COST BENEFIT ANALYSIS OF DRIVER HOURS OF SERVICE REGULATIONS FOR LONG-HAUL LTL CARRIERS

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ABSTRACT

Crash rates for trucks depend in part on the length of time drivers have been operating their vehicles. This paper investigates bounds on the reduction in crash rates due to the imposition of hours-of-service regulations, which limit the number of hours drivers operate their vehicles. Methods for analyzing probability distributions for trip length, and odds ratios for crashes (as a function of hours driven) are developed. The study is a first step toward a broader cost/benefit analysis of regulations, based on analysis of data from the fatal accident reporting system (FARS).

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1. INTRODUCTION

Safety is an important concern of the freight industry. The National Highway Traffic Safety Administration reported in its annual 2002 traffic safety report that tractor-trailers constitute only 3 percent of the total number of registered vehicles operating in the country but are involved in almost 10 percent of all fatal vehicle crashes. The Federal Highway Administration stated that large trucks were involved in 4183 fatal crashes in the year 2002. Safety has been a challenging issue for both trucking operators and the federal government. Several studies have been carried out over the years to determine the principal causes of truck crashes. Fatigue, alcohol abuse, human negligence, and sleep deprivation stand out as some of the chief causes for truck crashes, but no single factor, but rather a combination of factors is usually responsible for a crash.

This research the effect of driving hours of service (HOS) regulations on fatality rates for truck involved crashes. HOS regulations permit drivers to operate their vehicles and be on duty for a stipulated amount of time during the day as well as the week. As truck drivers spend a majority of their work time behind the wheels of their vehicles, truck safety can be gauged by analyzing HOS regulations. All trucking organizations have to comply with HOS rules, and any change in these HOS rules also affects the operations of the truck operators. Truck operations are extremely complex and have various pricing factors and operating costs. Changes in HOS regulations can affect these factors and consequently have a marked effect on trucking networks. As a step toward understanding the costs and benefits of HOS regulations, this paper computes upper bounds on the number of lives saved due to imposition of HOS constraints.

2. BACKGROUND

Freight transportation systems provide for the mobilization of materials and finished goods. Such systems encompass a range of transportation modes – air, land and sea. They support the economic backbone of any nation and of the world market in general. Although economic efficiency, quality of service, and reliability are prime requirements for any freight system, safety is also a critical requirement, particularly for trucks, which share the roads with passenger vehicles, pedestrians and cyclists.

Trucks are the most commonly used vehicles for the movement of goods, especially measured as a percentage of all shipments transported. Truck vehicles are classified according to size, body type, axles and axle configuration, weight, tractor trailer, truck configurations, etc. The Motor Vehicle Manufacturers Associations (MVAA) has defined trucks in eight weight classes, as follows (Table 1).

Size Class	Weight Class	Gross Vehicle Weight (lbs)	Axles/ Tires	Examples
Heavy-Heavy	8	> 33000	7/22+ 6/18+ 5/18	3-axle tractor semi trailer Twin trailer or “doubles”
Heavy-Heavy	8	>33000	4/14 3/10	Concrete mixers Dump trucks 3-axle tank trailer 3-axle tractor flatbed trailer
Heavy	7	26,000-33,000	3/10	City tractor with 28 ft pup trailer 4-axle tractor semi trailer 3-axle semi trailer
Light-Heavy	6	19,500-26,000	2/6	Beverage truck Home heating fuel truck
Light-Heavy	5	16,000-19,500	2/6	Stake truck
Light-Heavy	4	14,000-16,000	2/6	Flat bed
Medium	3	10,000-14,000	2/6	Metro van (UPS, FedEx)
Medium	2	6,000-10,000	2/4	Step van (Mail)
Light	1	< 6,000	2/4	Pickup truck, van

Table 1. Truck Classification by MVAA.

Trucking operations can be classified according to the nature of service that is provided. Truckload trucking is a form of door-to-door transportation service. The carrier assigns a truck along with a designated driver team that handles the goods on a door to door basis. The materials are picked up from the originating location and shipped straight to the customer. Unlike TL services, LTL trucking transports multiple shipments at a time. Carriers establish regular services through networks of terminals, which sort and consolidate smaller shipments into larger truckloads. Private truckers or operators have a fleet of trucks to serve their internal transportation needs, such as Walmart or Krogers. Private trucking is quite prominent in the retail-wholesale sector, food and beverage sector, construction and mining and in logging, due to large demands among a relatively small number of locations. By contrast, for-hire truckers carry freight for a fee to others. Both private and for-hire carriers can operate as either an LTL or a TL carrier.

Independent contractors are non-employees who perform services for a carrier organization. These independent contractors are not under the direct control of the organization to which they offer their services. A good example of an independent contractor is the employees working for FedEx Ground. They often utilize their own trucks and equipment, purchase their own work benefits and are directly responsible for truck safety, training and vehicle maintenance. In contrast, an employee works at the direction and control of an employer on a regular basis.

2.1 <u>Trucking Regulations</u>

Regulations are a prescribed set of rules set down by a governing body to control or govern a conduct or a mode of operation. Regulations are applied in every facet of industrial operations, including the trucking organization. Since the development of the trucking industry in the late 1930s the federal government decided to implement a set of rules to ensure that truck drivers worked within a prescribed set of rules and the integrity of the organization was maintained.

Driver Hours of Service (HOS) were designed to ensure that drivers worked within an optimum time frame, and got sufficient rest periods. The HOS rules were implemented in 1939. The rules remained largely unchanged until 1962, when one modification was proposed. Under the unmodified set of rules, a truck driver could operate a vehicle for a maximum or ten hours, after which a minimum eight hour period was required as off-duty. A truck driver could be on-duty for a maximum of fifteen hours, followed by a mandatory eight or more hours of off-duty. Finally, a driver could operate a vehicle for no more than sixty hours in a seven day period or seventy hours in an eight day period.

In 1995, the Congress, after hearing concerns about the rising number of commercial motor vehicle crash fatalities decided to re-assess the current rules. In January 2004, a new set of rules were implemented. The newer regulations proposed that a driver could operate a commercial vehicle for no longer than eleven hours followed by a minimum ten hour rest period. Also the driver could remain on-duty for a maximum of fourteen hours, after which a break of ten or more hours was required. The rest of the regulations remained unchanged, while some new regulations were added. Table 2 below shows the old and revised HOS.

Old Hours-of-service rules (until January 2004)	**New Hours-of-service rules (from January 2004)**
Maximum driving time of ten hours.	Maximum driving time of eleven hours.
Minimum eight hour off-duty time.	Minimum ten hour off-duty time.
Maximum of fifteen hour on-duty time	Maximum of fourteen hour on-duty time.
Sixty hours on duty in a seven day period	Sixty hours on duty in a seven day period
Seventy hours on duty in a eight day period	Seventy hours on duty in a eight day period

Table 2. Old and new driving hours-of-service.

Along with the revision of the driving hours of service, further revisions were proposed and newer regulations were added. These included the following:

- A driver may restart a 7/8 consecutive day period after taking 34 or more consecutive hours off duty.
- Drivers can extend the 14 hour on-duty period to a maximum of 16 hours if the following occurs:
    1. They are released from duty at the normal work reporting location for the previous 5 duty tours and,
    2. They return to the normal work reporting location and are released from work within 16 hours and,
    3. They have not used this exception within the last 6 days, except following a 34 hour restart of a 7/8 day period.

Exceptions to the regulations were added for the benefit of the commercial vehicle drivers. These were the following:

Exceptions

Drivers are allowed to split on-duty time by using sleeper berth periods while complying with the new regulations. Drivers can accumulate the equivalent of ten consecutive hours off-duty by taking two periods of rest in the sleeper birth provided.

- Neither period is less than 2 hours.
- Driving time in the period immediately before and after each rest period when added together does not exceed 11 hours and,
- The driver does not drive after the 14th hour after coming on duty following 10 hours off-duty, where the 14th hour is calculated by,
  - (A) Excluding any sleeper berth period of at least 2 hours which, when added to a subsequent sleeper berth, totals at least 10 hours, and,
  - (B) Including all on-duty time, all off-duty time not spent in the sleeper berth, all sleeper berth periods of less than 2 hours, and any sleeper berth period not described in paragraph 3(A).

Oil field operations, ground water well drilling operations, construction materials and equipment operations, and utility service vehicle operations must comply with the new 11-hour driving, 10 consecutive hours off duty, and 14 hours on duty requirements of the new rule. However, the 24-hour restart provisions applicable to these operations remain in effect. Agricultural operations retain their current statutory exemption from driving time requirements for transportation occurring within a 100 air-mile radius of a farm or distribution point during planting or harvesting season within each State, as determined by the State.

2.2 Truck Crashes

The word "crash" is defined as 'to undergo a sudden damage or destruction on impact'. The term "accident" and "crash" are often used to entail the same meaning, but accident implies an incident based on chance or pure luck. A crash on the other hand, happens due to a combination of factors or a chain of events. For this paper, any incident that involves the collision of a truck with any other vehicle or object and pedestrians will be treated as a crash.

