Improving Trucking Safety: Effects of Driver Hours of Service Regulations

Final Report

Metrans Project 05-10

November 9, 2006

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DISCLAIMOR

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. These then are applied to economic statistics for truck crashes to compute bounds on the benefits of hours-of-service restrictions. We also analyze costs of restrictions through use of a linear programming model that optimizes trucking operations in the presence of constraints on driver tour lengths. In conclusion…

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DISCLOSURE

Project was funded in entirety under this contract to California Department of Transportation.

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. 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 creates methods for bounding 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 must comply with HOS rules, and any change in these HOS rules also affects the operations of the truck operators. 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. We also evaluate economic costs and benefits of HOS constraints based on the bounds that we have created, along with modeling truck operations.

2. BACKGROUND

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. 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.

Driver Hours of Service (HOS) are intended to ensure that fatigue does not reduce safety. HOS rules were implemented in the United States 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 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 January 2004, a new set of rules was implemented. The new regulations limit a driver to no more 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 1).

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 1. 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 five 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.

Some exceptions to these rules are applicable to commercial motor vehicle (CMV) operators. Truck 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 that neither period is less than two 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 operate after the 14^{th} hour.

The effect of HOS rules on truck safety and its economic impact on trucking operations has been observed by the Federal Motor Carrier Safety Administration (FMCSA). Table 2 shows the significant impact of HOS on both truck safety and truck operations, according to the FMCSA.

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 2. Hours of Service (HOS) related statistics for large trucks.

The National Center for Statistics and Analysis (NCSA) compiles crash data and issues periodic reports on truck crashes. The FARS data utilized in this paper are developed by NCSA and are often used to generate reports similar to the one shown above. 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. NHTSA has been recording fatal truck crashes since 1975.

The national Motor Carrier Management Information System (MCMIS), another system similar to FARS, is operated by the FMCSA. MCMIS includes information on the safety robustness of commercial motor carriers. Fatal crashes involving large trucks are collected in MCMIS.

The remainder of this paper is directed at developing probabilistic models to compute upper bounds on the reduction in crashes due to the imposition of hours-of-service regulations. Section 3 reviews related literature. Section 4 develops and demonstrates probabilistic models, and Section 5 provides an economic assessment of costs and benefits of HOS regulations. Section 6 provides conclusions and Section 7 discusses implementation.

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.

Driving hours of service has been an active field of research. Kaneko and 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. 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.

Jones and Stein (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 Kaneko and Jovanis (1990), and Wylie et al (1997).

Braver et al (1992) surveyed 1249 tractor-trailer drivers, of which 73% reported that they 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. 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) found significant changes in the driving performance of truck and bus drivers in the ten hour time frame. Drivers committed more errors and were physically less aware of 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 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 et al (1993), which examined motor carrier safety. The authors found that driving time was strongly associated with crash risk. The likelihood of a crash increased significantly after the fourth hour of driving and kept on increasing with longer driving hours.

In 1995, the National Transportation Safety Board (NTSB) examined single vehicle truck accidents with respect to drivers' pattern of duty and sleep. 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 in the last 24 hours prior to the crash, and split sleep patterns were important parameters 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 less than the 8 hours of sleep for the set of exposure drivers. 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.

Wylie (1997) et al investigated the degree of recovery afforded to truck drivers by rest periods. A group of five 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 to four different conditions. The first group of three drivers was allowed no off duty periods; the second group of five drivers was allowed a 36-hour period off and then worked for four additional days; the third group of six drivers was given 36 hours off and then worked an extra day. The final group of six drivers was given a break of 48 hours and then allowed to work an additional day. The analysis showed that night drivers performed worse than their daytime counterparts. The subjects who 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. The experiment showed that a 48-hour break is significantly better than either 24 or 36 hours.

Mackie and Miller (1978) determined that truck drivers operating on irregular schedules received less sleep and showed signs of fatigue prior to 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. 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 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. 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 use of two drivers to operate the vehicle continuously. The drivers periodically relieve each other at the wheel and drive under the given HOS regulations while also taking the prescribed breaks from 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) also found that sleeper drivers tended to display greater driver fatigue and worse performance when compared to single drivers, when in both cases the two sets of drivers drove along the same route. Sleeper drivers showed worsened driving skills, increased 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. The authors found that sleeper drivers obtained less sleep than single drivers before commencing their driving operations. The study showed that sleeper drivers experience disrupted sleep and lower arousal levels that culminate in degraded driving performance.

O'Hanlon (1981) carried out a similar study to Mackie and Miller (1978). He determined that drivers 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 around midnight. Sleeper drivers are more prone to such decline in driving conditions and are unable to effectively respond to situations during late night and early morning driving.

Hertz (1988) related increased crash likelihoods to sleeper berth operations. Crash risk for sleeper drivers were similar to that of single drivers. This result contradicted 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. Dingus et al (2003) reported that single LTL drivers were more frequently involved in critical incidents than their team counterparts. Team drivers were more able to manage their fatigue levels and critical incident involvement than single drivers. Single drivers were four times more likely to be involved in a critical incident than team drivers.

Research into the science of sleep also provides insights into the challenge of maintaining safe operations toward the end of long driver tours. Carskadon and Dement (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.

Researchers have approached the subject of human sleep with 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 body fluids accrue in human blood when the human body is awake. These substances cause the feeling of exhaustion and during sleep, 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 the phenomenon of *Circadian Rhythms*, 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 that control appetite, energy, mood and sleep (see, for instance, Halberg et al, 2003). 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. 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. The SCN is a cluster of 50,000 neurons, or 10,000 cells, one on each side of the brain. 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) assessed 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 slept poorly due to the 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 performance 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 perform poorly 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 that 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 (NASA, 2006). 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 found that some flight crews admitted to nodding off during the flight and also sometimes arranged 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. 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.

4. BOUNDING METHODOLOGY

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 are created to 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. From these distributions, we provide a set of methods of computing an upper bound on the reduction in crashes due to the imposition of HOS constraints.

4.1 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. The distributions are defined as:

- ⇒ 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) = $\int_x^{\infty} g(z)\,P(T>x|z)\,dz$, 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) $\leq$ P(x).

Let the accident rate per unit of time be denoted as a(x), where x denotes the time traveled since departure. 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.

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

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) as explained below. This can be summarized as Reduction in crashes = H(x) – Transference to shorter trips.

The term “transference to shorter trips” represents the transfer of risk from the ends of long trips to substituted shorter trips. For instance, if a trip that would otherwise take 10 hours is truncated to eight hours, the deleted two hours of duty must be covered in another trip of shorter length. The hours-of-service constraint reduces total crashes if the crash risk for the final two hours of duty is shorter than the crash risk for the substituted hours. The transference value must be non-negative, and therefore H(x) is an upper bound on crash reduction.

