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The University of California
Transportation Center

University of California
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Exploratory Analysis of Motor Carrier Accident Risk and Daily Driving Patterns

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INTRODUCTION

A. BACKGROUND

Interstate motor carriers are subject to limitations on the hours that their drivers may be on-duty and driving. The regulations include a requirement that a driver be off-duty for a minimum of 8 hours after driving for 10 hours or being on-duty for 15 hours. There are also cumulative restrictions for on-duty time over several days: 70 hours on duty in 8 days for carriers operating 7 days a week and 60 hours in 7 days for those operating 5 days a week. These limitations, referred to as the hours of service regulations, were initiated in the 1930's. Since then the U.S. highway system has changed dramatically as has the nature of the trucking business and the technology of the vehicles. Despite these changes, there have been rather limited attempts to assess the safety implications of the hours of service for contemporary conditions.

One of the difficulties in assessing the safety implications of hours of service policies is to understand the interrelationships between the regulatory policy (i.e. hours of service) and other factors underlying safe driving. A companion paper (Kaneko and Jovanis, 1990) focuses on variations in accident risk with alternative driving schedules and over several days. While accident risk variation within a day has seen limited previous study, multi-day assessments were extremely limited in the literature. The remainder of this section reviews the motor carrier driver fatigue literature to identify the extent to which it deals with daily driving effects.

In a major book on fatigue, safety and the truck driver, MacDonald discusses the inconsistency and vagueness in how researchers have defined and used the concept of fatigue (MacDonald, 1984). For some it is subjective, dealing primarily with individuals' perceptions of how they feel. Others use physiological correlates or performance decrements to study fatigue. An excellent review of psychological, physiological and performance components of fatigue is contained in a recent review by Australian researchers (Haworth, et. al., 1988).

There also appears to be confusion in some studies of the distinction between fatigue attributable to continuous driving and other time-related driving factors.

Circadian rhythms are changes in body function that follow an approximate 24 hour period so there is a point of low rhythm which corresponds to generally depressed levels of arousal. In addition, sleep deprivation, which arises because of a combination of on-duty time and off-duty activities, may also influence arousal and, ultimately, accidents.

Fatigue is a sufficiently vague concept that it does not appear to be a useful focal point for this study. As an alternative, declines in performance as measured by accident risk are used as a measure of the quality of the driving task. The research recognizes the separate effects of declined performance due to cumulative driving over several days, and circadian effects. The focus of the study is on accidents and exposure that occur during actual motor carrier operations. All effects other than sleep deprivation during off-duty hours are thus considered.

Perhaps the most extensive studies of hours of service and accident risk were conducted in the 1970's as part of a series of studies sponsored by the National Highway Traffic Safety Administration (NHTSA), (Harris, et al., 1972; Harris, 1977; Mackie, et al., 1974; Mackie and Miller, 1978). These studies included analyses of retrospective accident data and field tests, with an instrumented cab, of a set of drivers asked to drive particular schedules. The effects of heat, noise, vibration and cargo loading activities were also assessed.

These studies consistently found that a higher proportion of accidents occurred in the last half of a trip. Separate analyses of single vehicle accidents and crashes for which the driver was reported as "dozing at the wheel" showed particularly strong increases in accident risk as a function of continuous hours driving. Circadian effects were significant for the "dozing" drivers as the accident risk was highest from 2-6 a.m. While there were some studies that included separate collection of exposure data, most of the analyses with accident data compared the actual number of accidents with those "expected" if there was no increased risk due to hours driven. This method assumes that accident involved drivers are representative of the general population of drivers. The studies also relied primarily on accident data from the then Bureau of Motor Carrier Safety (now the Office of Motor Carriers of Federal Highway Administration) although some data were provided directly from carriers. The studies using accident data and exposure from actual motor carrier operations do not explicitly consider the effect of

total hours driven during preceding days nor the time of day when the driving occurred during those days.

The 1978 report by Mackie and Miller describes the findings of a series of field experiments (Mackie & Miller, 1978). A set of drivers operated a truck along a fixed route in California using predetermined driving schedules for a week. Detailed physiological, perceptual and driving performance data were collected at several points during the duty regimen. The study found significant consistent evidence of reduced driving performance, particularly during the fifth and sixth days on duty, particularly for drivers who undertrook moderate cargo loading, and particularly for rotating rather than fixed schedules. Unfortunately, the schedules assigned to all drivers exceeded the USDOT maximums established for interstate operations. It is problematic that fatigue manifested itself most often during these illegal hours. Further, the number of alternative driving schedules that were examined was extremely limited and could not typify those in broad trucking operations. Nevertheless, despite its experimental shortcomings, the study has significant scientific merit and does provide a baseline for comparison in this research.

There have been several recent studies that have explored aspects of accident risk and driving hours. The Insurance Institute for Highway Safety (IIHS) recently completed a study of drivers in sleeper berth operations (Hertz, 1989). While representing a rather unique type of over-the-road operations, Hertz found that regularity of schedule was an important predictor of road safety. In another study (Transportation Research and Marketing, 1985), a non-random set of accidents (primarily in the western U.S.) were selected for detailed follow-up. Interviews with firms and family members were used to reconstruct how the truck driver spent his time both on and off duty, in the day or so prior to the crash. The findings were that fatigue was a major contributing factor because of a combination of excessive (and illegal) hours of work and lack of rest during off-duty time. While the findings are of interest, the study suffers from methodological shortcomings: the criteria for selection of crashes would seem to be biased toward severe outcomes and the method used to determine the contribution of fatigue to accident occurrence seems subjective.

Studies have also been conducted in Europe. Hamelin, in an analysis of professional and non-professional drivers, found that the professional driver had lower

accident rates than non-professionals, particularly during extended driving. He concluded that the professionals could better cope with the rigors of on-road performance (Hamelin, 1987). Fuller reached similar conclusions in his study of driving performance in Ireland (Fuller, 1981). No difference was found in the mean following headway of drivers, even after extended hours on-duty and driving.

Further research seeking to relate accident risk and motor carrier driving patterns can take any of several paths. One could seek to obtain detailed physiological and perceptual data from drivers undertaking truck driving tasks. This approach, best exemplified by Mackie and Miller (1978) is both costly and subject to criticism for its non-representativeness of actual driving conditions. An alternative is in-depth study of selected accidents (e.g. TRAM, 1985). This approach also can be questioned regarding generalizability. A third approach is to analyze accident data from actual truck operations, conduct some comparisons with non-accident events and seek to identify accident patterns that support or refute a relationship with time of day and driver hours regulations (this is much in the spirit of the research by Harris in 1972 and 1977).