Vehicular - especially truck crashes always involve the damage and destruction of property and sadly sometimes that of life itself. Different factors contribute to the occurrence of crashes. Attenuation of human functions, machine failure, changes in the surrounding environment and various other factors are responsible for crashes. Fatal crashes involve the loss of life and are of serious concern to the transportation related governing bodies in the US. The National Highway Traffic Safety Administration (NHTSA) maintains a central database termed Fatality Analysis Reporting System (FARS). FARS is a census of all fatal crashes that occur on public roadways. It is considered to be the most reliable national crash database, although it only contains fatality related data. Significant portions of the data for this paper will be used from FARS.

NHTSA has been recording fatal truck crashes since 1975. Although large trucks account for only 3 percent of the total number of registered vehicles operating in the United States, they account for almost 10 percent of all fatal vehicular crashes. Trucks, unlike automobiles, account for higher miles driven per year, due to their inherent job nature. A truck spends more time traveling than a car. In the last twenty years, there has been a 42 percent increase in registered large trucks and a staggering 93 percent increase in the number of miles driven by large trucks. In the same time frame, with the increasing figures of trucks and miles driven, the crash figures have actually declined. Vehicle involvement rate for large trucks has slid by 49 percent and the number of large trucks involved in fatal crashes has declined by 2 percent in each year.

The effect of HOS rules on truck safety and its economic impact on trucking operations has been observed by FMCSA. Table 3 shows the significant impact of HOS on both truck safety and truck operations.

Hours of Service (HOS) Related Statistics for Large Trucks	
1997-2000 Average Fatalities in Fatigue-Related Crashes	375
1997-2000 Average Injuries in Fatigue-Related Crashes	7,500
2002 Total Cost of Fatigue-Related Crashes (1999 Dollars)	$2.3 billion
Lives That Could Have Been Saved in 2002 by 100% HOS Compliance*	75 to 120
Estimated Annual Cost Savings to Motor Carriers of 100% HOS Compliance*	$900 million to –$1.3 billion
Net Benefits of Rule*	$1.1 billion to –$600 million

*Depending on baseline. Positive dollar figures are based on the assumption that all drivers were in compliance with the old HOS regulations. Negative dollar figures are based on the assumption that some drivers were not in compliance with the old HOS regulations.

Source: FMCSA Regulatory Evaluation, "Hours of Service of Drivers; Driver Rest and Sleep for Safe Operations," RIN2126-AA23.

Table 3. Effect of HOS on Safety & Large Truck Operations.

The National Center for Statistics and Analysis (NCSA) compiles crash data and brings out periodic reports of truck crashes. The FARS data utilized in this paper are developed by NCSA and is often used to generate reports similar to the one shown above. The national Motor Carrier Management Information System (MCMIS), another system similar to FARS is operated by the Federal Motor Carrier Safety Administration (FMCSA). MCMIS includes information on the safety robustness of commercial motor carriers. Fatal crashes involving large trucks are collected in MCMIS.

2.5 Summary

The statistics compiled above are testimony to the need for evaluation of truck safety. While several methods have been adopted that try to evaluate truck safety, the effect of hours of service on truck networks has not been significantly addressed. Under the present HOS regulations, drivers can only drive for a certain time period. This means that longer inter-terminal distances cannot be covered by a single driver, unless the company has a sleeper team policy, as time constraints are placed upon the operating drivers. Thus, HOS regulations directly affect trip lengths. Any change in the operations of a trucking organization, due to HOS policies, especially with respect to network designs or operating costs, will affect the operation of the organization. Trucking companies try to minimize their costs and remain profitable while actively pursuing the needs of their clients. A balance has to be brought between the company costs and the safety of truck operations.

3. LITERATURE REVIEW

The prime factor of interest in this paper is driving hours of service. Driving hours of service has been an active field of numerous studies and ongoing research. The present HOS regulations have witnessed heated debate between the federal authorities and the trucking lobby for failing to account for the health and safety benefits of the truck drivers. HOS regulations stipulate the conditions under which truck drivers are allowed to drive their vehicles and/or be on duty. Any change in HOS rules affects trucking operations to a certain degree. Trucking organizations operate in a highly dynamic environment. Reduction in operating costs, increase in revenue and compliance with clients' demands are often the primary goals of any organization. These goals can be directly or indirectly affected by any change in HOS regulations. For example, if driving hours are curtailed from a maximum of ten hours to eight, the truck driver may not be able to cover the entire distance between a given origin and destination. This may force the company to change their operating procedures. One of the steps taken by the company can be hiring additional drivers to compensate for the lower driving hours. This means an increase in operating costs for the organization. This would be highly inconvenient for the organization as they have to re-evaluate their strategies to compensate for the higher operating costs while seeking increased revenues. The goal of this paper is to achieve a balance between the costs and benefits of trucking operations and truck safety. The sections below review HOS rules, driving hours, sleep science, irregular driving hours and nighttime driving.

3.1 Driving hours

Jovanis (1990) examined the issue of consecutive or multiple driving days and crash risks. A national LTL firm participated in the study which allowed the usage of its data. The observations collected from the company after accounting for missing or incomplete data totaled 1066 drivers. This included 382 crash involved drivers and 684 exposure drivers. The exposure data was collected randomly using the same terminal and time period as that of the crash drivers. The ratio of crash to exposure drivers was roughly 2:1. Seven days of driving data, preceding the day of incident, were collected for crash involved drivers. Similar procedures were applied for the exposure drivers. A week's data was meant to signify the usual driving pattern of the truck driver. Using the data set, a non-linear binary logistic regression was applied. Cluster analysis was carried out to identify several distinct driving patterns. The authors determined that the highest levels of crash risks were involved with nighttime and early morning driving patterns. The daytime and early evening driving proved to have the lower levels of risk. The study had several important implications. It showed that time of day was a strong factor in crash risks. Hours of driving was established also as an important factor. The elevated crash risks associated with early morning and nighttime driving proves this claim valid. Continuous hours of driving demonstrated some confounding effects but it showed that crash risks increase with nine or more hours of driving.

Jones et al. (1987) tried to determine the connection between driving hours and crashes. They used a case control study that tried to examine the relative risk associated with long hours of driving. A sample of 332 tractor-trailer crashes was used for the study. For every crash there were three randomly selected exposure trucks. These trucks were in the same traffic stream and time as the crash involved trucks, but only a week later. The sample of truck crashes was used with 1, 2, and 3 case controls respectively for analysis. The authors found out that the relative risk of drivers who had driven for more than 8 hours was almost twice than those for those drivers who drove for lesser hours. Moreover they found out that drivers violating logbook regulations, drivers aged 30 and under and interstate operators were associated with higher crash risks. The study suggested that longer driving hours led to increased crash risks. This has been upheld by Jovanis (1990), and Wylie (1997).

Braver (1992) carried out a comprehensive survey of 1249 tractor-trailer drivers and determined that 73% of the interviewed drivers had violated hours of service rules. 31% of the violators reported driving more than the legal limit of 60 hours in 7 days or 70 hours in 8 days, more than 25% of these violators stated that they worked 100 hours or more per week and 19% told that they had fallen asleep at the wheel one or more times during the previous month while operating a tractor-trailer. Violation of hour of service rules have been found out in other instances. Braver (1992) conducted a study involving over 1200 truck drivers in truck inspection stops. The results obtained from the study showed that drivers violated HOS rules due to irregular route driving, receiving lower pay rates, penalized for late arrivals and delays in services, carrying perishable commodities and being assigned unrealistic delivery deadlines. Over half of these drivers who violated the HOS regulations believed that they should be allowed to drive more than ten hours a day and have more flexibility in their work schedules.

Harris and Mackie (1972) through their studies involving truck and bus drivers, determined significant changes in the driving performance of these drivers in the region of the ten hour time frame. Drivers committed more errors and were physically less aware to external stimuli. Although the study noted the differences among drivers, the attrition effects started developing during the fourth hour of driving and kept on increasing, until the driver either stopped driving, or took a short break. Mackie and Miller (1978), through their studies on truck driver fatigue determined that significant increases in driver performance errors are strongly associated with longer hours of driving. Cumulative fatigue effects also start showing up with multi-day driving schedules.

A time dependent logistic regression model was determined by Lin (1993), which examined motor carrier safety. Crash and exposure data from a national less-than-truckload was obtained to carry out the requisite analysis. It was found out that driving time was strongly associated with crash risk. The likelihood of a crash risk increased significantly after the fourth hour of driving and kept on increasing significantly along with longer driving hours.

From the above mentioned sections, it appears that longer driving hours are correlated to increased levels of crash risks. The effects seem to be more pronounced after the ninth driving hour. The recent amendments in the HOS regulations allowed an increase from a maximum of ten to eleven hours of consecutive driving. The research carried out in this study will try to determine the verity of the above mentioned statement and investigate the effects of longer hours of driving on truck safety.