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 F(x); the probability 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:

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

Therefore, F(x) can be rewritten as,

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

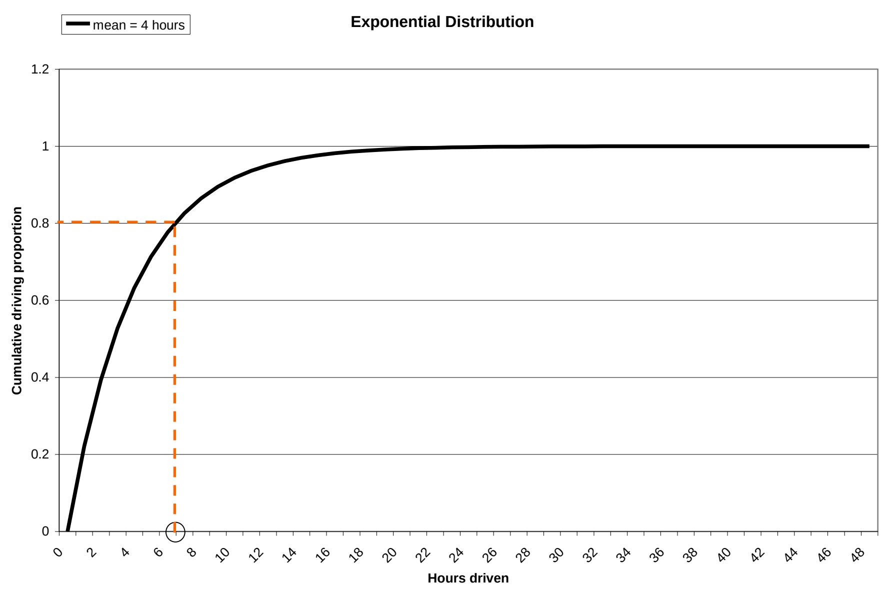

Figure 1: Exponential distribution of driving times with mean = 4 hours.

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:

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

$$or, F(x) = 0.173805 - 0.121605 = 0.0522$$

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 four 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). Differentiating F(x) yields the function f'(x). This is shown as the following:

$f'(x) = -\frac{dF(x)}{dx}$, 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). For this example, suppose 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 by dividing the integrals. Using the same example given above, and assuming an 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 transferred 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 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:

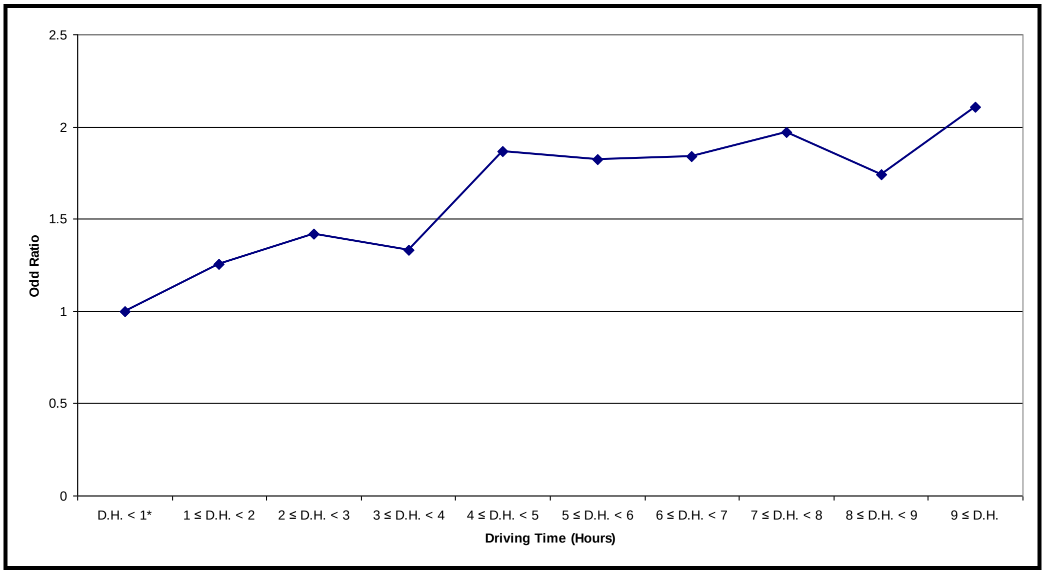

Figure 2: Odds ratio.

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 zero, 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.

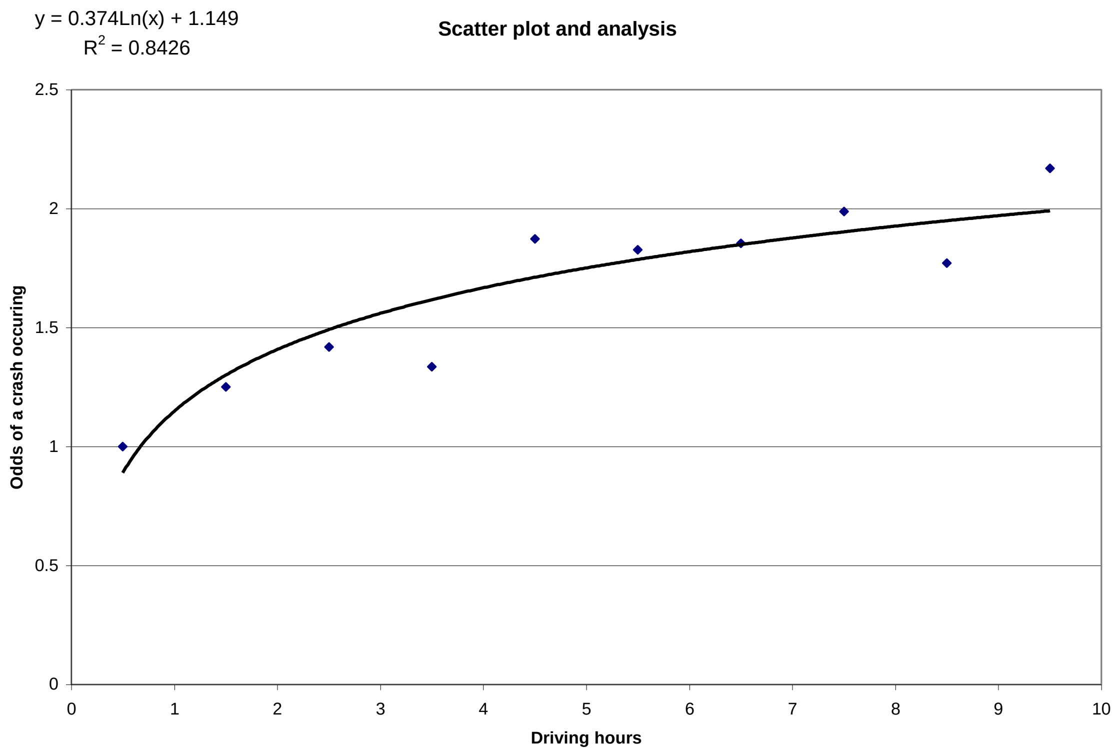

Figure 3: Trend line of odds ratio data.

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

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

The R^2 value for this fit is 0.8426. 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 ten hours, has been plotted in Figure 4 for illustration. The plot and the methodology are described below.