The approach taken in this research is to follow the lead provided by Harris and his colleagues and seek to identify relationships between accident risk and driving hours. In particular, this paper seeks to identify changes in accident risk with time of day as well as over a multiday period. The multiday pattern specifically considers the time of day of on-duty hours as well as the cumulative number of hours. The approach is predicated on the belief that, as it relates to safety policy, a primary concern is to focus on the effect of driving patterns on performance; i.e. a safely completed trip or an accident-producing trip. While driver health and welfare issues are also an important consideration, the focus of this study is on driving patterns and accident outcomes. Rather than rely on information from accident reports or driver interviews that attempt to specifically attribute causality to factors such as fatigue, the approach in this research is more empirically-based. By linking specific patterns to accident risk, it is hoped that high-risk as well as low risk patterns will be identified. The linkage to real driving and on-duty time can then be related to existing and proposed hours of service regulations to determine their safety effectiveness.

B. OBJECTIVES OF THE STUDY

The review of the literature suggests that there is a clear need to develop a method to analyze the effect on accident risk of different daily driving patterns. In particular, it is important to consider both the time of day when the driving occurs and the times of day of driving over multiple days so that the cumulative effect of multiday driving can be assessed.

A second objective of the research is to test the method with data from trucking company operations. These should include data from accident reports as well as a comparable set of non-accident (i.e. exposure) data so that relative accident risk can be assessed.

METHODOLOGY

A. WHAT IS A DRIVING PATTERN?

A driving pattern, for the purposes of this research, is a description of the status of the driver over several days. The status of the driver includes off duty, on-duty and driving, and on-duty but not driving (as defined by USDOT). A driver's status is typically recorded for each of every 15 minutes throughout the day. If a driver is involved in an accident, the pattern is interrupted while forms are completed, repairs undertaken and individuals are treated as necessary. For drivers not involved in accidents, driving patterns continue, dependent on the need to move freight and the constraints imposed by hours of service limits. There are obviously a very large number of driving patterns that are possible over multiple days. In order for this research to succeed, there is a need for a statistical method to identify drivers with similar driving patterns so the effect of the pattern on risk can be assessed.

B. STATISTICAL METHODS

Statistical analysis of the driving patterns proceeds in two phases. First, data are presented on the change in accident risk with time of day. These are disaggregate data consisting of a sample of accidents and when they occur during the day. To provide a measure of exposure to risk, a sample of non-accident trips are analyzed. The exposure data includes the beginning and ending time of each trip; the driver is assumed to be exposed to the risk of an accident throughout this time. While it is true that drivers do take breaks for meals and other purposes, for these initial exploratory studies, this seemed like a reasonable starting point.

Second, there is a need for a method to extract similar driving patterns from a large pool. It is important that this determination of similarity be conducted in a way that is blind to accident occurrence. That is, the method should first group drivers with similar patterns; once similar patterns are identified, knowledge of the accident involvement of drivers with particular patterns can be used to assess accident risk.

Disaggregate exposure trips present no problem in this regard. A trip for a driver for one day can be randomly selected and the driving pattern that day and many previous days can be coded. Accidents are more problematic because the occurrence of the accident interrupts the driving pattern, producing unknown biases. In order to avoid these biases the following approach is adopted. Driving patterns are described for the 7 days prior to the accident or comparable exposure trip. This approach simplifies the statistical treatment of the data but results in the implicit assumption that the observed driving pattern over 7 days is carried into the eighth day. As will be seen shortly, the patterns that result from this analysis are regular enough that this does not appear to be an unreasonable assumption. The day of interest does not have to be the eighth day, but can be any day that corresponds to any hours of service regulation. The carrier used in the empirical modeling operated seven days a week so the operative cumulative restriction is 70 hours in 8 days.

Cluster analysis is a method that classifies objects by creating homogeneous groups. An individual driver for is considered as the object; each driver is assigned to a cluster based upon the similarity of the driving pattern over seven days with other drivers in the cluster. The driving patterns provide important information including: (i) hours on-duty and off-duty over seven days; (ii) the time of day that the on-duty and off-duty hours occurred; and, (iii) trends of on-duty and off-duty time over several days. Cluster analysis does not yield a single optimum set of clusters for a data set. The user has the option to select the number of clusters desired and the clustering algorithm assigns each observation to its most statistically similar cluster. A range of cluster numbers can be used, but some criterion is needed for selecting the clusters to be carried to the next step of the analysis.

The procedure used in this research tested a range of clusters from 5 to 9; the maximum number of clusters was determined by a rule of thumb that approximately 100 observations be contained in each cluster. The recommended clusters were determined by a Chi-squared test that sought to determine if the relative occurrence of accidents was independent of the number of clusters (n). A 2 by n contingency table was constructed and the clusters that best differentiated accident risk were chosen for further modeling.

C. Data Used to Identify Driving Patterns

All data are obtained from a national less-than-truckload firm. The company operates "pony express" operations from coast to coast with no sleeper berths. The findings are thus not intended to typify the trucking industry as a whole. As the carrier does take reasonable steps to adhere to USDOT service hour regulations, the vast majority of drivers in the study can be considered as operating within legal duty hour limits. The empirical results are intended as a test of the proposed methodology and as a contribution to the admittedly scant research base on accident risk and driving patterns.

Two sets of data are used in the analysis. To examine variation in accident risk throughout the day, accident and exposure data from 1984 and 1985 are used. The accidents include all those experienced by the carrier for the two years in question (independent of DOT reportability thresholds). Exposure data were determined by obtaining a random sample of two non-accident trips for every accident that occurred. While the sample was obtained at random, it does not represent the true probability of an accident. Detailed analysis of data from one terminal (Chang, 1987) reveals that accidents occur approximately once in every 3000 trips. Rather than build the huge data bases necessary to test this true probability, a two-to-one oversample of exposure to accidents is used so that the relative probability of an accident is determined. As one is primarily concerned with the relative probability with respect to a set of predictor variables, this seems like a reasonable approach.

The time of each accident is recorded on the accident report. The time of day when each exposure trip is on the road is known from the driver's daily log. As the carrier operates LTL with timed runs between fixed terminals, there is little incentive for the driver to falsify logs. Note that exposure trips are on the road for several hours each day and thus must be counted as exposed to risk for each hour they are operating.

Multiday analyses required additional data. For the accident data, the first day through the seventh day are defined by specifying the date of the accident as the eighth day. Thus the patterns may be thought of as representing the effect of prior driving pattern over 7 days on accident risk in the eighth day. Similarly, for the exposure data, by defining the date of the exposure trip as the trip on the eighth day, the first day through the seventh days are used to characterize the effect of prior driving pattern.