3.2 Sleep Science

Carskadon (1981) defined human sleep as a reversible behavioral state of perceptual disengagement from unresponsiveness to the environment. Sleep was originally thought to be a passive and simple occurrence that did not involve any of the inherent complexities of the human body. Sleep is now regarded as an extremely complex and active state which consists of several stages and cycles. Sleep consists of two basic stages – non Rapid Eye Movement (NREM) and Rapid Eye Movement (REM). NREM involves four stages in which the final two stages are jointly termed as Slow Wave Sleep (SWS). These stages collectively perform the function of sleep.

Human sleep is a hotly debated issue. Researchers have approached the subject using different methods. Some researchers have categorized sleep as a phenomenon that is vital for physical and mental restoration while conserving energy. Others have hypothesized that substances from body fluids accrue in human blood when the human body is awake. These substances cause the feeling of exhaustion and during the sleep phenomenon, the substances are removed. Horne (1988) suggested that sleep is a state of decreased human activity during which the body tends to conserve proteins due to lack of food intake for long periods of time. Sleep has been associated with a certain phenomenon that occurs in the human body. This phenomenon is termed *Circadian Rhythms*.

Halberg (2003) stated that the word circadian is derived from the Latin word *circa diem*, meaning about a day. Circadian rhythms are the regular changes in physical and mental characteristics that occur in humans during the course of 24 hours. Circadian rhythms are the body's natural cycles that control appetite, energy, mood and sleep. The rhythms are akin to rhythms or cycles found in nature. The human body responds to natural cycles such as the 24 hour day and night period. When functioning properly, the human circadian rhythm will respond to the day and night cycle. During daytime, the human body produces cortisol, serotonin, other hormones and neurotransmitters that awaken a person and cause human body temperature and blood pressure to increase. At sunset, the circadian rhythm responds to the diminishing light level and causes the body to produce melatonin, decrease blood pressure and cause the human body to fall asleep. This rhythm is controlled by the *Suprachaismatic Nuclei* or SCN. SCN is the master clock in human bodies. It is the primary circadian rhythm that controls all other rhythms. The SCN is a cluster of 50,000 neurons, or 10,000 cells, one on each side of the brain. The SCN sits in the hypothalamus region of the brain and works with several time keeping genes and external *zeitgebers* or "time givers". SCN along with the ancillary mechanisms control the secretion and diminution of hormones, chemicals and neurotransmitters that determine appetite, moods, consciousness and sleep. The disruption of circadian rhythms can affect the human body to varying levels. Sleep disorders, loss of sleep and fatigue are some of its effects.

Patrick and Gilbert (1896) were among the first to carry out a comprehensive study on sleepiness. Subjects were kept awake for 90 hours and the results obtained from monitoring reaction time, motor speed and memory were used to demonstrate the harmful effects of prolonged wakefulness. Rhodes (2001) carried out an assessment on the hours of work of aircraft maintenance engineers (AMEs). He reported that AMEs, on average, were working over 50 hours per week when overtime was included. Many extend their 12 hour shifts or work 5 or more days of 10 hour shifts in a row. Many of these AMEs spend many days with little rest and minimal sleep. AMEs in rotating shifts obtained poor sleep due to noisy environment. Over 30% of the AMEs indicated that their performance levels were seriously affected when they had to work overtime, especially during night shifts. The study revealed that there was evidence that some AMEs in Canada were extremely fatigued and were possibly pushing their limits. Their fatigue is either chronic or acute or a combination of both. Accrued sleep debt and increased levels of fatigue were reported due to increased workload and continuous work schedule.

Heslegrave (1997) reported on performance measures for Air Traffic Control (ATC) workers. ATC workers, who were working for 8 hour shifts in the morning and evening, suffered a drop in their performance levels at the end of their shift. However this drop in the performance level was more pronounced for workers at the end of their 8 hour night shifts. Also the performance levels of ATC workers operating on backwards rotating shifts and 5 consecutive night shift patterns were observed. These workers were found to show poor performance during the night shifts when compared to evening or day shifts, and the performance degraded further from the second night onwards. Consecutive night shifts have another shortcoming as noted by Rhodes (1996). He observed ATC workers who operated five consecutive night shifts accumulated a sleep debt of more than 10 hours due to a low average of daytime sleep and poor sleep quality. The melatonin levels of these ATC workers showed that the workers' circadian rhythms never adopted a nocturnal pattern.

The Fatigue Countermeasures Program being carried out by NASA's Ames Research Center since 1980 has collected information on fatigue, sleep, performance in flight operations and circadian rhythms. The goal of this research group was to understand the extent of fatigue, sleep loss and circadian disruption in flight operations. The effect of these factors on flight crew performance was studied and ways were being developed to mitigate the factors and improve flight crew performance at the same time. Field studies have shown that in long haul flight operations and non-24 hour duty or rest cycles, the circadian desynchronization associated with transmeridian flights and the sleep loss from nighttime flying are linked to fatigue. The project studies noted that fatigue was created due to short-haul operations, long duty days, sleep loss as a result of short nighttime layovers and shortened sleep intervals due to progressively earlier crew reporting times. Overnight cargo crews also suffer from fatigue as regular nighttime flying causes incomplete circadian adaptation. Duty periods ending in the morning hours lead to sleep loss due to the human body's circadian tendencies and biological clock signaling the human body to remain awake during the morning hours. Flight crews have periodically acknowledged that fatigue was a big concern for them. The project recorded the fact that certain flight crews admitted to having nodded off during the flight and also sometimes arranging for one pilot to take naps in the cockpit seat. The research body suggested small periodic breaks as a countermeasure against fatigue. Small breaks reduce nighttime sleepiness and also mask the sleepiness for moderate periods of time.

Eddy (2005), in his paper on sleep deprivation among physicians, commented that 24 hours of sustained wakefulness produced impairment similar to having a blood alcohol level of 0.1 %. Physicians appeared to work far more hours than the guidelines prescribed for employees in the 1930s. He noted that studies of physicians have shown that sleep deprivation led to impairment in language and math skills, impaired ECG translation, increased error rates in intensive care unit, and signs of less empathy and poor communication skills with patients. Resident doctors are not permitted to work more than 80 hours a week with no shift longer than 24 consecutive hours. Studies in New York state hospitals showed that prior to 1989, resident doctors were working 100 to 120 hours per week. An audit carried out after a decade on in 12 New York hospitals shows that 60% of surgical residents were working for more than 95 hours per week. A study by Parshuman (2004) showed that even if residents complied with the regulations, they worked long hours with little sleep and suffered significant psychological stress. New York State is currently the only state in North America that has implemented binding limits for physician work time. Other states have implemented guidelines but they have been ignored in a majority of cases. Eddy found out that after age 45, older physicians have trouble getting deep sleep and are unable to recoup their sleep debts. These physicians are less able to return to their normal functions after a sleepless night when compared to their younger colleagues.

The sections above deal with the science of sleep and its associated effects. It appears that modern society has altered the sleeping habits of many. The fast paced lifestyles, restricted schedules, and the demand for more work have caused many to work longer, thus curtailing their sleeping hours. Poor sleep and cumulative sleep debt have deleterious effects on the human body. The buildup of fatigue and lowering of performance levels are the most visible signs. Humans are more prone to commit errors or make poor judgment while performing their jobs under increased fatigue levels. The aviation and transportation industry has adopted regulations that ensure that the operators are not overworked and achieve sufficient rest. Truck drivers are no exception to this situation. The past and current HOS regulations have tried to ensure that truck drivers get sufficient rest after their work hours so that they can improve their performance levels.

3.3 Truck Sleep Studies

The National Transportation Safety Board (NTSB) carried out a study involving single vehicle truck accidents. The board wanted to determine the role of specific factors, such as drivers' pattern of duty and sleep, and determine what remedies could be achieved. The data collection involved single vehicle crashes that tend to occur at night. 96 hours of data preceding the drivers' crashes was utilized for this study. 107 single vehicle crashes, in which the driver survived, were used. A similar amount of exposure data was also collected. A multivariate statistical analysis was carried out on the data elements. The results showed that the duration of the last sleep period, total hours of sleep obtained in the last 24 hours prior to the crash, and split sleep patterns were some important parameters used in predicting fatigue-related crashes. Moreover the truck drivers involved in crashes were found to have slept on an average of only 5.5 hours, nearly 2.5 hours lesser than the 8 hours sleep obtained by the set of exposure drivers. However the mode of data collection relied heavily on drivers' memories. Crash involved drivers were asked to recount their last 96 hours of on duty routines before the crash. The study indicated that driving at night with a sleep deficit appeared to be more critical in predicting fatigue-related crashes than just nighttime driving.