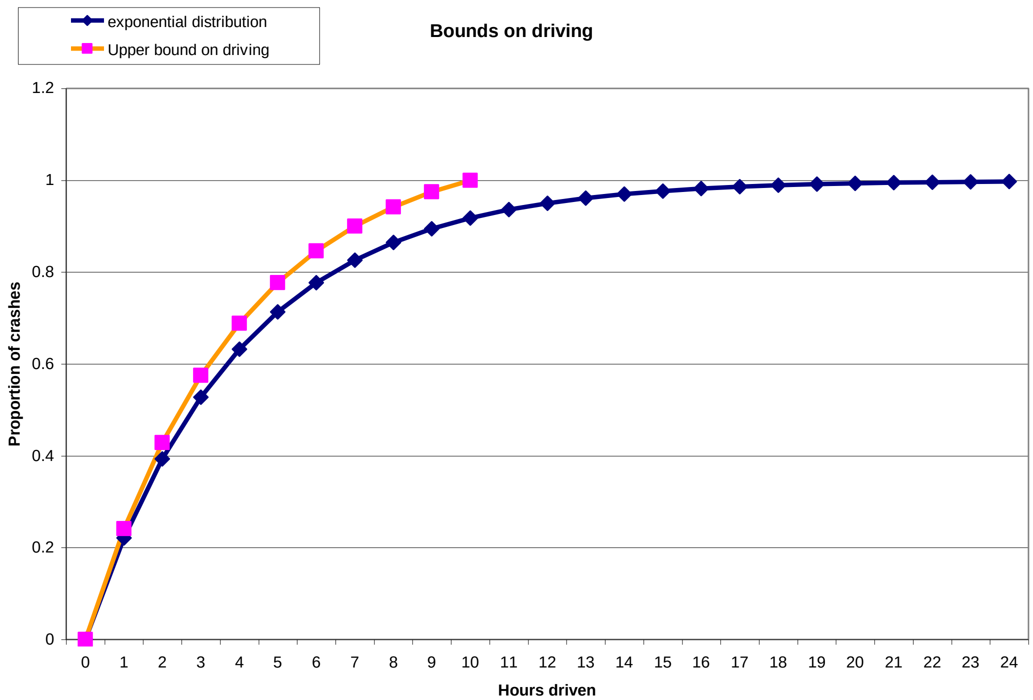

Figure 4: Upper bounds on driving hours (exponential distribution).

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 ten 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:

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

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

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

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

Hence the reduction was computed to be 4.2%. 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 3.

	Upper Bound on Hours							
Mean Driving Time	**μ**	**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 3: Reduction in crashes due to upper bounds.

A similar procedure may be adopted to determine the reduction of crashes due to HOS constraints for other probability distributions. We will now use the normal distribution as an example. We will later utilize coefficient of variation values of .15 and .3, with mean trip lengths ranging from two to eight hours, and upper bounds ranging from six to 12 hours. But first, we use a mean driving time of eight hours, and a standard deviation of 2.4 hours for illustration (Figure 5). All values used in the example provide a very small probability of negative outcomes.

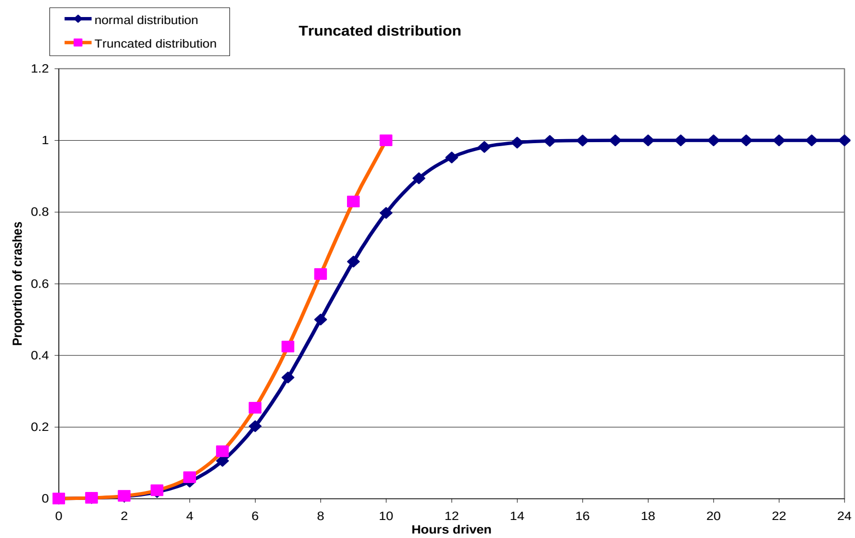

Figure 5: Upper bounds on driving hours (normal distribution).

If the trip length is restricted to no more than 10 hours, then

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-(x-\mu)^2/(2\sigma^2)} dx$$

$$F(HOS) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{10} e^{-(x-8)^2/(2*(0.2.4)^2)} dx = 0.797671$$

$$F'(x) = \frac{F(x)}{F(HOS)}$$

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

The reduction in crashes can be expressed through the equations below.

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

$$\text{Re}\,duction = 1 - 1.2536 * \frac{\int_0^{10} \frac{d(\int_{-\infty}^{x} e^{-(x-8)^2/(11.52)}dx)}{dx}(1.149 + 0.374\ln x)dx}{\int_0^{\infty} \frac{d(\int_{-\infty}^{x} e^{-(x-8)^2/(11.52)}dx)}{dx}(1.149 + 0.374\ln x)dx}$$

$$\text{Re}\,duction = 1 - 0.9801 = 0.0199$$

A reduction of 1.99% is obtained when a constraint of 10 hours is applied on the driving hours. The table below shows the reduction of crashes for g(x) as the normal distribution. The mean driving time and the variance in driving times of truck drivers in the US are unknown parameters. A study carried out by FMCSA in 2003 has indicated that the average trip length lies in the region of 6 hours, but the variation in driving times was not recorded. Keeping this fact in mind, calculations were carried out by varying both the mean and the upper bound to get a wide spectrum of different plausible scenarios.

σ =15% of μ	**Upper Bound**					
Mean Driving Time	**μ**	**8**	**9**	**10**	**11**	**12**
	6	0.0924%	0.003%	0%	0%	0%
	7	0.868%	0.1787%	0.017%	0%	0%
	8	2.36%	0.985%	0.27%	0.0437%	0.0031248%
	9	4.067%	2.31%	1.08%	0.373%	0.085%

Table 4a: Reduction in crashes due to upper bounds (σ =15% of μ).

σ =30% of μ	**Upper Bound**					
Mean Driving Time	**μ**	**8**	**9**	**10**	**11**	**12**
	6	1.428%	0.5%	0.17%	0.04%	0.007%
	7	3.17%	1.739%	0.8%	0.339%	0.11%
	8	5.104%	3.33%	1.99%	1.08%	0.5%
	9	7%	4.99%	3.405%	2.19%	1.318%

Table 4b: Reduction in crashes due to upper bounds (σ =30% of μ).

From the tables above it can be concluded that a maximum reduction of 7% in crashes is achieved when the mean driving time is 9 hours and an upper bound of 8 hours is applied to the driving time. In this case a normal distribution was adopted to replicate the driving hours. The actual empirical distribution of driving times is unknown; hence it has been assumed that the exponential and normal distributions replicate the empirical one.

4.3 Preliminary Analysis of FARS Data.

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 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 data are divided into four categories – crashes, persons, vehicles and drivers. Out of 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. In addition to the FARS data, an extra set of variables are produced by TIFA, collected from police reports and surveys. TIFA data provides the length of time that drivers had been driving at the time of the crash. The driving times are obtained from the driver surveys collected by TIFA, as well as through police reports or from operator logs. This time is a lower bound for hours of service at time of crash, as the driver may have completed a prior trip in the same duty period. In many instances, however, the two times would be the same. Due to the absence of data on hours of service at time of crash, the following analysis is based on driving time at time of crash.