Data from January through June of 1984 are used to determine driving patterns and include nearly 1600 accident and non-accident-involved drivers..

If a 7-day interval is considered, the number of variables are 672 (4 time periods per hour x 24 hours x 7 days). Computer memory limitations dictate that the finest time resolution that can be used is 30 minutes, decreasing the number of variables to 336 (2 x 24 x 7). The methods used to transform the 15 minute data to 30 minute intervals are as follows:

- If both 15 minute intervals have the same working status, the new variable (30 minute interval) has the same working status.

- On-duty and driving, and on-duty and not driving are treated as one working status which is on-duty (this is consistent with DOT cumulative hours regulations).

- If one of two 15 minute intervals is off-duty and another is on-duty, the new variable is treated as off-duty.

The last transformation may cause a slight underestimate of hours on-duty, but, if typical hours on-duty last for 3 to 5 hours continuously this approximation will not cause any substantial error. Because most driving trips in our data include consecutive driving times of greater than 3 hours, the approximation seemed reasonable.

RESULTS OF DATA ANALYSIS

A. Accident Risk and Time of Day

Consistent with the descriptions in the previous two sections, Table 1 is constructed to assess the relative accident risk throughout a day. The first row is the number of accidents occurring in each 2 hour period. The second row (labeled "exposure") is the number of non-accident-involved trucks on the road during the same two hours. The risk is the ratio of the number of accidents to number of exposure units.

TIME

	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	TOTAL
Number of Accidents (A)	344	292	322	279	240	228	203	194	213	212	245	242	3014
Number of Exposure Units (E)	2406	2269	2072	2044	1930	1861	1798	1628	1693	1952	2167	2337	24157
Relative Risk (A/E)	.143	.129	.155	.136	.124	.109	.112	.119	.126	.109	.113	.104	.125

Table 1. Relative Accident Risk By Time of Day

It is clear that elevated accident risk occurs from midnight to 8 a.m. The highest risk occurs from 4-6 a.m. These findings are consistent with the theory of circadian rhythms which argues a diurnal drop in arousal typically from 4-6 a.m. each day. The table is also generally consistent with results reported by Harris (Harris, 1977) for drivers diagnosed as "dozing" at the wheel compared to a sample of non-accident driving times obtained by interviews at truck stops.

The findings are interesting but of limited utility. They are for only one day (the accident day or a random day of interest) and are not related to driving schedule. They are more related to truck movement than an analysis of driver policies such as hours of service. Additional insights can be obtained by examining multiday driving patterns.

B. Overview of Multiday Driving Patterns

After experimenting with 5 - 9 clusters to describe driving patterns, the cluster analysis with 9 homogeneous driving patterns was used for further modeling. This decision was based on two factors. First, the 9 cluster results most clearly identified groups with dissimilar accident risks. The null hypothesis of independence was rejected of the 2 x 9 contingency table at the .05 significance level. The second factor is that the 9 cluster patterns appeared to be the most clearly discrete. Cluster analysis allocates observations to clusters based upon their statistical distance from cluster centroids. As observations are added to the clusters, the centroids shift, possibly resulting in previously assigned observations being misclassified. In all previous clusters (i.e. 5-8) there was a need to conduct 2 consecutive cluster analyses with the output of the first cluster being used as input to the second. In no case was more than 2 runs necessary. The 9 cluster case was the only one that did not result in any re-assignment of observations. Computer memory requirements and sample size restrictions prohibited testing of 10 or more clusters.

Figure 1 shows the overall average driving pattern while Figure 2 - 10 represent individual clusters. The horizontal scale represents the elapsed time for each of the seven 24-hour periods. The time scale starts at midnight (point 0) and runs to 24 hours for the first day; 24-48 is the second driving day and so on until 144-168 representing the seventh driving day, just prior to the accident day. The vertical scale represents the percentage of drivers within the pattern that were driving or on-duty at that time. For example, in Figure 2, about 30% of drivers in pattern 1 are on-duty at midnight at the

Figure 1

Overall Average

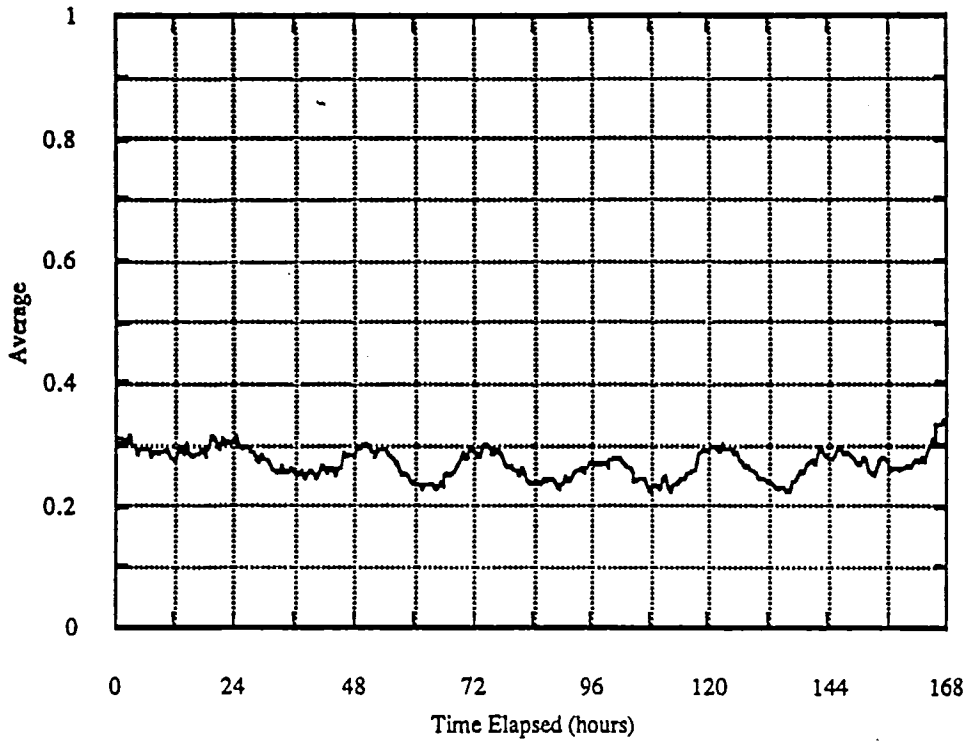
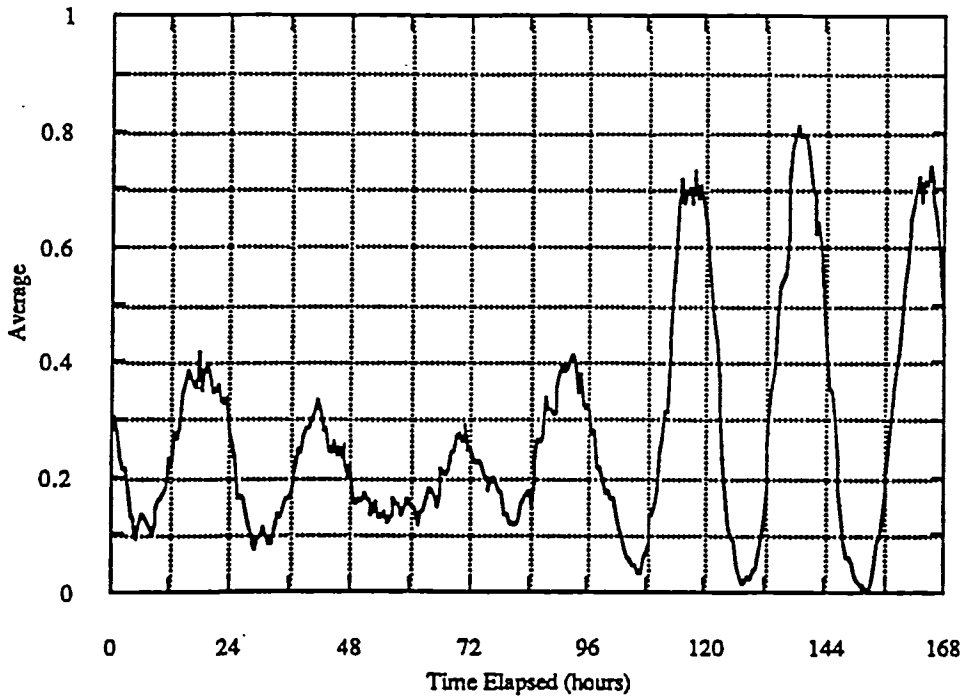