Rogers (1999) tried to determine the effects of loading/unloading duties on driving performance, off duty hours required to re-establish duty fitness, and decrement of driving performance while following a pre-set driving pattern. Using 10 truck drivers on a truck simulator (FAAC DTS –2000), data collection was carried out to observe driving performance. The driving age ranged from 31 to 49 with the average being 43.2 years. The drivers were asked to perform several tasks. These included the loading and unloading of loaded boxes, driving in the simulator under various driving conditions, and taking rest to achieve driving fitness. They were asked to operate on a 14 hour on duty and 10 hour off duty schedule for 15 days with a weekend rest of 58 hours between the two weeks of driving. The study revealed mixed effects for the loading / unloading duties. The drivers recovered to baseline driving performance within 24 hours at the end of the driving week and were fit for duty after 36 hours. It showed that drivers who completed a week's worth of driving and obtained regular sleep were unlikely to need more than 24 hours to recover. The findings suggested that 32 hours off duty were sufficient as a minimum safe restart period. The 14-hour on duty 10-hour off duty 5-day driving schedule did not appear to produce any significant cumulative driving fatigue. A mid-day break for about 1 hour during driving dramatically improved the driving performance. The study showed that a minimum of 24 hours was needed as a break period for drivers to recuperate.

A study carried out by Wylie (1997) investigated the degree of recovery afforded to truck drivers by rest periods. A group of 5 drivers who had driven for four 13-hour periods with night starts were given a 36 hour period off and then allowed to drive for four more consecutive 13 hour night driving periods. Another group of 20 drivers who drove four 13-hour day trips with daytime starts were allocated in four different conditions. The first group of 3 drivers was allowed no off duty periods; the second group of 5 drivers was allowed a 36-hour period off and then worked for four additional days; the third group of 6 drivers was given 36 hours off and then worked an extra day. The final group of 6 drivers was given a break of 48 hours and then allowed to work an additional day. A major drawback of this study was the small sample size. This led to limitations in the potency of the conclusions but the study did provide some of the better estimates of recovery and effects of off duty hours on truck drivers. The analysis of the data showed that night drivers performed poorer than their daytime counterparts. The subjects who have had no off duty hours displayed a significant decline in their driving performance. Truck drivers with break periods of 36 hours showed a minimal decline in driving performances, while those with a 48 hour break had no decrement in their driving performance. From the analysis, it seemed that a 48-hour break was preferable over a 36-hour break. Daytime drivers fared better than nighttime drivers, but both the groups were not subject to the same conditions. The experiment showed that a 48-hour break is significantly better than either 24 or 36 hours.

Wylie (1997) surveyed driver fatigue and alertness in different truck stops of the country. A total of 511 truck drivers responded to the on-site survey. Significant conclusions were drawn from the survey. A quarter of the drivers who used their berths while on the road split their rests and spent fewer hours sleeping compared to drivers who took continuous rest. A significant portion of the drivers stated that they slept less to maintain their schedule. Also 60 percent of the drivers felt that daytime sleeping was not as beneficial as nighttime sleeping. The results obtained showed that sleep debt and irregular sleep habits can lead to fatigue.

Mackie and Miller (1978) determined that truck drivers operating on irregular schedules received less sleep and showed prior signs of fatigue than drivers operating on regular schedules. However, both sets of drivers were allowed to sleep for the same period of time. Due to the sleep debts accumulated by the irregularly scheduled drivers, they performed less reliably than their regular counterparts. In many cases, research has shown that fatigue effects increase significantly when the human body experiences a low arousal level in its circadian rhythm. The low level of arousal usually occurs between 2 am until 6 am in the morning. Hertz and Jovanis (1991) both observed through their independent studies that there was a strong likelihood of a crash with night-time driving. A Swedish study by Kecklund (1995) found out that the crash risk for trucks was 3.8 times higher between 3 am and 5 am when compared to the crash risk associated with daytime driving.

Smiley (1997) in a literature review felt the need for further research to evaluate the recuperative value ascribed to off duty hours and driver rest periods. Few studies have addressed this issue and the conclusions lack a strong scientific foundation. The recovery study by Wylie et al (1997) was one of the studies that addressed the issue to a certain extent. However the study was lacking due to its diminutive data size and lack of records on sleep recovery periods. Smiley recommended further review of the study by Wylie et al (1997), further collection of data pertaining to on duty and off duty activities of truck drivers, and assessment of alertness and sleep quality under different driving schedules.

3.4 Nighttime Driving

Wylie (1997) studied the effects of nighttime driving. He found that drivers operating on a night schedule experienced higher crash risk levels than daytime driving. In a study on LTL truckers, Jovanis (1990) found that consecutive hours of driving were closely associated with crash risk likelihoods. Drivers also appeared to be affected by nighttime operations, and nighttime drivers showed marginally stronger levels of association with increased crash likelihood. Jovanis (1991) used multi-day driving patterns to predict similar results. Drivers operating under irregular schedules accumulate sleep debt and are at greater risk than regularly scheduled drivers. Hayworth (1989) conducted a study at the General Motors-Holden Proving Ground on subjects driving for six hours either during the day or night. The eyelid closure and lane excursions of these subjects were continuously monitored over the course of the study. It was found out that lane excursions were more recurrent at night than at daytime. The nighttime test subjects also failed to react to external stimuli more frequently than their daytime counterparts. Several of the nighttime subjects also fell asleep at the wheel during the test periods. It was determined that a greater level of performance deterioration and fatigue occurs for drivers who have been operating their vehicles for nine to ten hours during the nighttime. Lin (1993), using time-dependent logistic regression models on a 1984 crash and exposure LTL data set, determined four types of driving patterns. Three of these patterns involved nighttime driving and the fourth pattern included infrequently scheduled drivers. All of these patterns showed significant statistical association with crash likelihoods. It appears that nighttime driving is linked to significantly higher levels of decline in driving performance.

3.5 Sleeper Operations

Trucking companies often utilize a very different approach to solve the problem of driving long distances, especially when the truck driver is constrained from driving more than a certain number of hours due to HOS regulations. This involves the usage of two drivers to operate the vehicle continuously to cover trips that take more than 100 hours to be finished. The drivers periodically relieve each other at the wheel and drive under the given HOS regulations while also taking the prescribed breaks from driving. The driver who is relieved often rests or sleeps in the sleeper berth located behind the driving wheel, while the vehicle is in operation. The drivers usually relieve each other after four to five hours of driving. This operation looks ideal for operations as the drivers can relieve each other as many times as they want. However, sleeper berths appear to have their share of problems with respect to driving performance and truck safety.

Mackie and Miller (1978) found that sleeper drivers tended to display greater driver fatigue and performance deterioration when compared to single drivers, when in both cases the two sets of drivers drove along the same route. Sleeper drivers showed worsening driving skills, increases in lane tracking variability, and more critical events that displayed driver drowsiness. In a majority of these cases, the sleeper drivers had undergone shorter driving times than their single counterparts. It was determined that sleeper drivers obtained less sleep than single drivers before commencing their driving operations. The study showed that sleeper drivers experience disrupted sleep and experience lower arousal levels that culminate in degraded driving performance.

A similar study was performed by Williamson (1992) in Australia. Interviews carried out by Australian sleeper drivers found that these drivers experienced more fatigue. Breaks taken by these drivers after their driving shifts provided little or no significant improvement in restoring their driving capabilities. The large distances to be covered and the longer amount of time spent on the road outweigh any benefits obtained from sleep or diving breaks taken by sleeper drivers.

O'Hanlon (1981) carried out a study similar to Mackie and Miller (1978). He determined that drivers usually displayed a decline in their driving performance at some point during their four to five hour driving operations, but the effects are more pronounced in night driving, especially during midnight. Sleeper drivers are more prone to such decline in driving conditions and are unable to respond to situations effectively during late night and early morning driving.

Hertz (1988) related increased crash likelihoods to sleeper berth operations. A data set comprising 418 fatally injured tractor-trailer drivers and 15,692 non-injured drivers in property damage accidents was analyzed. Univariate analysis was used to determine the confounding factors along with logistic regression to adjust for these confounding factors. Crash risks for sleeper drivers were similar to that of single drivers. This result was contradictory to the hypothesis that sleeper drivers are subject to higher crash risks. However, the usage of sleeper berths in two shifts increased the crash risks significantly. Hertz found that crash risks did not arise due to disturbance in sleep from truck motion but due to the splitting of sleep into two periods. Drivers who split their sleep periods and relieved each other tended to face decreased driving performance and increased fatigue and subsequently higher crash risk levels.

3.6 Summary

The sections described above cover different facets of the trucking industry. Some of these include issues such as driving hours, sleep debt, etc. Driving hours is a vital factor in analyzing truck safety. While a plethora of studies have been carried out on driving hours, there is no sufficient model that predicts the precise relationship between driving hours and the notion of truck safety. Researchers have hypothesized that drivers driving for longer hours have a greater chance of being involved in a crash. However the exact relation between driving hours and crash occurrences is unknown. A question such as “What happens if the driver has been driving for 8 hours, 10 hours or even 12 hours non-stop?” has no precise answer. Longer driving hours may appear impractical, and it can be speculated that the chances of the driver being in a crash are quite high but no definite answer is available. Similar issues arise in the case of sleep studies. Studies have shown that a minimum duration of 8 hours of sleep is required for the body to erase any effects of fatigue. However, it is unknown whether all truck drivers get proper rest. Insufficient information exists on how truck drivers utilize their off-duty hours. This lack of suitable data compounds problems further. Questions such as “How will the trucking network be affected if driving hours are reduced” or “How can truck safety and trucking costs be balanced together?” require answers that have not been dealt with sufficiently. Relatively little is known about the interaction of trucking costs and truck safety. This paper aims to shed light on such aspects. Armed with the conclusions drawn from the statistical and network models and by filling these literature gaps, this paper will strive to achieve a balance between the costs and benefits incurred in a LTL trucking network while allowing the truck drivers to operate in a domain of mitigated crash levels and increased truck safety.