We now turn to the FARS data sets from the years 2000 until 2003, which provide 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 data sets has been shown in Figure 6, and Figure 7 represents the cumulative distribution for driving hours at time of accidents, or the 1-H(x) distribution, for all three data sets.

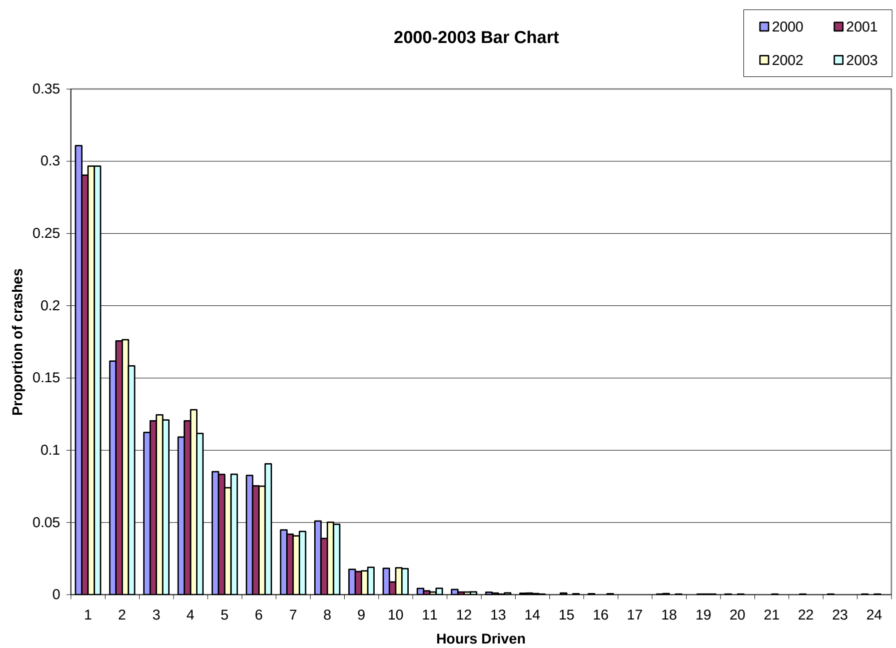

Figure 6: Bar chart - proportion of crashes for years 2000-2003.

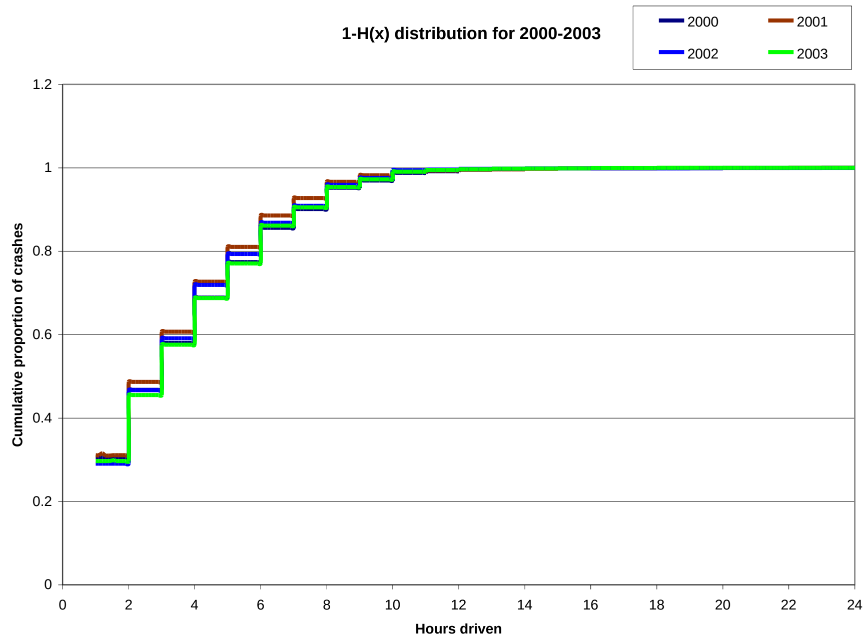

Figure 7: 1-H(x) distributions for years 2000-2003.

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 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	Mean driving time = 3.5478 hrs
	Year 2000	***Year 2001***	***Year 2002***	***Year 2003***
1	0.694255	0.689204	0.709677	0.70344
2	0.532619	0.513631	0.53331	0.545088
3	0.420318	0.393312	0.408836	0.424233
4	0.311263	0.272992	0.280856	0.312674
5	0.226225	0.189749	0.206872	0.229315
6	0.143784	0.114504	0.131837	0.138829
7	0.098994	0.072701	0.091164	0.095135
8	0.048036	0.033806	0.041024	0.046483
9	0.03051	0.017812	0.024544	0.02758
10	0.012334	0.009088	0.005961	0.009606
11	0.008114	0.006543	0.004208	0.005268
12	0.004544	0.004726	0.002454	0.003409
13	0.002921	0.003635	0.002104	0.002169
14	0.001947	0.002545	0.001403	0.001859
15	0.001947	0.001454	0.001403	0.00124
20	0.000649	0.000364	0.000701	0

Table 5: H(x) empirical distributions for years 2000-2003.

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.

4.4 Mean Hours Until Crash

In addition to affecting crash rates, HOS constrains can affect the mean driving hours at time of crash. HOS constraints have the effect of truncating the distribution of time until crash and, hence, reduce its mean value. To examine this effect, Table 6 contains the values for the proportion of crashes at every given hour. The mean hour was determined by adding the product of the individual driving times with their respective probabilities and then dividing the value by the sum of the probabilities.

Driving hours	**Mean driving time = 3.544 hrs**	**Mean driving time = 3.33 hrs**	**Mean driving time = 3.453 hrs**	**Mean driving time = 3.5478 hrs**
	Year 2000	***Year 2001***	***Year 2002***	***Year 2003***
1	0.305745	0.310796	0.290323	0.29656
2	0.161636	0.175573	0.176367	0.158352
3	0.112301	0.120319	0.124474	0.120855
4	0.109055	0.12032	0.12798	0.111559
5	0.085038	0.083243	0.073984	0.083359
6	0.082441	0.075245	0.075035	0.090486
7	0.04479	0.041803	0.040673	0.043694
8	0.050958	0.038895	0.05014	0.048652
9	0.017526	0.015994	0.01648	0.018903
10	0.018176	0.008724	0.018583	0.017974
11	0.00422	0.002545	0.001753	0.004338
12	0.00357	0.001817	0.001754	0.001859
13	0.001623	0.001091	0.00035	0.00124
14	0.000974	0.00109	0.000701	0.00031
15	0	0.001091	0	0.000619
20	0.001298	0.00109	0.000702	0.00124

Table 6: Probability values for proportion of crashes.

For example, if the mean driving time was to be examined, given that the truck driver can only drive for a maximum of six consecutive hours, the individual probabilities from one to six hours of driving would be multiplied to their respective driving times, and the sum of the product would be divided by the sum of the probabilities. This method uses the weighted mean concept and provides a reasonably accurate estimate of the average driving hour before the crash occurs. An example has been shown in the following paragraph, assuming the driver can only drive for a maximum of four consecutive hours. Then:

$$\max .HOS = 4$$

$$E(X \mid X \leq 4) = \frac{1*0.305 + 2*0.161 + 3*0.112 + 4*0.109}{0.305 + 0.161 + 0.112 + 0.109}$$

$$or, E(X \mid X \leq 4) = 2.035$$

This means that the average driving time before a crash occurs is 2.035 hours, given that four hours is the upper bound for driving times. Table 7 below provides the mean driving times for different HOS constraints.

