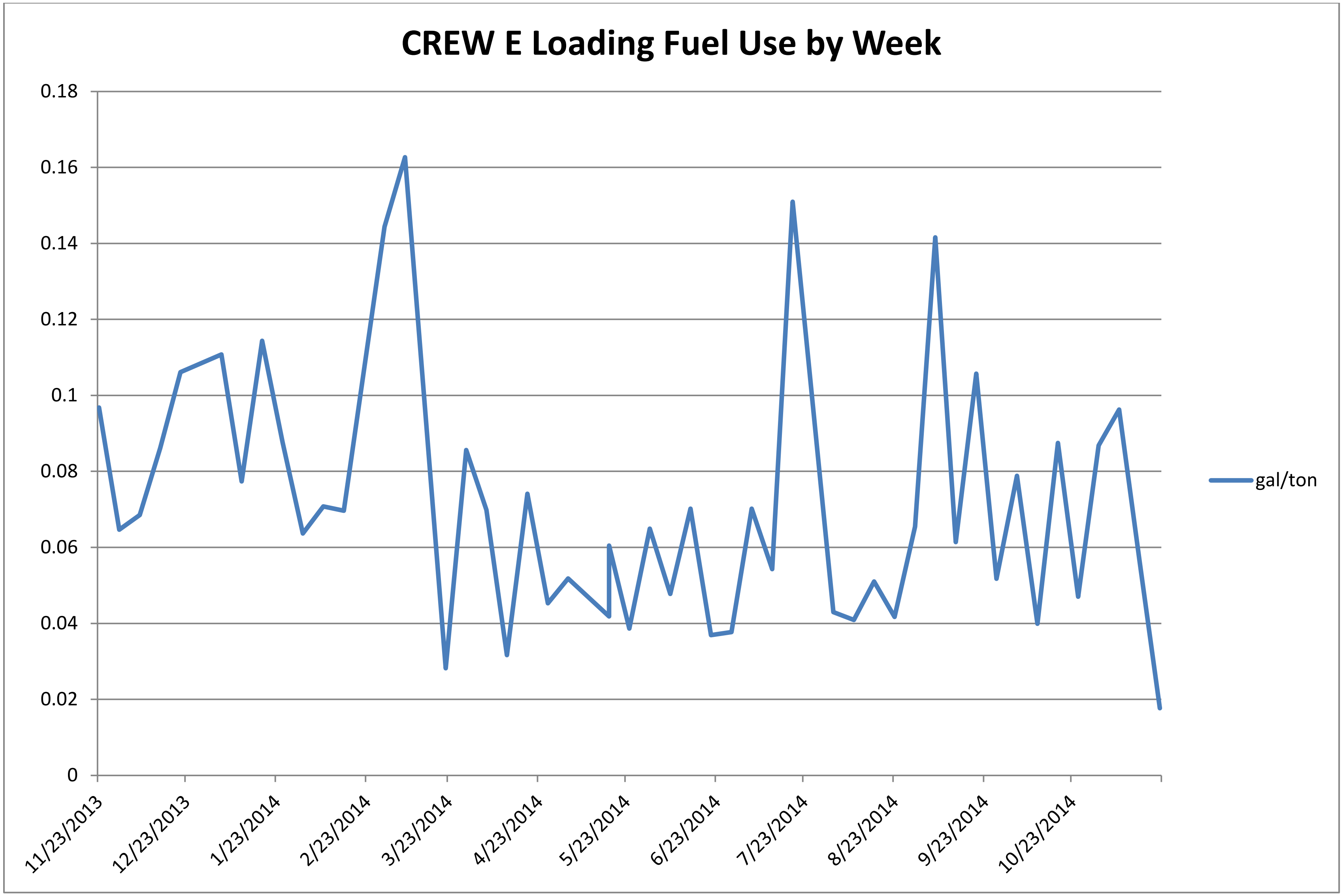
CREW D Loading Fuel Consumption by Week



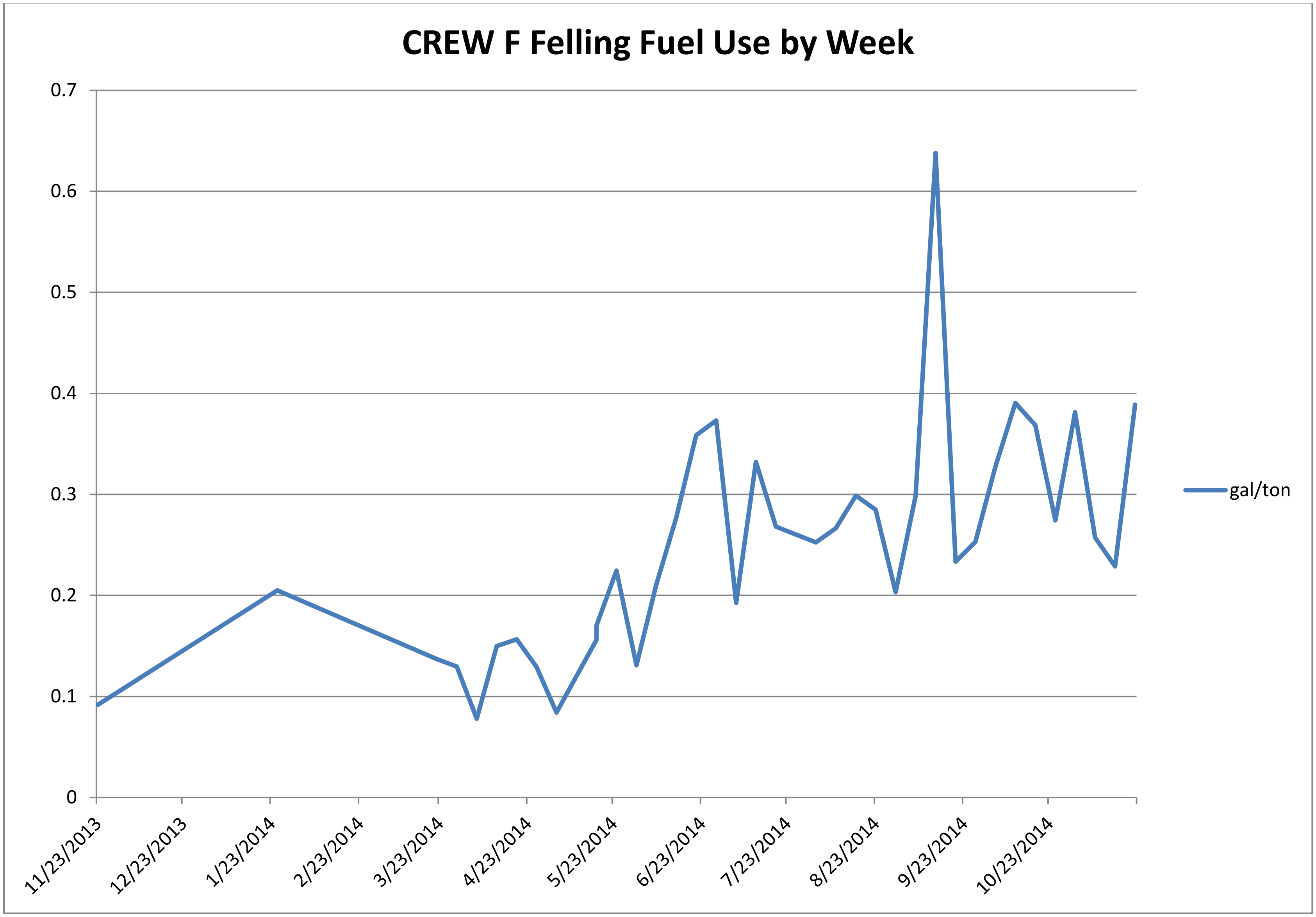