4. METHODOLOGY

Truck safety will be evaluated by analyzing the effect of HOS constraints on crash likelihood of truck drivers, focusing on fatal accidents. Federal HOS regulations were introduced in 1939, underwent changes in 1962 and were largely unmodified until January 2004, when the present HOS regulations allowed drivers longer driving and break periods, but cut down on the overall on-duty periods. Studies have shown that longer driving hours are statistically linked to increased levels of driver fatigue and higher crash risks. By analyzing driving hours from FARS data, statistical models can be used to evaluate the effect of driving hours on crash risks. The analysis could lead to the creation of a new set of constraints that stipulate the maximum amount of time a driver can operate his vehicle, his on-duty and break periods, etc. These constraints will act as modified HOS rules.

The sections that follow cover evaluation of the data, creation of probability distributions, their application on the data set and the forthcoming results.

4.1 <u>Evaluation of the Data Set</u>

FARS, an acronym for Fatality Analysis Reporting System, was implemented by the National Highway Traffic Safety Administration (NHTSA), and is maintained by the National Center for Statistics and Analysis (NCSA). NCSA was established in 1976, and its primary goal is to provide analytical and statistical support to NHTSA and the highway community in the general areas of human, vehicle and roadway characteristics with respect to crash frequencies and injuries. NCSA maintains an exhaustive set of data collected from its own internal data sources as well as data from other governmental agencies. FARS is once such data set. FARS contains data on a census of fatal traffic crashes occurring within the fifty states, Washington DC, and Puerto Rico. For data to be recorded in FARS, a crash must involve a motor vehicle that has been traveling on a public roadway and the crash results in the death of a person, (vehicle driver, occupant or pedestrian). FARS has been used since 1975 and has since collected information on about 1 million motor vehicle fatalities. Data are recorded in FARS under several different categories based on vehicle types, crash types, environment, people, etc. To analyze truck safety, fatality data for all truck involved crashes are selected in the beginning. However, because many vehicles classified as trucks are smaller service vehicles, we focus only on trucks that weigh more than 10,000 lbs.

FARS data are divided into four categories – crashes, persons, vehicles and drivers. The first attribute, crash, contains variables such as crash date, crash time, day, month, year, etc. It also contains information regarding the arrival of EMS services, the number of fatalities and other factors. Persons, as the attribute suggests consists of age, injury severity, alcohol involvement and other human factors. Vehicles include the type of vehicle involved in the crash, body type, make, model, travel speed, etc. Finally, drivers consists the drivers' physical attributes, current license status, prior convictions, prior traffic accidents and other human factors. Out of all the variables listed in the data, a few, including the crash time, date, day, month, year, age of person, the number of hours driven and the trip type are used in the analysis of crash risks. The latter two variables are not directly linked to the FARS data, but are obtained from a different survey data set called Trucks Involved in Fatal Accidents (TIFA). TIFA has been collected since 1980 by University of Michigan Transportation Research Institute (UMTRI) Center for National Truck and Bus Statistics in conjunction with NCSA. The TIFA data set contains almost all the variables from the public version of the FARS files. In addition to the FARS data, an extra set of variables are produced by TIFA. These variables are obtained from the information in the TIFA survey form. The survey form information is produced by telephone interviews with truck drivers, truck owners or other involved parties. Some of the values of the TIFA variables are collected from state police reports. The TIFA survey also collects information regarding the physical details of the trucks including the cab style of the power unit, the weights, lengths, axle counts, trailer types, cargo type and cargo weight.

TIFA acquires data from information contained in police reports. However, a lot of the truck crash data remained unavailable due to the absence of police reports. For the year 2000, out of a total of 5,275 medium and heavy truck crashes, 186 of the 188 Pennsylvania cases, 61 out of 122 Mississippi cases, 16 Nevada cases, 6 Utah cases, 3 Texas cases, 1 Missouri case and 1 California case were missing. However, the overall response rate was significant, totaling about 95%. For 2001, a total of 414 police reports, out of 5141 files, were missing. Out of these missing files, virtually all the police reports for crashes in Pennsylvania and Illinois were unavailable. The overall response rate, was a healthy 92%. In 2002, 687 cases out of 4950 files went unreported. The majority of the files for crashes in Mississippi, Nevada, and Nebraska were missing. Police reports could not be obtained from Illinois, Iowa, New Jersey, New York, Ohio, Oklahoma, Pennsylvania and Texas. The response rate was 82%, which appeared to be a significant drop when compared to the previous two years.

The formats of police reports vary from state to state, but all of them include the identities of the owner(s) and driver(s) of the vehicles involved. Brief information of the incident is recorded in these files, although some states may remove them from the records. However some states did not reveal information regarding the crashes. For these states, TIFA worked to match the FARS data against the corresponding file in the MCMIS crash file using case matching algorithms. The next step in this process was the survey of truck drivers and owners. Information was collected by phone interviews. If attempts in contacting the truck driver or the owner were unsuccessful, the TIFA team would then contact other parties such as the police officer investigating the crash or the tow truck operator for more information. If no knowledgeable respondent was located, most of the data would be compiled from the police reports.

4.2 Truck Safety

Past literature on truck safety has shown that longer driving hours are statistically linked to higher crash risks. Drivers who spend more time behind the wheel driving are more likely to be involved in a crash. The reduction in driving hours would consequently reduce the chance of a crash occurring. The measurement of this reduction can be carried out using suitable probability distributions and a statistical framework. Probability distributions have to be created that compare drivers who have had a crash after being on the road for more than x hours against those drivers who have had no crashes after time x. The review and analysis of such distributions has been carried out in the next section.

4.2.1 Analysis of Probability Distributions

In this section we develop and analyze probability distributions, which are then used to evaluate reductions in crash rates under a set of scenarios involving different HOS constraints. Probability distributions are specifically used to predict the proportion of accidents that happen after a certain time x as well as the reduction in accidents due to adherence to modified HOS constraints. From these distributions, the reduction in crashes can be estimated for modified HOS constraints. The first step is to identify probability distributions:

- ⇒ P(x) is the probability that a randomly selected vehicle on the road will have a trip length greater than *x* hours and g(x) is its assigned probability density function.
- ⇒ F(x) is the probability that a randomly selected truck on the road has driven for more than *x* hours at the time it is selected.
- ⇒ H(x) is the probability that an accident involved truck has driven for more than *x* hours.

X is defined as the trip length in hours and is a random variable. It can be stated that,

F(x) = $\int_x^\infty g(z)$ P(T>x|z), where T is the elapsed time for a randomly selected truck on the road.

$$F(x) = \int_x^\infty g(z)\left(\frac{z-x}{z}\right)dz$$

$$= \int_x^\infty g(z)dz - x\int_x^\infty \frac{g(z)}{z}dz$$

Hence, F(x) = P(x) - $x\int_x^\infty \frac{g(z)}{z}dz$, therefore F(x) $\geq$P(x).

Now, let the accident rate per unit of time be denoted as a(x), where x denotes the time traveled since departure. Hence the total accidents for vehicles that have driven more than x can be quantified as:

Total accidents beyond time x = $\int_x^\infty f'(z)a(z)dz$

Where, $f'(x) = -\frac{dF(x)}{dx}$, or

$$f'(x) = g(x) + \int_x^\infty \frac{g(z)}{z}dz - g(x) = \int_x^\infty \frac{g(z)}{z}dz$$

Now, to determine the proportion of accidents for vehicles that have driven greater than x, the distribution H(x) is created.

$$H(x) = \frac{\int_x^\infty f'(z)a(z)dz}{\int_0^\infty f'(z)(a(z))dz}$$

If a(z) is constant, then the distribution F(x) is created. The reduction in fatalities if trip length is constrained can be computed as the difference between the above function H(x) and the transference to shorter trips (trips with lesser driving hours).
This can be summarized as

Reduction in crashes = H(x) – Transference to shorter trips.

The term “transference to shorter trips” represents the transfer of driving from long trips to short trips due to the application of upper bounds for driving hours. For example, if 20% of long haul LTL truck drivers are behind the wheels of their trucks for more than 10 hours, the upper bound allows such drivers to keep on driving up to 8 hours. Hence the remaining 2 hours must be served in a separate daily cycle. While drivers operating for longer hours are linked to higher crash risks, drivers having shorter trip lengths have lower odds of being involved in a crash. The goal is to split up the operating times of longer trip length drivers by applying upper bounds on driving hours and reducing the odds of having a crash. The crash risk for drivers who have to complete the remaining trip, albeit lower, is the transference to shorter trip proportion. These drivers would have had a high chance of being involved in a crash, but the odds are significantly reduced due to the driving hours constraint. Hence the total reduction in crashes can be summarized as the difference in proportion of drivers who have a crash after driving for more than x hours and the proportion of drivers who would have had a crash if they had driven longer, but are now placed in the shorter trip category.