Upper bounds on driving	**Expected number of driving hours**			
	Year 2000	***Year 2001***	***Year 2002***	***Year 2003***
4	2.035813	2.068999	2.125303	2.068982
5	2.361578	2.370122	2.393459	2.386007
6	2.711904	2.678571	2.705171	2.765741
7	2.92507	2.873383	2.897376	2.970204
8	3.196728	3.079759	3.164167	3.226843
9	3.301637	3.176165	3.262761	3.339069
10	3.424907	3.236242	3.38871	3.459953
11	3.457135	3.256131	3.402109	3.492835
12	3.487772	3.272094	3.417227	3.508704
13	3.503256	3.282746	3.420588	3.520499

Table 7: Expected number of driving hours at time of crash.

Note for Table 5 that the mean time until crash increases at a less than linear rate, approaching an upper bound, representing the time observed in the FARS data.

Any truck crash imposes several costs on the driver of the truck, the vehicle itself, any other drivers and vehicles involved in the crash and on society as well. In addition to property damage, injuries and fatalities, there are several costs associated with emergency services, travel delays and costs incurred by the trucking operator or organization. An analysis of costs and savings that can be achieved by modifying the driving hour constraints is focused in this paper. Costs have been calculated for those crash involved trucks that weigh over 10,000 lbs.

5. ECONOMIC ASSESSMENT

This section is focused on an economic assessment of the costs and benefits of HOS constraints. In Section 6.1, we combine the bounds created in Section 4 with available data on the costs of truck involved collisions in the United States to compute bounds on the economic savings due to HOS constraints. In Section 6.2, we utilize a truck fleet optimization model to estimate costs on trucking operations associated with imposition of the constraints.

5.1 Impact on Crash Costs

Crash costs were estimated by applying data on the costs of truck crashes from Miller and Spicer (2000) to our bounding data. Miller and Spicer accounted for these costs: medical costs, emergency costs, property damage, lost productivity and monetized quality adjusted life years (QALYs). Miller used crash databases including FARS and the General Estimate System (GES) to determine the costs. Trucks were categorized as follows:

1. Straight truck with no trailer.
2. Straight truck with trailer.
3. Straight truck unknown if with trailer.
4. Truck tractor with one trailer.
5. Truck tractor with two or three trailers.
6. Truck tractor with unknown number of trailers.
8. Medium/heavy truck, unknown if with trailer.
8. All large trucks.

Medical costs include hospital, physician, rehabilitation, prescription and related costs. Also coroner costs and burial costs for fatalities and claims costs of medically related loss compensation are taken into account. Emergency service costs include police, fire, ambulance and helicopter services. Property damage stood for all costs related to repairing or replacing damaged vehicles, cargo and other property. Lost productivity included wages, fringe benefits, household work lost by the injured and costs incurred in processing productivity loss. Monetized quality adjusted life years (QALYs) implied the pain, suffering and quality of life lost by a family due to death or injury. The monetized quality of life years in 2004 dollars amounts to approximately $ 3 million in case of a fatal injury. Initial costs had been calculated by Miller in terms of 1997 dollars. The final values were adjusted to 1999 dollars and these values were used as the initial data for his paper. We made further adjustments to estimate the costs in 2004 dollars, taking into account two main elements: changes in annual vehicle miles traveled by trucks and inflation.

The FARS data system reported that truck miles traveled in millions had increased from 191,477 million to 226,504 million in 2004. This implies that truck miles traveled increased by an average of 2.24%/year over the last seven years. The consumer price index increased an average of about 2%/year since 1997 (derived Bureau of Labor Statistics data). We also examined the total number of truck involved fatalities occurring annually since 1997, which fluctuated between 4,900 and 5,316 deaths per year. The value has remained steady for the last five years; hence, changes in the annual rates of fatality were excluded in the final calculations. On combining the first two factors, the final costs for all large truck crashes were computed using the year 2004 as the reference or the base line. The final cost values in millions are shown in Table 8.

Truck type	Medical costs	Emergency costs	Property Damages	Lost productivity	Total lost productivity	Monetized QALYs	Total
Straight truck no trailer	507	27	747	2,164	3,729	5,054	10,064
Straight truck with trailer	60	4	87	241	578	1,006	1,735
straight truck unknown with trailer							
Bobtail	24	2	50	155	203	156	435
Truck-tractor, 1 trailer	538	36	942	2,562	5,754	8,969	16,239
Truck-tractor, 2 -3 trailers	24	2	32	83	451	962	1,470
Truck-tractor, unknown # of trailers	2	0.2	6	8	13	13	33
Medium/heavy truck, unknown if with trailer	5	0.4	12	30	42	31	89
All large trucks	1,160	71	1,875	5,243	10,769	16,190	30,066

Table 8: Total crash costs in millions by truck type (in 2004 dollars).

The total cost due to truck crashes was approximately $ 30.1 billion in 2004. Table 8 represents the component costs as well as the costs for the different trucking types. Out of the $30.1 billion, monetized QALYs accounted for the largest share, with a value of $16.2 billion. Total lost productivity followed with a value of $ 10.8 billion and the rest was split between medical costs, emergency and property damages.

We now turn to reduction in costs by applying constraining driving hours. In Section 4, bounds on reduction in crashes were created from four probability distributions, three theoretical (based on exponential and normal distributions), and the fourth empirical based on FARS data. For each distribution and HOS value, we applied the calculated bound for the reduction in crashes to the total economic costs due to truck involved crashes, as shown above. Results are provided in Figures 8-11 for the four distributions, and in Table 9 for the empirical distribution. For the empirical data, we provide multiple graphs, each derived from the empirical distribution for a different year. We also provide a graph representing the average data among all of the years examined. One note to point, before discussing the results, is that the figures predict a savings, even for HOS values that exceed the current limit. This is because our graphs assume perfect compliance, when in reality some crashes occur beyond the legal limit.

We observe the following:

- The greatest savings occur when the both when the mean driving time is long, and when the variability is large. This is because more trips would otherwise exceed the bound imposed by the hours of service constraint.

- The savings increase as the hours of service constraint is tightened. Of all the examples, the greatest savings occur with an exponential trip length distribution with a mean of eight hours and an HOS constraint of six hours, in which case the potential savings is no more than $6 billion per year.

- As a more realistic estimate, an 8 hours HOS constraint could provide up to $1.2 billion in annual savings, as derived from the empirical distribution, or with a normally distributed trip length of 9 hours with a standard deviation of 1.35 hours.

- The total achievable economic savings, while significant, is quite small relative to the size of the United States economy (a factor on the order of .01%).