Figure 2

Pattern 1 Used for Modeling



end of the first day (hour 24). The percentage of drivers on duty then drops to about 10% at 6:00 am on the second day (hour 30).

What is most startling about the figures is the difference in interpretation that is possible when comparing the aggregate pattern (Figure 1) to the individual clusters. Figure 1 merely reflects for this firm what has been commonly reported elsewhere for the industry as a whole. Truck drivers are on-duty throughout the day, for all seven days but there is a slight increase in the percentage of drivers on-duty in the evening and early morning hours (centered around midnight from about 6 pm until 8 am). Overall, the change in drivers on duty is from slightly more than 30% at midnight of the seventh day to a low of about 22% around noon of days 3,4,5,6.

Individual driving patterns are quite clearly identified using the clustering technique. In addition to a summary of the on-duty trends for each cluster a relative accident risk is reported. The relative accident risk associated with each cluster, n, is calculated as:

$$\text{Relative Accident Risk n} = \frac{a_n}{a_n + e_n}$$

where: a_n = number of trips resulting in an accident within cluster n

e_n = number of trips resulting in no accident in cluster n

n = number of clusters as determined by screening procedure (in this case n = 9).

In addition to the relative accident risk, a number of descriptors are used for each pattern. These include the times of day of most frequent on-duty and driving time, the most frequent off-duty times, the mean and standard deviation of the total hours on-duty per driver for the 7 days, the mean and standard deviation of the consecutive hours driving per driver (a measure of average trip length) and the mean and standard deviation of the driving cycle. A driving cycle is defined as the time elapsed between a period of driving or on duty time and the subsequent off duty time that is at least 8 hours (consistent with DOT regulations). The rationale is that the driving and on-duty time dictates (causally) the requisite hours off duty. Off-duty times in excess of 24 hours (and their previous on-duty times) are not included in the reported statistics because the driving cycle is intended to measure the periodicity of individual driving patterns per driver. Off-duty times in excess of 24 hours are likely caused by reaching the limit of DOT cumulative hours levels. When a driver is off-duty in excess of 24 hours it is assumed that a substantial recovery occurs from the effect of any previous continuous driving

The following paragraphs contain summary descriptions of each of the nine driving patterns displayed in Figures 2-10, respectively.

- Pattern 1

The most frequent driving periods in this pattern occur from early afternoon (about 3 p.m.) until about midnight but frequently extending until 3 - 4 a.m. Off-duty hours are thus most frequent from 4 a.m. until noon. Driving is somewhat irregular for the first 4 days of the pattern but is quite regular over the last 3 days; for example, over 80% of the drivers are on duty at 10 p.m. of the sixth day. This driving pattern is associated with a somewhat high level of accident risk, a relative accident risk of 0.420.

- Pattern 2

The most frequent driving periods in this pattern occur from early morning (about 2 a.m.) until slightly before noon. Off-duty times occur from early afternoon until near midnight. Driving is somewhat irregular during the first 4 days of this pattern but highly regular for the last three with steep peaks; for example, nearly 75% of the drivers are on duty at 11 a.m. on the sixth day. This driving pattern is associated with a somewhat high level of accident risk, a relative accident risk of 0.420.

- Pattern 3

The most common on-duty hours in this pattern are in the morning, beginning after midnight and extending until nearly noon. The most common off-duty time is noon to midnight. Driving becomes very infrequent during the last 2 days of the pattern but is highly regular during the first 5 days; for example, on the fourth day nearly 80% of the drivers are on-duty at about 6 a.m. This pattern is associated with moderate accident risk, a relative accident risk of 0.398.