An example of how the functions F(x) and H(x) can be obtained from a given P(x) distribution and accident rate a(x) is described below. For illustration, it is assumed that P(x), the probability that a randomly selected trip length is greater than X hours, is an exponential distribution, g(x) is its assigned probability density function and the mean of the given distribution is denoted by $1/\lambda$, where $1/\lambda$ denotes the driving time in hours.

Suppose that we need to find the probability F(x) that a randomly selected truck on the road has driven for more than 7 hours at the time it is selected. The plot of the distribution and the requisite calculations are shown in Figure 1. Hence, we have the following:

$$P(x > X) = 1 - P(x \le X)$$

$$or, P(x > X) = 1 - (1 - e^{-\lambda x})$$

$$or, P(x > X) = e^{-\lambda x}$$, by using the cumulative distribution function of P(x).

$$and, g(x) = \lambda e^{-\lambda x}$$

$$or, g(z) = \lambda e^{-\lambda z}$$

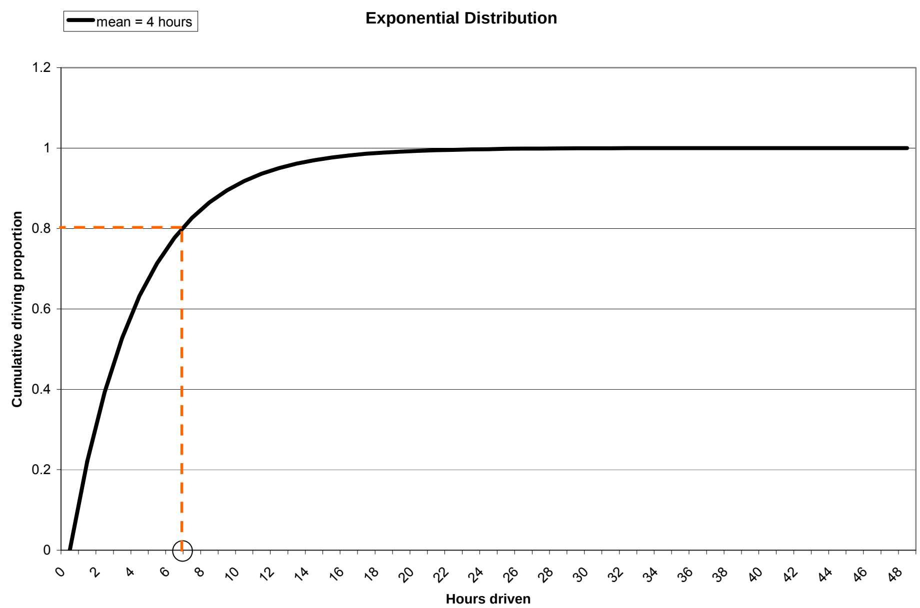

Figure 1. Exponential distribution of driving times with mean = 4 hours.

Now, F(x) as defined previously is equal to P(x>X) - $x\int_x^\infty \frac{g(z)}{z}dz$. Therefore, F(x) can be rewritten as,

$$F(x) = e^{-\lambda x} - x\int_x^\infty \frac{\lambda e^{-\lambda z}}{z}dz$$

$$or, F(x) = e^{-\lambda x} - \lambda x\int_x^\infty \frac{1}{z}e^{-\lambda z}dz$$

On integrating the right hand side, a rather complex function is obtained. This is written as,

$$F(x) = e^{-\lambda x} - \lambda x[\ln|z| + \sum_{i=1}^{\infty}\frac{(-\lambda z)^i}{i.i!}]_x^\infty$$

This function F(x) is the probability distribution that a randomly selected truck on the road has driven for more than *x* hours. Therefore, the probability F(x) is calculated as follows:

$$F(x) = e^{-0.25*7} - 1.75\int_7^\infty \frac{1}{x}e^{-0.25x}dx\ ^*$$

$$or, F(x) = 0.173805 - 1.75 * 0.0694887$$

$$or, F(x) = 0.173805 - 0.121605$$

$$F(x) = 0.0522$$

Hence, the probability that a randomly selected truck on the road has driven for more than 7 hours at the time it is selected, given that the mean driving time is 4 hours is 0.0522, or about 5 %. Once F(x) is derived, principles applied previously can be utilized again to obtain the distribution H(x). The differentiation of F(x) yields the function f'(x). This is shown as the following:

$$f'(x) = -\frac{dF(x)}{dx}, \text{ or}$$

$$f'(x) = \int_x^\infty \frac{g(z)}{z} dz = \lambda \int_x^\infty \frac{1}{z} e^{-\lambda z} dz$$

$$or, f'(x) = \lambda [\ln|z| + \sum_{i=1}^\infty \frac{(-\lambda z)^i}{i.i!}]_x^\infty$$

This value of f'(x) can be used for creating the function for H(x).

$$H(x) = \frac{\int_x^\infty f'(z)a(z)dz}{\int_0^\infty f'(z)(a(z))dz}, \text{ where a(z) is the accident rate.}$$

For this example, it is assumed that the accident rate is a logarithmic function of z (the driving hours) and is represented as a(z)=b(ln(z)+c). Hence the distribution H(x) can be rewritten as the following:

$$H(x) = \frac{\int_x^\infty f'(z)a(z)dz}{\int_0^\infty f'(z)(a(z))dz}$$

$$or, H(x) = \frac{\int_x^\infty (\lambda \int_x^\infty \frac{1}{z} e^{-\lambda z} dz) b(\ln z + c) dz}{\int_x^\infty (\lambda \int_x^\infty \frac{1}{z} e^{-\lambda z} dz) b(\ln z + c) dz}$$

The distribution of H(x) can be obtained dividing the integrals. Using the same example given above, and an assumed accident rate a(z) $=10^{-4}$(ln(z) + 1.5), the probability H(x) that an accident involved truck has driven for more than 7 hours is calculated as the following:

* (Numerically computed using Mathematica 5.2)

$$H(x) = \frac{\int_7^\infty (0.25\int_x^\infty \frac{1}{z} e^{-0.25z} dz)(\ln x + 1.5)dx}{\int_0^\infty (0.25\int_x^\infty \frac{1}{z} e^{-0.25z} dz)(\ln x + 1.5)dx}$$

$$or, H(x) = 0.15055$$

Hence, the probability that an accident involved truck has driven for more than 7 hours is 0.150552 or 15 %, which is an upper bound on crash reductions with a 7 hour HOS constraint. By subtracting the crashes for trips that are placed in the shorter trip category, the actual reduction in crashes could be obtained. This example can be modified to account for different types of distributions for P(x) and different functions for the accident rate a(x). While P(x) was assumed to be exponential, other distributions such as uniform, log-normal or gamma can be used to obtain results. The same holds true for the accident rate a(x). Several other functions, including linear, exponential, quadratic or even a constant, can be applied for the accident rate to explore other scenarios.

4.2.2 Analysis of Odds Ratio

In this section we use the concept of "odds ratio" to develop a more precise estimate of reduction in crash risks due to HOS constraints. This concept was utilized by Jovanis to demonstrate that truck drivers operating their vehicles for longer hours have greater likelihoods of being involved in crashes. Using data from LTL truckers operating in the years 1984-1985, Figure 2 was produced:

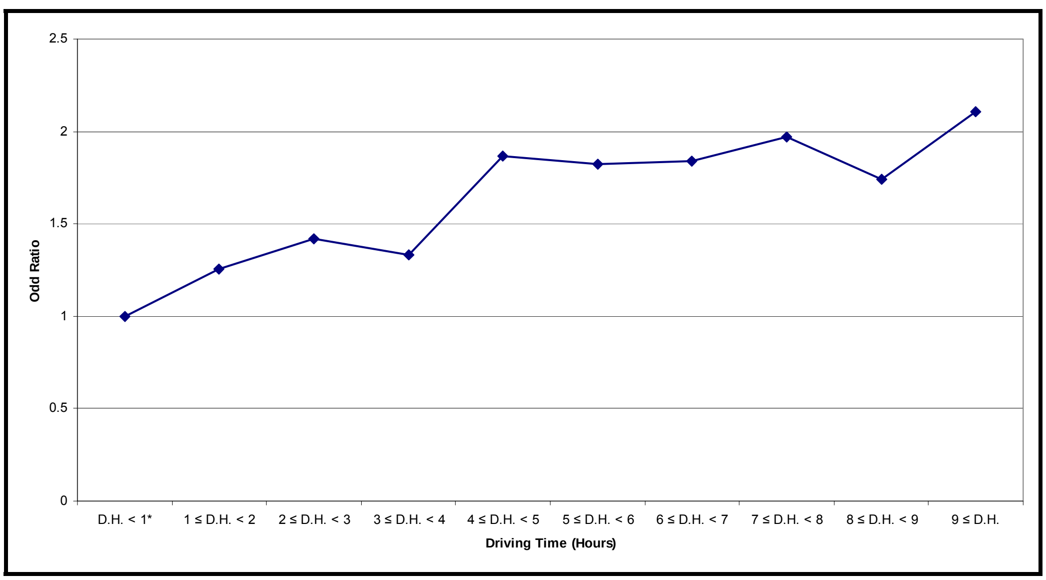

Figure 2. Odds ratio.