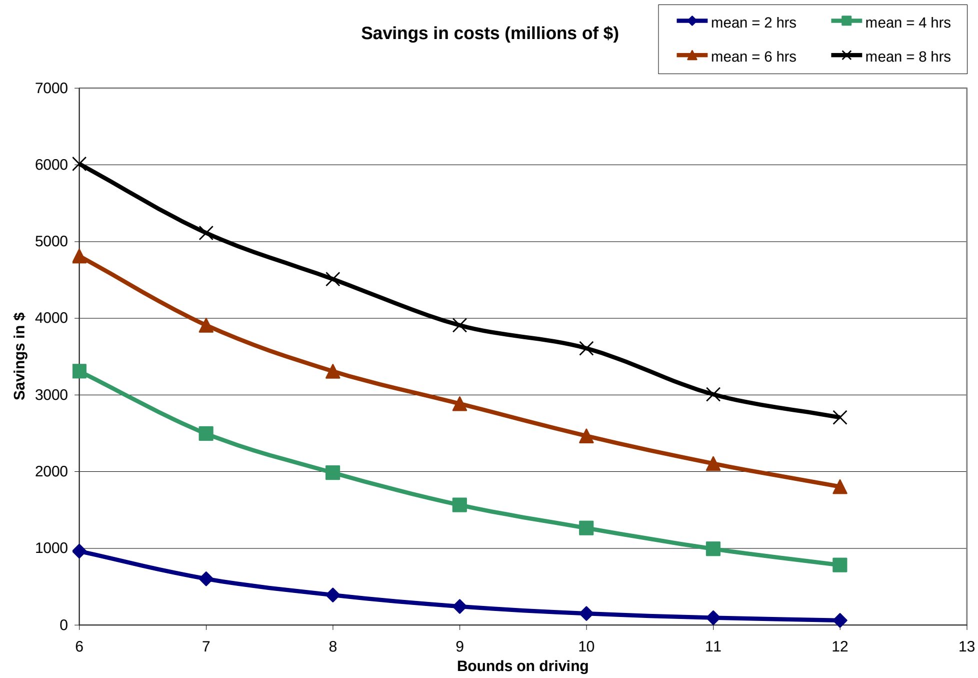

Figure 8: Savings in cost for exponential distribution.

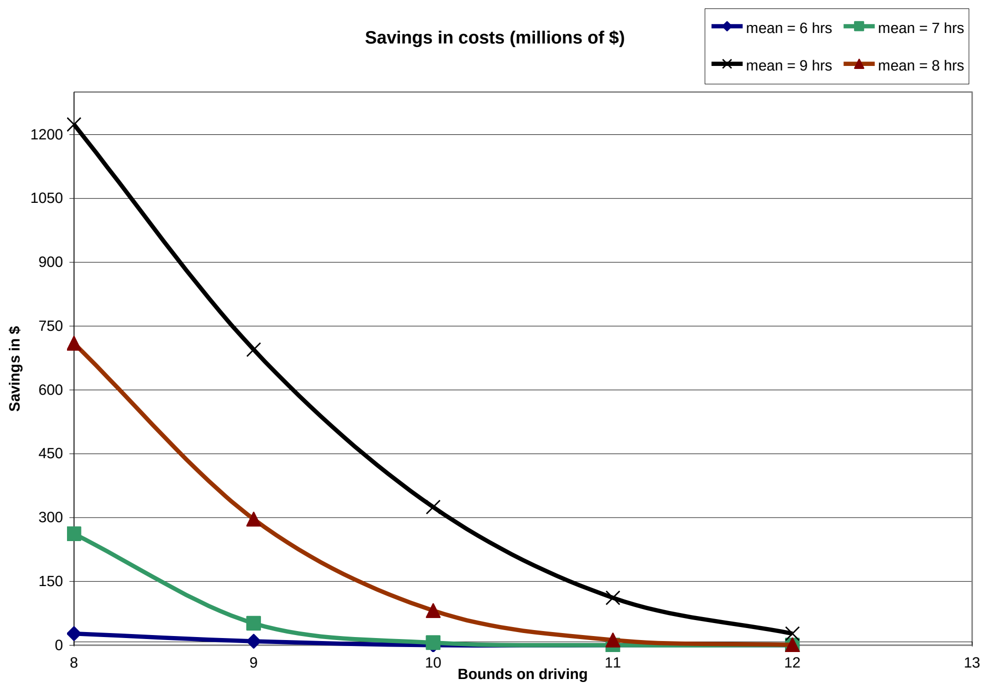

Figure 9: Savings in cost for normal distribution (SD = 15% of mean).

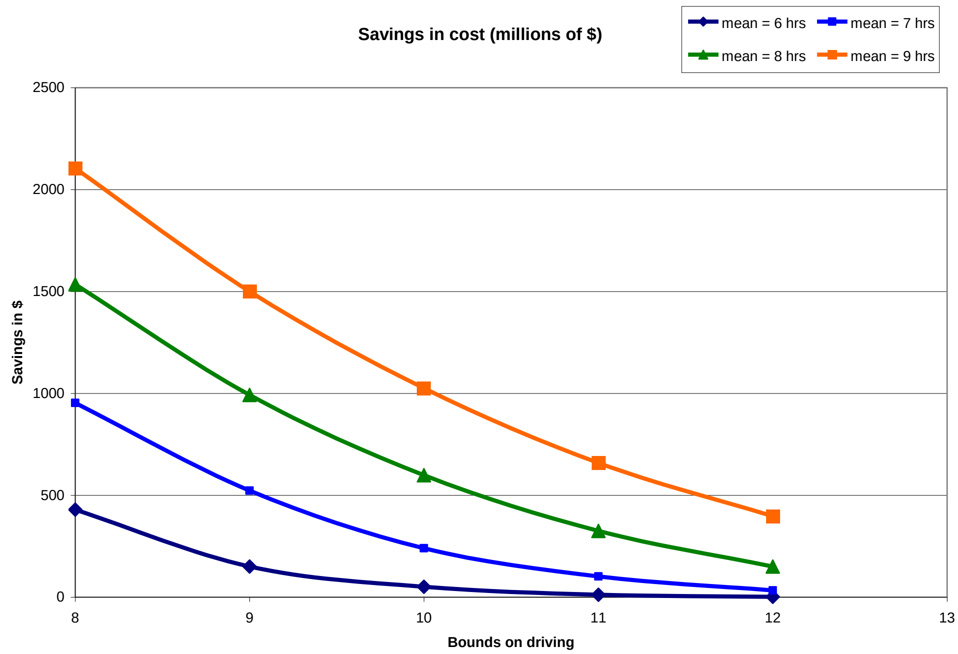

Figure 10: Savings in cost for normal distribution (SD = 30% of mean)

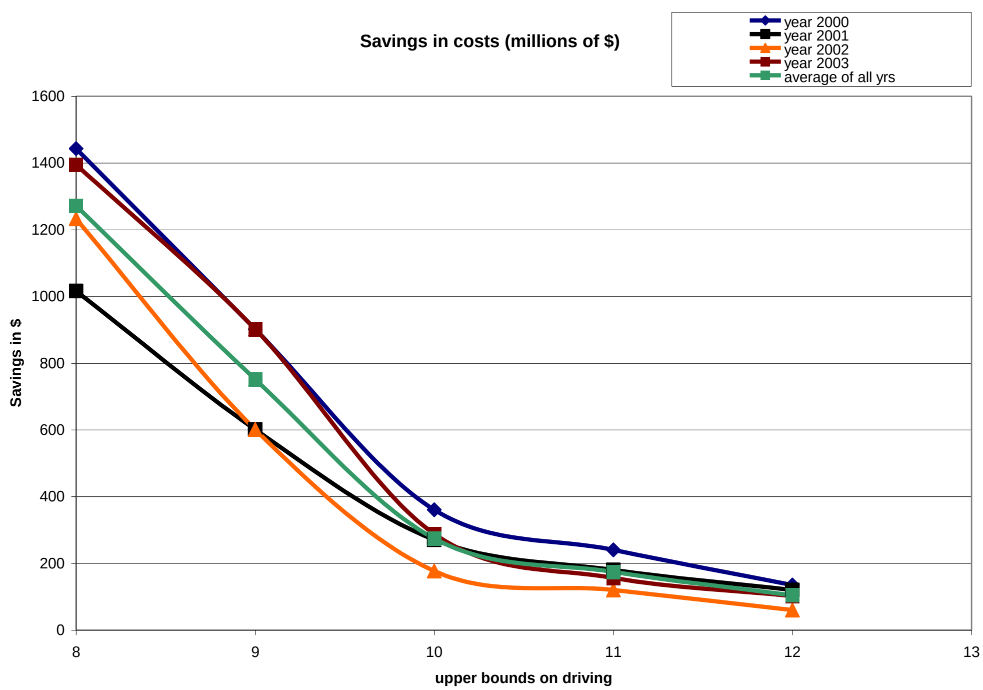

Figure 11: Savings in cost for empirical distribution.