Figure 3

Pattern 2 Used for Modeling

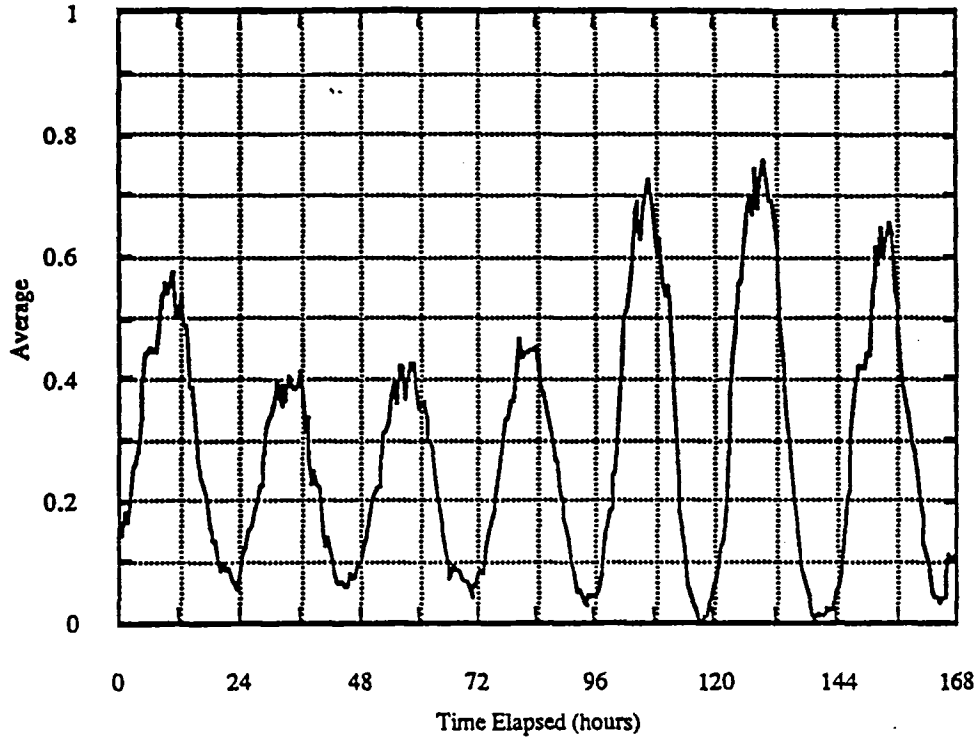
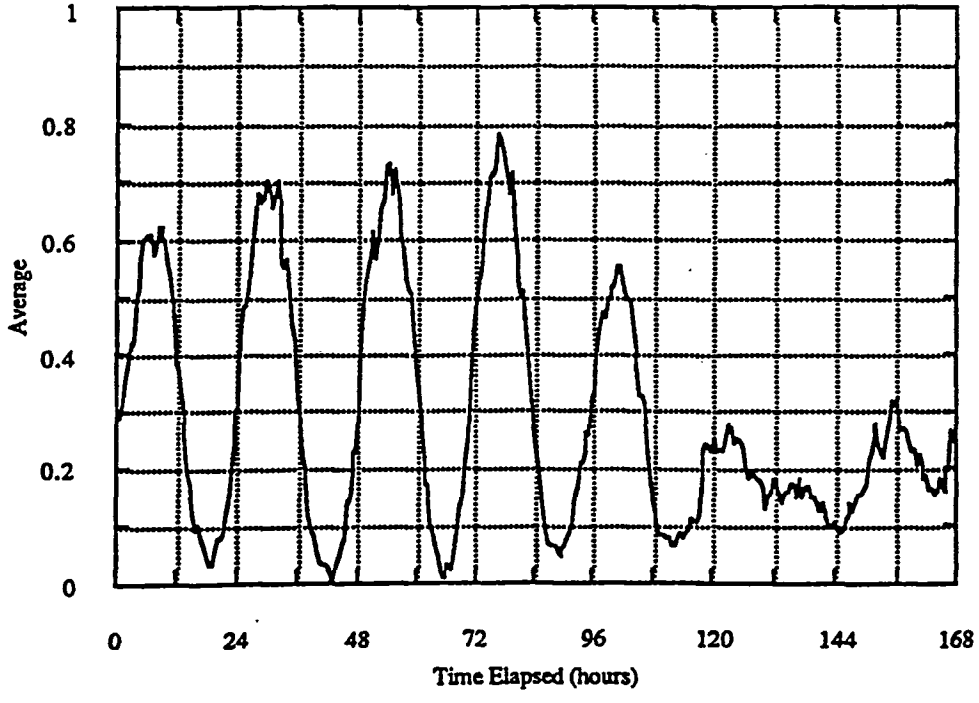


Figure 4

Pattern 3 Used for Modeling



- Pattern 4

The most frequent on-duty hours in this pattern are from morning, about 10 a.m., through the afternoon, until about 6 p.m. Hours are very regular for the first 3 days but somewhat less so during day 4 and even less so during 5. Driving is rather unlikely during days 6 and 7. Off-duty hours typically occur from evening (about 6 p.m.) through early morning (about 6 a.m.). Nearly 80% of the drivers in this group are on-duty at noon on the first and second days. This pattern is associated with rather low level of accident risk, a relative accident risk of 0.322.

- Pattern 5

The most frequent on-duty time for this group of drivers occurs from early evening, around 8 p.m., through early morning, about 6 a.m. Off-duty times are typically late morning through early afternoon. The pattern is highly regular during the first 2 days (more than 80% of the drivers on-duty at the beginning of the second day) and somewhat less so during days 3, 6 and 7. The least frequent on-duty days are 4 and 5. This pattern has comparatively little variability in on-duty time and is associated with the lowest level of accident risk, a relative accident risk of 0.241.

- Pattern 6

This pattern contains drivers that are very infrequently scheduled, particularly during the first 6 days. On the seventh day, only 30% of the drivers in this pattern are on-duty from mid-night until about 6 a.m. This pattern is associated with moderate accident risk, a relative accident risk of 0.388.

- Pattern 7

The most frequent on-duty times for drivers in this group are from about noon until about 6 p.m. The most likely off-duty time is from midnight until about 10 a.m. The pattern is quite regular on the last 3 days of the 7 day period with nearly 80% of the drivers on-duty during day 6 and somewhat less so during days 5 and 7. The first 4 days of the pattern demonstrate somewhat more variability but there is a pronounced peak period as typically 40% or more of the drivers are on-duty during the peak time. This pattern has a moderate relative accident risk of 0.340.

- Pattern 8

The most frequent driving times start at about 10 p.m. and continue through about 10 a.m. The most frequent off-duty times are 10 a.m. through about 10 p.m. The