CREW E Felling Fuel Consumption by Week



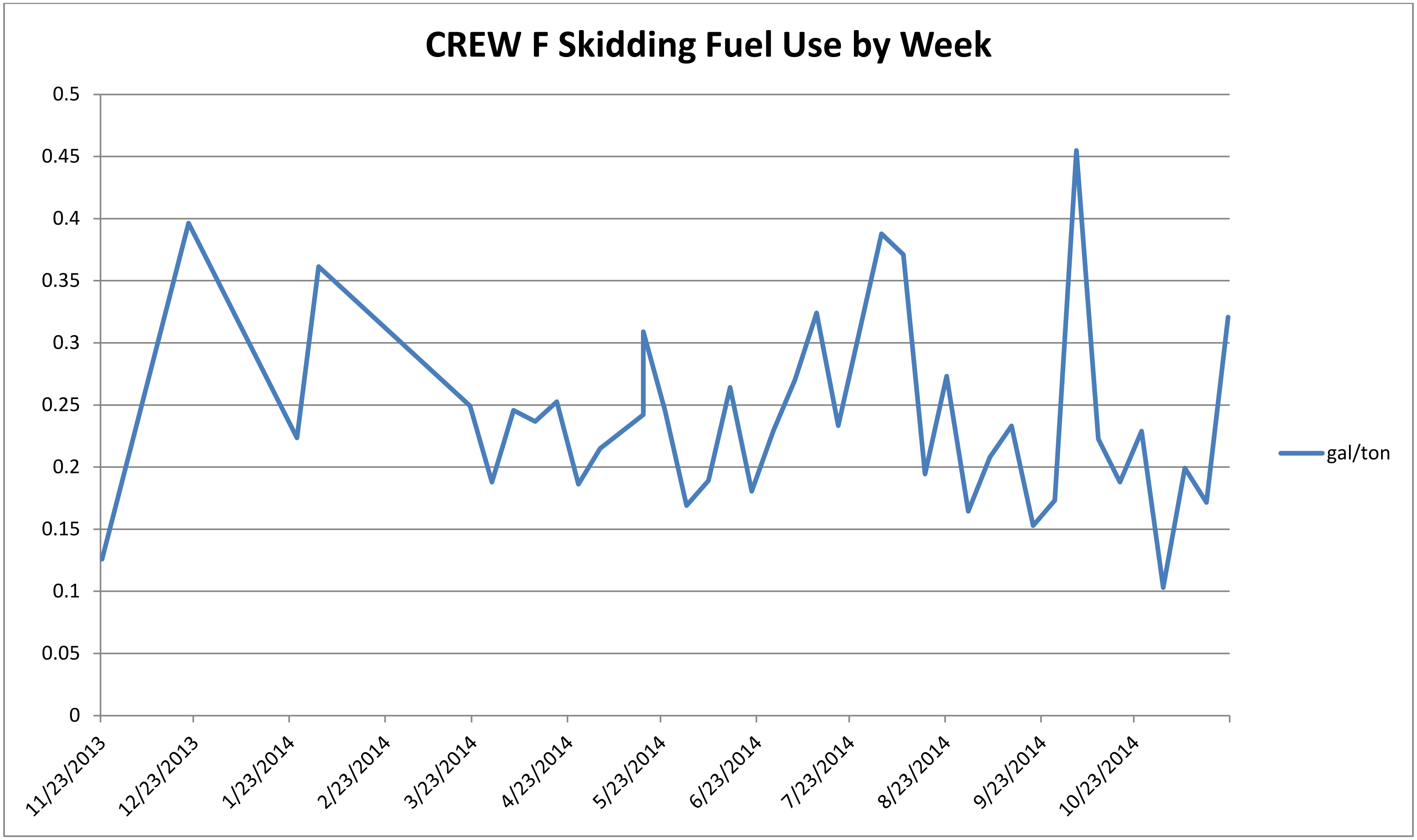
CREW E Skidding Fuel