Truck type	Bounds on driving				
	8	9	10	11	12
	Reduction Percentage				
	4.23%	2.48%	0.91%	0.58%	0.35%
	Total savings in cost				
Straight truck no trailer	$426	$252	$92	$58	$35
Straight truck with trailer	$73	$43	$16	$10	$6
Bobtail	$18	$11	$4	$3	$2
Truck-tractor, 1 trailer	$687	$406	$148	$94	$56
Truck-tractor, 2 -3 trailers	$62	$37	$13	$9	$5
Truck-tractor, unknown # of trailers	$1	$1	$0	$0	$0
Medium/heavy truck, unknown if with trailer	$4	$2	$1	$1	$0
All large trucks	$1,272	$752	$274	$174	$104

Table 9. Average reduction in costs for empirical distribution (millions of dollars).

5.2 Operating Costs

In this section, we estimate the operating costs to carriers associated with HOS restrictions by evaluating sample trucking networks. We have used a prototypical network linking the 50 largest metropolitan areas (in terms of the population size) in United States under a range of parameter settings, analyzing the sensitivity of cost to input parameters.

The analysis builds from the network optimization code developed by Caliskan and Hall (2006). In their work, a static linear programming (LP) model was formulated to optimize equipment and crew movements in long-haul trucking networks where drivers are required to return home within a reasonable amount of time. The model represents three types of driver routes, which we call relay, meet-and-turn, and sleep teams. A relay is a simple out and back route, completed in a day. A meet-and-turn entails matching drivers traveling in the opposite direction between pairs of cities, which meet at a mid-point, exchange loads, and return back to their home in the same day. A sleep route is a team of two drivers who alternately sleep and drive. These routes extend over multiple days.

A column generation algorithm was created and networks with up to 40 randomly generated nodes were optimized. We applied a post optimization heuristic to merge the short routes from the LP so that driver could serve more than one short route per day, as long as the total hours served by a driver is less than the pre-defined maximum service hours.

The optimization code requires, as input, these data:

- Average daily demand between each city pair
- Distance and travel time between each city pair
- Cost per mile and cost per day for truck/driver combinations
- Cost per mile for truck trailers

Distances were determined by applying the ArcView GIS system to the NTAD (national transportation atlas database) to calculate actual road distance between each city pair. Travel time was inferred from the distances, assuming a constant 50 miles per hour speed.

Daily demands were estimated from a gravity model based on 2004 populations estimates for the metropolitan areas. Two methods were used to estimate the demand, both of which assume that demand is proportional to the product of the city population sizes. Let d_{ij} denote the demand on arc (i,j); dis_{ij} denote the road distance of arc (i,j) and p_i denotes the population of city i. The first method assumes demand is inversely proportional to the distance between the two end-node cities:

$$d_{ij} = \alpha_1 \cdot \frac{p_i}{10000} \cdot \frac{p_j}{10000} \cdot \frac{1}{dis_{ij}} \text{ where } \alpha_1 = \frac{3000}{8505.61}$$

The second method assumes demand is inversely proportional to the power of 1.5 of the distance between the two end-node cities:

$$d_{ij} = \alpha_2 \cdot \frac{p_i}{10000} \cdot \frac{p_j}{10000} \cdot \frac{1}{dis_{ij}^{1.5}} \text{ where } \alpha_2 = \frac{3000}{1121}.$$

We normalize both cases to make the max $\{d_{ij}\}$ = 3000. (8505.61 and 1121 are the largest demand quantity as for Case 1 and Case 2 before normalizing).

5.2.1 Post Processing to Merge Shorter Routes

The basic algorithm in Caliskan and Hall (2006) does not explicitly account for fixed daily costs of driver wages. Thus, the program does not provide any incentive for a single driver to serve multiple routes in a shift, each serving one four hour route. We developed a post processing heuristic that merges shorter routes into combined routes in order to reduce the required number of drivers, and thus reduce fixed daily routes. The heuristic accounts for both the demand on each route, as well as the nodes served, as illustrated in the following example. Suppose that the initial steps of the algorithm produce two routes: one with duration 3 hours and flow 100 (meaning 100 trucks are needed to serve this route); another has duration 4 hours and flow 300. Both routes visit node number 1 and the maximum service time allowed per day for a driver is 8 hours. We can then merge these routes into one new route with duration 7 hours and flow 100 = min{100,300}, and a second route with duration 4 hours carrying the remainder flow of 200. Hence, 100 fewer drivers are needed as a consequence of this merge operation.

As shown in this example, there are two criteria to merge routes: 1. the summation of the routes' duration is less than Hour of Service per day for a driver; 2. the routes have at least one common node. In the post processing procedure, we use two methods to record the information: one is "Route," which contains the duration, flow, and nodes for a single route; another is "RouteBin," which is a set of merged routes served by a driver, defined by a total duration, flow, and node set. Each route inside a RouteBin must have at least one common node with all other routes in the RouteBin. The duration of a RouteBin is defined as the summation of the duration of every Route that it contains. We maintain two vectors of RouteBins, one is the in-processing vector, "ToBePackedRouteBins"; another is the vector containing the finished RouteBins, "FinishedRouteBins". We repeatedly select the longest-duration RouteBin from the ToBePackedRouteBins and try to merge it with another shorter RouteBin. If the longest duration RouteBin cannot be merged, it is removed from the ToBePackedRouteBins and put into the FinishedRouteBins; otherwise, it will be merged with another RouteBin, in which case a new RouteBin is generated, one RouteBin is removed and another is modified accordingly. This process repeats until there are no more possible merges (ToBePackedRouteBins is empty). Details of the heuristic follow in Table 10.

5.2.2 Computational Experiments and Results

We have analyzed the following parameter sets:

- Maximum hours of service per day: 7 hours, 8 hours, 9 hours and 10 hours.
- Fixed daily cost per driver, ranging from $35 to $200
- Per mile cost for trucks ranging from $1 to $1.40
- Maximum hours of service ranging from 7 to 10 hours.
- 30 minutes cushion is subtracted from the HOS constraint for meet-and-turn drivers
- Sleeper teams are permitted to cover routes extending up to five days.