Figure 5

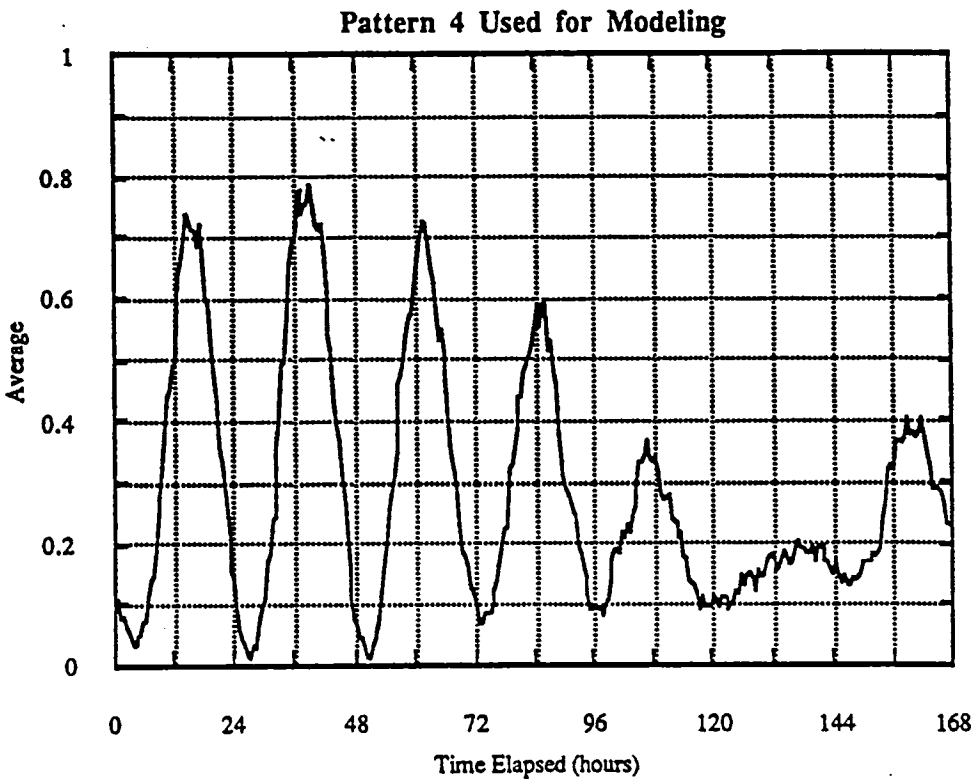


Figure 6

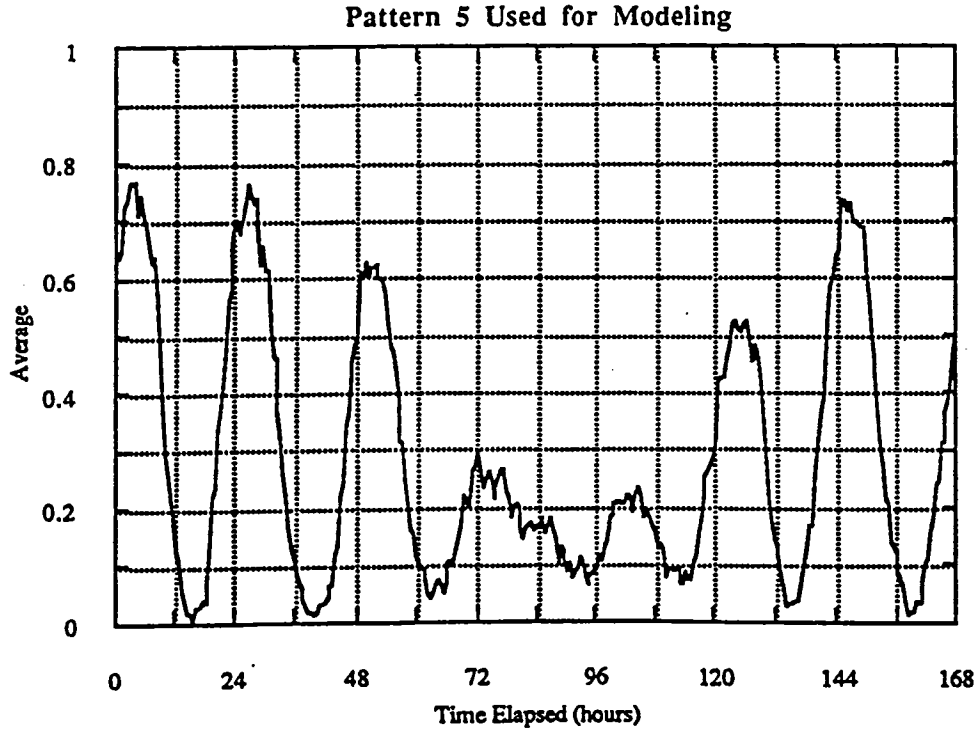


Figure 7

Pattern 6 Used for Modeling

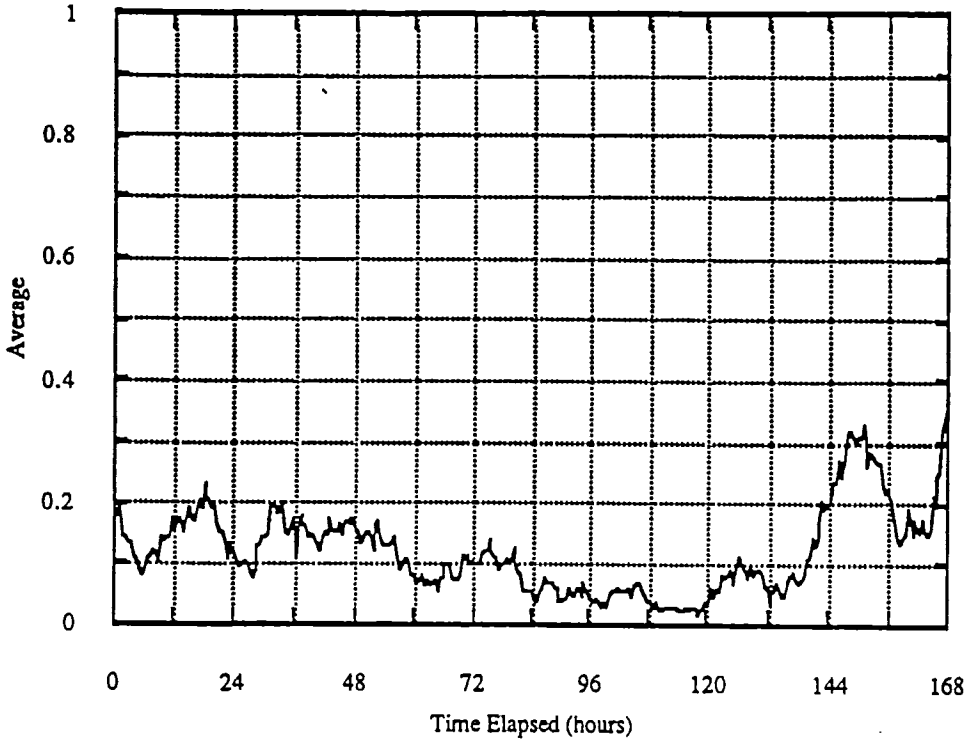
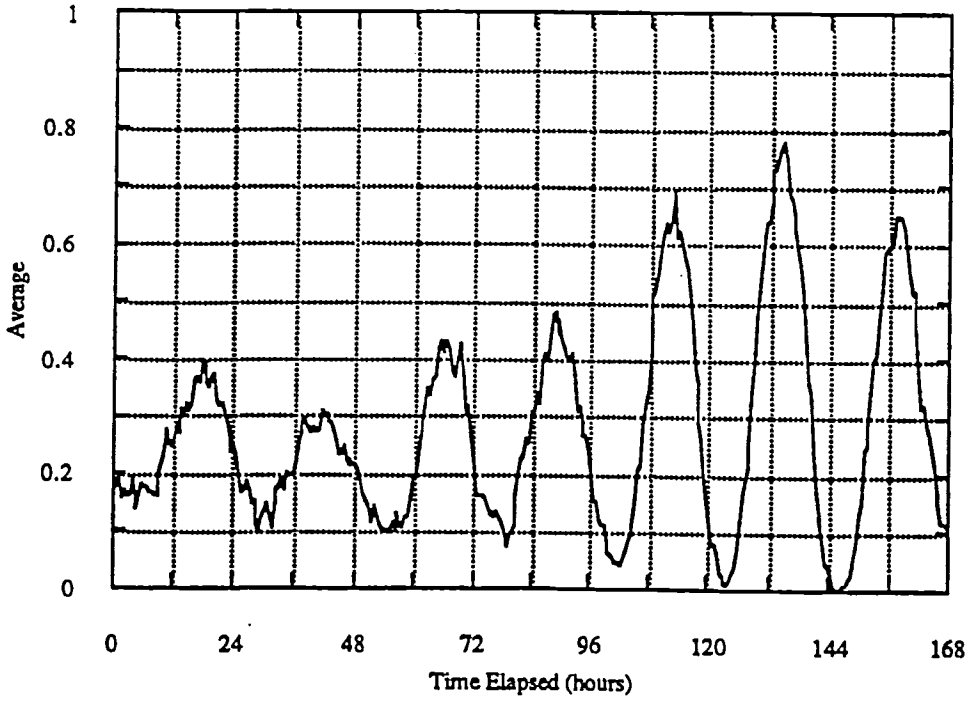