Figure 2 shows that the odds ratio for a crash when the driver has just started driving is normalized to one. As time increase, the odds of a crash start increasing. At the end of nine hours of driving, the odds of a crash occurring have doubled. This implies that the driver is twice as likely to be involved in a crash after driving for more than nine hours compared to the initial starting state. With reference to the equations drawn in the previous section, the following equation can be stated:

$$Odds\_ratio(x) = \frac{a(x)}{a(0)}, \text{ where}$$

a(x) is the accident rate per unit time and x denotes the time traveled since departure.
a(0) is the accident rate per unit time when x = 0.

The equation calculates the odds ratio at time x by determining the ratio of accident rates at time x and at time 0 respectively. The odds ratio graph is plotted in Figure 3 using data obtained from Figure 2. The data from the graph are used to construct a model that allows the prediction of the crash odds. A regression analysis was carried out to determine the most precise relation between driving hours and crash odds. This scatter plot also contains the trend line that displays the relationship between the parameters.

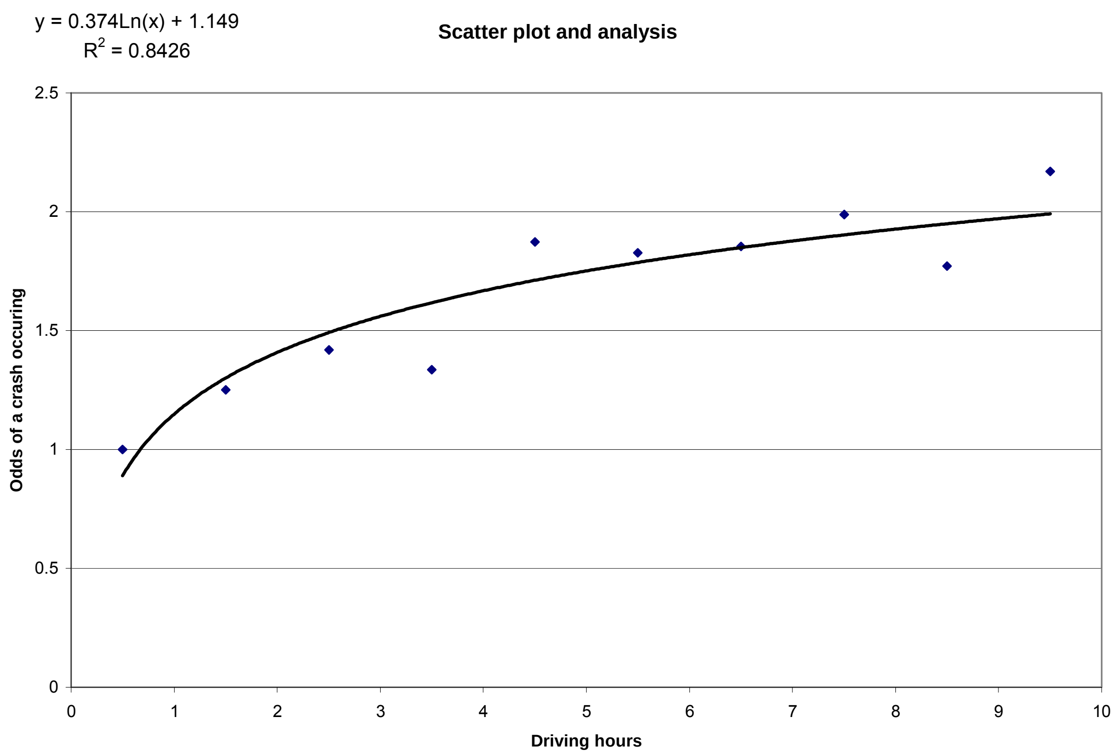

Figure 3. Trend line of given data

The relation appears to be logarithmic in nature and is defined by

$$crash\_odds = 1.149 + 0.374\ln(x)$$

The R^2 value, as denoted in the graph above, measures the variation of the data set being explained by the predictor variable. The value for this fit is 0.8426, which implies that the regression equation is satisfactory in explaining the relationship between the parameters. This equation can be utilized in further steps, especially to determine crash likelihoods of drivers who have been on the road for more than x hours. Also modified HOS constraints can be built based on the crash likelihood values predicted by this equation.

We now develop a method to compute the reduction in accidents due to HOS constraints assuming that the HOS constraint truncates the distribution P(x). An exponential distribution for driving time is used as illustration. A graph showing the exponential distribution of proportion of crashes against driving times with a mean driving time of four hours and an upper bound of 10 hours has been plotted below for illustration. The plot and the methodology are described below.

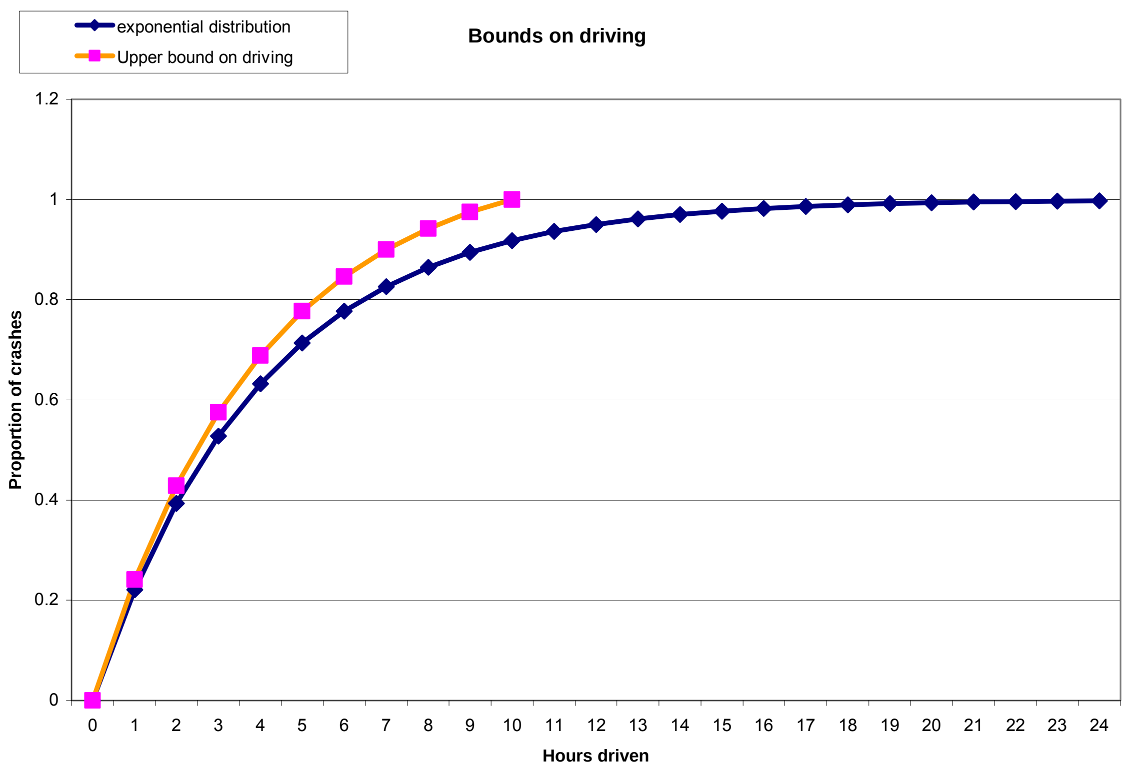

Figure 4. Upper Bounds on Driving Hours

From the graph above, any point on the driving hours can be chosen and the corresponding reduction in crashes can be determined by employing the relevant methods. In this example, it is desired to determine the reduction in crashes if trip length is restricted to no more than 10 hours. In such a case, the following steps are employed.

$$F(x) = 1 - e^{-0.25x}$$

$$F(HOS) = 1 - e^{-0.25*10} = 1 - e^{-2.5} = 0.9179$$

$$F'(x) = \frac{F(x)}{F(HOS)} = \frac{1 - e^{-0.25x}}{0.9179}$$

$$Odds\_ratio(O.R.) = 1.149 + 0.374 \ln x$$

Hence the proportional reduction in crashes can be expressed as the following:

$$\text{Reduction} = 1 - \frac{\int_0^{10} \frac{d(F'(x))}{dx} O.R.(x)dx}{\int_0^{\infty} \frac{d(F(x)}{dx} O.R(x)dx}$$

$$\text{Reduction} = 1 - \frac{\int_0^{10} \frac{d(\frac{1-e^{-0.25x}}{0.9179})}{dx}(1.149 + 0.374\ln x)dx}{\int_0^{\infty} \frac{d(1-e^{-0.25x})}{dx}(1.149 + 0.374\ln x)dx}$$

$$\text{Reduction} = 1 - \frac{\int_0^{10} 0.2723e^{-0.25x}(1.149 + 0.374\ln x)dx}{\int_0^{\infty} 0.25e^{-0.25x}(1.149 + 0.374\ln x)dx}$$

$$\text{Reduction} = 1 - 1.089\frac{\int_0^{10} (1.149e^{-0.25x} + 0.374e^{-0.25x}\ln x)dx}{\int_0^{\infty} (1.149e^{-0.25x} + 0.374e^{-0.25x}\ln x)dx}$$

The reduction value can be computed by obtaining the ratio of the integral values. Using Mathematica 5.2 software, the value was computed to be equal to 0.756. Hence, the integral equation can be summed up as the following:

$$\text{Reduction} = 1 - 1.089\frac{\int_0^{10} (1.149e^{-0.25x} + 0.374e^{-0.25x}\ln x)dx}{\int_0^{\infty} (1.149e^{-0.25x} + 0.374e^{-0.25x}\ln x)dx} = 1 - 1.089 * \frac{5.10909}{5.80638}$$

$$or, \text{Reduction} = 1 - 0.958222 = 0.041778$$

Reduction in crashes with upper bounds of 6, 7, 8, 9, 10, 11 and 12 hours and mean driving times of 2, 4, 6 and 8 hours is shown in Table 4.