Consumption by Week



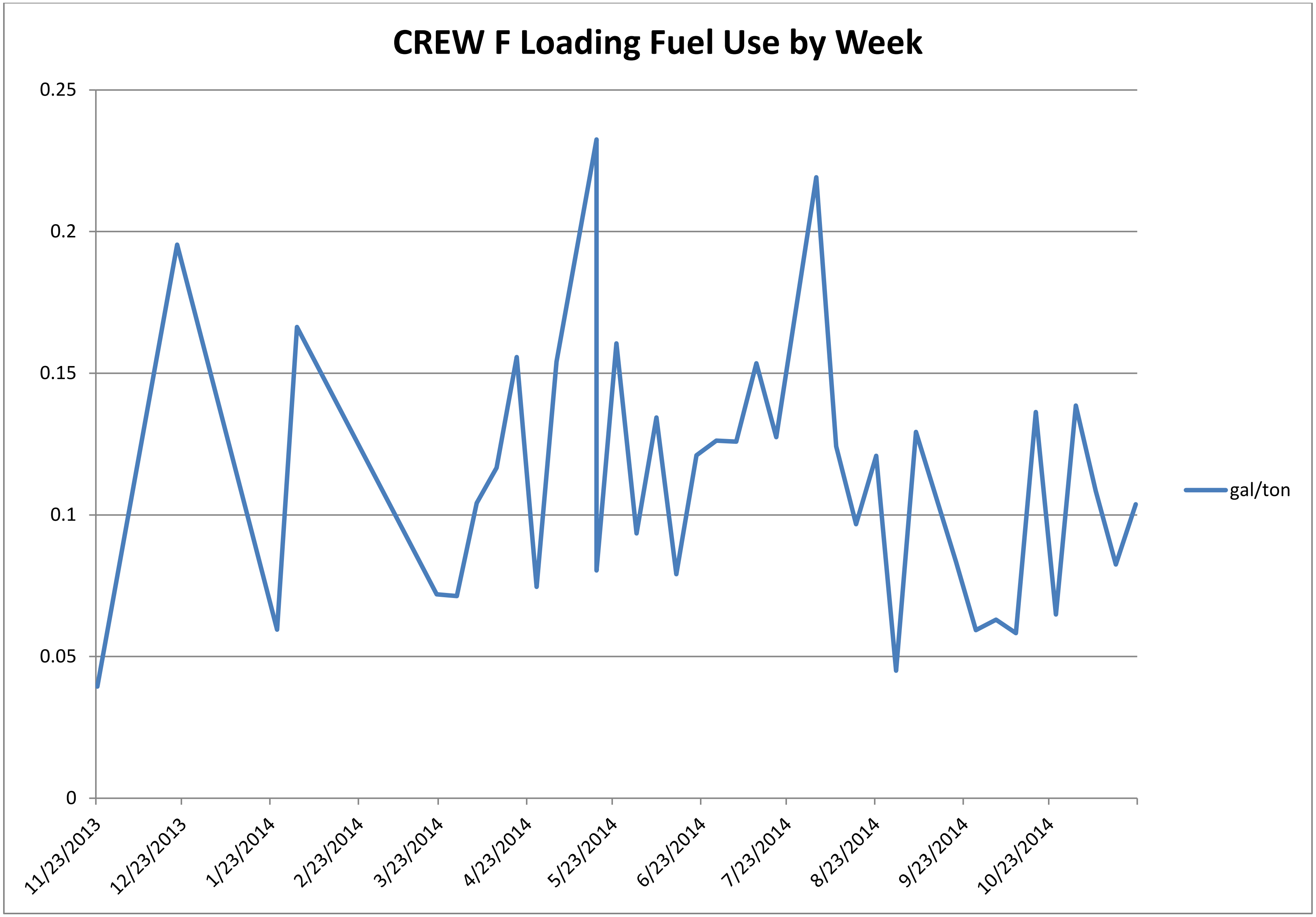
CREW E Loading Fuel Consumption by Week



CREW F Felling Fuel Consumption by Week



CREW F Skidding Fuel Consumption by Week



CREW F Loading Fuel Consumption by Week