Figure 8

Pattern 7 Used for Modeling



pattern is highly regular during the last 4 days with a peak of 70 % of the drivers on-duty on days 5, 6 and 7. The first 3 days exhibit much higher variability. This pattern has the highest accident risk, a relative accident risk of 0.442, in our data set.

- Pattern 9

The most frequent on-duty time for these drivers is throughout the afternoon and evening from about 6 p.m. until just before midnight. The most likely off-duty time is late morning and early afternoon. The most frequent on-duty days are 1 through 5 but there is much less-pronounced peaking within this pattern. This pattern is associated with rather low accident risk, a relative accident risk of 0.341.

C. Comparisons Between Patterns

By inspecting the clusters, several common trends emerge. Patterns 1, 2, 7 and 8 all contain relatively infrequent irregular driving during the first 3 - 4 days but highly regular driving thereafter. This is derived from, for example, the observation that 40% or less of the drivers in pattern 1 are on-duty or driving from about noon to midnight on days 1 - 4 but this percentage rises to 70% on day 5 and 7 and 80% on day 6. Conversely, patterns 3, 4 and 9 have regular driving during days 1 - 4 and more irregular driving thereafter.

Several sets of patterns have similar peak hours of driving within the day, but differ principally in which days during the 7 day period exhibit irregular duty hours. For example, both pattern 1 and 9 contain peak driving from early afternoon (e.g. 3 p.m.) until very early morning (e.g. 3 a.m.). The major difference is that pattern 1 has irregular duty hours on the first 4 days while pattern 9 exhibits irregular duty hours on days 5 - 7. This "phase shift" is also apparent in comparisons of patterns 2 and 3, 4 and 7, 5 and 8.

Additional insight is obtained by comparing the accident risk of the pairs of patterns that appear similar except for 3 - 4 day phase shift. Recall that these phase shift pairs are 1 and 9, 2 and 3, 4 and 7, and 5 and 8. Examination of the relative accident risks reveal that patterns which contain significant on-duty time during days 5 - 7 (these are patterns 1, 2, 7 and 8) have a consistently higher accident risk than the comparable paired patterns (i.e. 9, 3, 4 and 5) which have off-duty time during days 5 - 7. There thus does appear to be evidence of cumulative fatigue that occurs over

Figure 9

Pattern 8 Used for Modeling

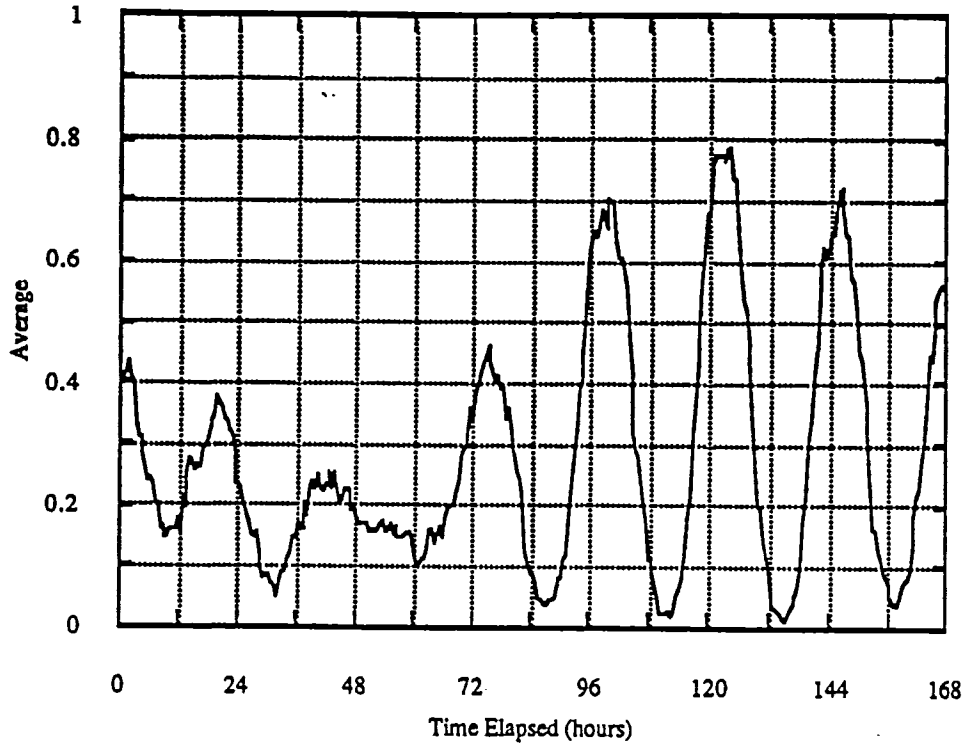
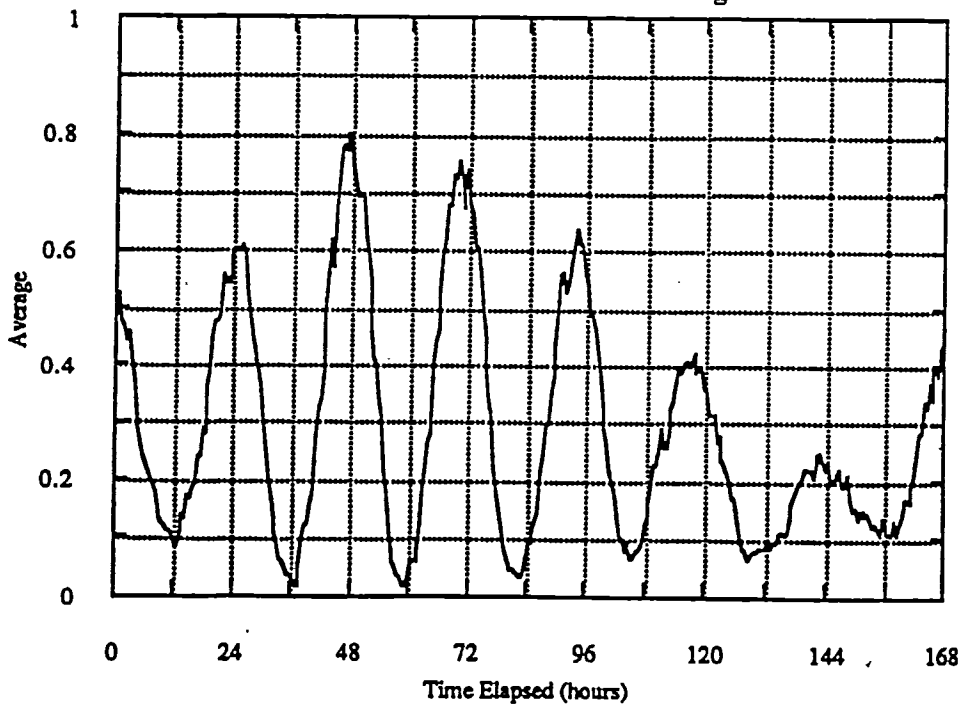