	Upper Bound on Hours							
Mean Driving Time		**6**	**7**	**8**	**9**	**10**	**11**	**12**
	2	3.2%	2.0%	1.3%	.80%	.50%	.31%	.20%
	4	11%	8.3%	6.6%	5.2%	4.2%	3.3%	2.6%
	6	16%	13%	11%	9.6%	8.2%	7.0%	6.0%
	8	20%	17%	15%	13%	12%	10%	9.0%

Table 4. Reduction in crashes due to Upper Bounds

4.2.3 Preliminary Analysis of FARS Data.

We now turn to the FARS data set, which provides a basis for determining the distribution H(x), the probability that an accident involved truck has driven more than x hours. A histogram of the 2000 data set has been shown in Figure 5, and Figure 6 represents the cumulative distribution for driving hours at time of accidents, or the 1-H(x) distribution, for all three data sets.

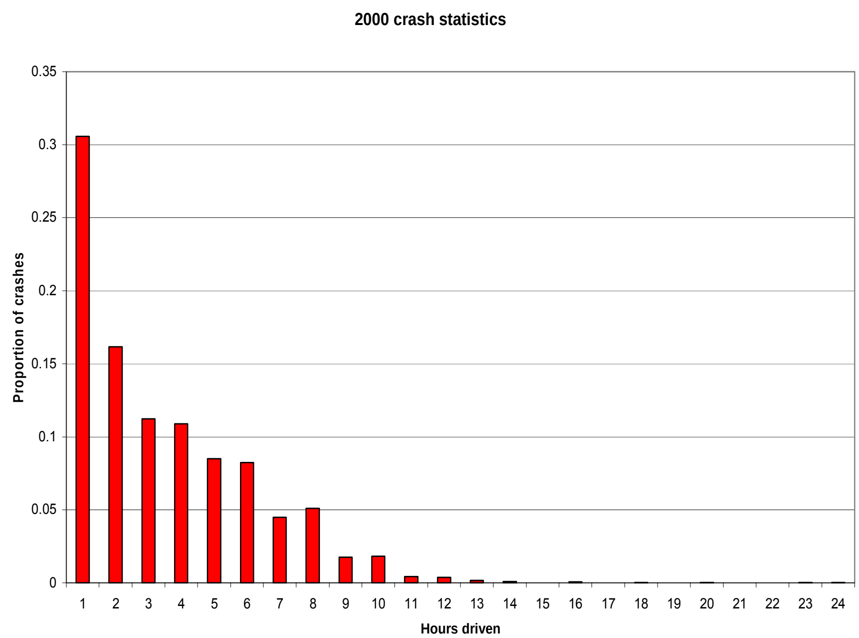

Figure 5. Bar chart - proportion of crashes for year 2000.

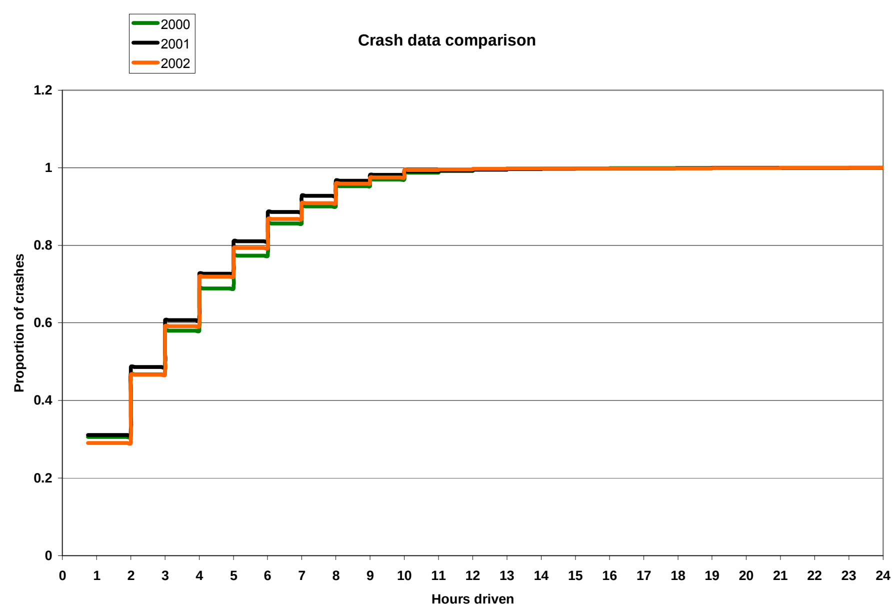

Figure 6. 1-H(x) distributions for years 2000-2002.

In the previous sections, reduction in crashes was computed by using the equation Reduction = H(x) – Transference to shorter trips. The upper bound for reduction in crashes is the value H(x), when the number of trips transferred is 0. Hence Reduction ≤ H(x), and in the table below the upper bounds for reduction are shown for each hour of driving. For example, in the 2001 data set, the mean driving time at time of accident is 3.33 hours. Assuming that drivers can only drive for a maximum of 8 hours, it can be seen that the total reduction in crashes is 0.033806. This means that there is a 3.33% reduction in crashes when drivers are only allowed to operate for a maximum of 8 consecutive hours. With the given mean driving times, and the driving hour constraints, the reduction in crashes can be found from Table 5.

Driving hours	Mean driving time = 3.544 hrs	Mean driving time = 3.33 hrs	Mean driving time = 3.453 hrs
	Year 2000	***Year 2001***	***Year 2002***
1	0.694255	0.689204	0.709677
2	0.532619	0.513631	0.53331
3	0.420318	0.393312	0.408836
4	0.311263	0.272992	0.280856
5	0.226225	0.189749	0.206872
6	0.143784	0.114504	0.131837
7	0.098994	0.072701	0.091164
8	0.048036	0.033806	0.041024
9	0.03051	0.017812	0.024544
10	0.012334	0.009088	0.005961
11	0.008114	0.006543	0.004208

Table 5. H(x) empirical distributions for years 2000-2002.

It can be noted from the table that an absolute constraint on trips of no more than eight hours would at most reduce fatalities by 3-5% compared to the current situation. This would depend on perfect enforcement, combined with an assumption of no transference of fatalities to shorter trips. In ongoing work, we are continuing to investigate reductions in fatalities by combining the distributional data, H(x), with the odds ratio model. This will lead to a more precise (and smaller) estimate of fatality reduction.

5. CONCLUSIONS

Driving HOS has been host to a plethora of studies and related research. The goal of concerned authorities has been to determine safer ways of operating trucks, while optimizing costs for trucking organizations. Studies have been conducted that have identified driver fatigue, lengthy driving hours, sleep debt and poor driving performance as some of the factors that have affected truck safety.

While it is impossible to study the role of each of these factors in detail, emphasis has been laid on the driving hours. Driving hours collected from drivers involved in fatal crashes through the FARS/TIFA data set were used in a suitable statistical model as one of the predictor variables to determine how driving hours influence the probability that a truck driver is involved in a crash. Once the results were obtained, the analysis of these results can show how driving hours are correlated to crash odds. If the data show that longer driving hours signify higher crash risk levels for drivers, a modified set of constraints would be created that allow the driver to drive for lesser hours and thus ensure that the drivers have lower odds of being involved in a crash. These modified constraints would then be used in a truck network model to determine how the constraints influence the model.

The effective analysis of trucking costs and benefits when subjected to HOS constraints is the primary goal of our future research. Every truck network is associated with a multitude of cost factors. These include the operating costs for sending a shipment from an origin to a destination, fixed costs, and costs incurred in sorting operations, etc. The reduction of such costs and maximization of earned revenue while subject to the HOS constraints will be investigated. The idea of integrating truck safety and trucking costs, two diverse topics, is quite challenging and can shed new light on the ongoing issue of truck safety.

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