Results of the analysis are provided in Table 11, leading to these observations:

- In the event that the fixed daily costs is a linear function of the HOS constraint (i.e., daily cost increases as the HOS constraint is extended), changes in the HOS rules have very little impact on cost, generally well less than 1% as the HOS constrain changes from 7 hours to 10 hours. Savings do occur when the HOS is extended, because more efficient routes can be constructed, but these savings are small.

- Alternately, if the fixed portion of cost is both significant and invariant to HOS, then change in HOS can have a large impact in cost. For instance, with a $200 daily cost and a $1/mile charge, costs increase by about 10% when the HOS constraint is tightened from 10 hours to 7 hours.

These examples provide insights into the impact of HOS and costs, but are not conclusive by themselves. The actual economic impact will vary significantly from company to company, depending on the type of freight served, particularly whether it is local or longhaul. The impact also depends on the competitive pay structure of employees, with the greatest advantage for extended HOS occurring when drivers demand a large guaranteed daily salary, independent of miles driven.

Input:
1. All routes with the duration, its flow quantity and nodes it passes through;
2. Maximum duration per day a driver can service. (HOS: Hours of service)

Procedure:
1. Select all routes whose duration is less than HOS into ToBePackedRoutes vector.
2. Sort ToBePackedRoutes vector according to its duration in descending order;
3. Make each route a RouteBin which only contain one route and its duration is the same as the route in it; put all RouteBins into ToBePackedRouteBins (automatically in an descending order of the duration of RouteBins). Set FlowSaving = 0.
4. while (ToBePackedRouteBins is not empty)

```
{
get the first RouteBin as FirstBin
for each RouteBin in the sequence
{
    get the RouteBin as CurBin
if (FirstBin can be merged with CurBin)
{
    NewBin.duration = FirstBin.duration + CurBin.duration;
    NewBin.nodes = FirstBin.nodes merge with CurBin.nodes;
    if (FirstBin.flow > CurBin.flow)
    {
            NewBin.flow = CurBin.flow;
FlowSaving += CurBin.flow;
            FirstBin.flow = FirstBin.flow - CurBin.flow;
            Remove CurBin from the ToBePackedRouteBins;
Insert NewBin into the ToBePackedRouteBins according to the descending order of duration;
}
else
{
            NewBin.flow = FirstBin.flow;
FlowSaving += FirstBin.flow;
            CurBin.flow = CurBin.flow - FirstBin.flow;
Remove FirstBin from the ToBePackedRouteBins;
Insert NewBin into the ToBePackedRouteBins according to the descending order of duration;
}
                        break;
}
}
if(FirstBin cannot be merged with any other RouteBins)
{
Remove FirstBin from ToBePackedRouteBins and insert it into FinishedRouteBins.
}
}
```

Output:
1. FinishedRouteBins;
2. total FlowSaving.

Table 10. Steps of heuristic.

			Maximum Tour Length					Cost= ('000s $)	
HOS	DP	Par	Relay	M & T	Sleeper	C1 $/mile	C2 $/day	CPLEX-Obj	Final-Obj
7 hour	D1	P1	7	6.5	70	1	175	$78,500	$78,500
	D1	P2	7	6.5	70	1.25	87.5	$78,500	$78,500
	D1	P3	7	6.5	70	1.4	35	$78,500	$78,500
	D1	P81	7	6.5	70	1	200	$81,367	$81,367
	D2	P1	7	6.5	70	1	175	$18,916	$18,907
	D2	P2	7	6.5	70	1.25	87.5	$18,916	$18,906
	D2	P3	7	6.5	70	1.4	35	$18,916	$18,912
	D2	P81	7	6.5	70	1	200	$19,611	$19,611
								$0	$0
8 hour	D1	P1	8	7.5	80	1	200	$78,449	$78,449
	D1	P2	8	7.5	80	1.25	100	$78,449	$78,439
	D1	P3	8	7.5	80	1.4	40	$78,449	$78,433
	D2	P1	8	7.5	80	1	200	$18,908	$18,790
	D2	P2	8	7.5	80	1.25	100	$18,908	$18,839
	D2	P3	8	7.5	80	1.4	40	$18,908	$18,880
								$0	$0
9 hour	D1	P1	9	8.5	80	1	225	$78,359	$78,359
	D1	P2	9	8.5	80	1.25	112.5	$78,359	$78,356
	D1	P3	9	8.5	80	1.4	45	$78,359	$78,345
	D1	P81	9	8.5	80	1	200	$76,179	$76,168
	D2	P1	9	8.5	80	1	225	$18,894	$18,793
	D2	P2	9	8.5	80	1.25	112.5	$18,894	$18,825
	D2	P3	9	8.5	80	1.4	45	$18,894	$18,861
	D2	P81	9	8.5	80	1	200	$18,361	$18,275
								$0	$0
10 hour	D1	P1	10	9.5	80	1	250	$78,317	$78,317
	D1	P2	10	9.5	80	1.25	125	$78,317	$78,313
	D1	P3	10	9.5	80	1.4	50	$78,317	$78,301
	D1	P81	10	9.5	80	1	200	$74,363	$74,360
	D2	P1	10	9.5	80	1	250	$18,888	$18,717
	D2	P2	10	9.5	80	1.25	125	$18,888	$18,804
	D2	P3	10	9.5	80	1.4	50	$18,888	$18,853
	D2	P81	10	9.5	80	1	200	$17,923	$17,788

Table 11. Total costs for operating truck tours.

6. CONCLUSIONS

Driving HOS has been the topic of a plethora of research aimed at determining safer ways of operating trucks while optimizing costs for trucking organizations. Studies have identified driver fatigue, lengthy driving hours, sleep debt and poor driving performance as some of the factors that have affected truck safety.

In this research, methods were developed for analysis of probability distributions were created to determine the effect of HOS rules on driving hours. By plotting exponential and normal distributions for driving times and applying bounds on driving hours, we found that reductions of 12 – 15 % and 2 – 5 % on crash rates were possible, respectively. An accident rate function was developed using data from LTL trucking companies and this accident rate was used in conjunction with the probability distributions to determine the reduction in crashes. Driving hours from the FARS/TIFA data sets were used to determine the reduction in crashes. By applying constraints on the driving hours, an upper bound on reduction of fatalities by about 3 – 5 % was possible when compared to the current situation. This also meant that drivers could only drive for a maximum of 8 or 9 hours, two hours lesser than the current HOS guidelines. The 3 – 5 % reduction in crashes is possible based on perfect enforcement of HOS rules, and an assumption of no transference of fatalities to shorter trips. From an economic perspective, very stringer HOS rules, limiting drivers to perhaps six hours per day, would reduce the cost of crashes by no more than about $1.2 billion per year. This number is consistent with prior FMCSA, which estimated the annual cost of fatigue related crashes to be $2.3 billion per year.

Using the H(x) probability distribution, we further determined that the average number of hours before a truck crash is approximately three hours, well below current HOS constraints. This is because the vast majority of driving occurs before reaching (or approaching) the constraint.

7. IMPLEMENTATION

Based on our research, we do not see justification for a change in current HOS regulations. While some benefit may be gained through more stringent regulations, or through more stringent enforcement, the monetized benefit appears to be small.

The tools that we developed can be applied in the future to evaluate the implications for changes in HOS constraints, either using theoretical or empirical distributions as a basis. This will enable calculating an upper bound on the monetized benefit due to any reduction in the allowed hours of service. Thus, we have provided a methodology to inform future discussion on hours of service policy.

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