Figure 10

Pattern 9 Used for Modeling



several driving days even for similar times of day. It is clear, however, that this effect is not consistent across all pairs: patterns 2 - 3 and patterns 4 - 7 show very small accident risk differences while pattern 1 - 9 and 5 - 8 have quite large differences.

A detailed comparison of the accident risk of the phase shift pairs provides additional insights regarding the cumulative effects of driving. Pattern 5 (with the lowest relative accident risk) has as a pair, pattern 8 which has the highest risk. One may think of these two patterns as being the same, except for the day within the driving pattern that the observation is initiated. For example, the drivers in Pattern 8 happen to have, as their first two days of observation, days of infrequent driving. Drivers in Pattern 5 have this occur during days 3 and 4. One can thus conceptualize that the two patterns are identical, and that drivers are at varying levels of risk at different times within the multiple days. Therefore, it appears that drivers who begin their trips near midnight and typically end them around 10:00 a.m. face a particularly high risk after driving for several consecutive days. For these drivers, cumulative fatigue appears substantial. Similar findings are apparent in comparing patterns 1 and 9: Pattern 1 drivers have much higher relative risk than Pattern 9 drivers, the principle difference being the amount of driving during day 5,6 and 7. One may conclude that night and early morning drivers are particularly susceptible to increased accident risk due to cumulative duty hours.

In contrast, consider the primarily daytime driving associated with patterns 4 and 7. The relative risk changes little when driving is conducted during days 1,2,3,4 (relative risk = 0.322) rather than 5,6,7 (relative risk of 0.340). Thus, for drivers on a fairly regular daytime schedule (i.e. 10 a.m. to 6 p.m.), there is little evidence of any effect due to continuous driving (i.e. cumulative fatigue). The phase shift pair 2 and 3 also illustrates a minimal difference in accident risk associated with the combination of frequent driving and a pattern of driving from roughly midnight until noon. While there is slightly higher risk associated with driving on days 5,6,7, there is much less than was observed for patterns 5 and 8. It appears that driving over multiple days only increases accident risk for patterns which have these last few driving hours during night or early morning. This interpretation is consistent for all four phase shift pairs.

D. Measures of Individual Driver Duty Hours Within and Across Patterns

Figures 1-10 provide useful information about driving patterns as a description of the aggregate behavior of sets of individuals. One is also interested in the duty hours of

individual drivers within each pattern and how these compare across patterns. For example, it would be useful to know if the length of driving time (i.e. mean and standard deviation of consecutive driving hours) varies across patterns. Of importance to circadian rhythms is whether daily driving really has a 24 hour cycle as is apparent from Figures 1-10. Because the patterns are measures of aggregate behavior, they may mask the driving cycles experienced by individual drivers. In this section, a number of measures of individual driver duty hours are discussed with their implications for safety.

Table 2 presents the mean and standard deviation of the consecutive hours driven per driver for each pattern. The consecutive hours driven is defined as the total driving time that occurs between 8 hour off-duty periods mandated by DOT regulations. There is remarkable consistency in mean driving hours across all patterns. The range is from 8.38 hours to 7.73, a mean difference of only about a half hour. The standard deviation values are more dispersed, particularly for pattern 6 (a value of 3.57 hours), which is the "odd" pattern with infrequent driving. Apparently pattern 6 also contains more short driving trips than other patterns. While there is some variability, the remaining standard deviations range from 0.91 to 1.47. More importantly, there does not appear to be any association between relative accident risk and either the mean or standard deviation of consecutive driving hours. Company scheduling policies seem to apply rather uniformly across the patterns so, aside from pattern 6, there are little differences across patterns.

Table 3 summarizes data on cumulative driving and on-duty (not driving) time for each driver during the seven days. The table presents statistics on the mean and standard deviation of three measures: driving time, time on-duty but not driving and the sum of two (total time on-duty). As in the previous table, pattern 6 stands out as one with considerably less driving. The mean cumulative hours are generally similar as are the standard deviations except for pattern 6 and the extremely low standard deviation for pattern 1.

If one considers the phase shift pairs discussed previously, an interesting pattern develops. For each pair, the pattern with the higher relative accident rate also has the lower cumulative driving hours over the seven days. It is erroneous to conclude that

PATTERN NUMBER	Continuous Driving (Hours/Trip)	
	Mean	Standard Deviation
1	7.81	1.31
2	8.38	0.91
3	8.33	0.93
4	8.23	1.28
5	8	1.47
6	7.73	3.57
7	8.01	1.01
8	7.9	1.18
9	8.06	1.43

Table 2. Continuous Driving Hours for Each Pattern

PATTERN NUMBER	Driving Time (Hours)		On-Duty Not Driving Hours		Total on Duty Time	
	M*	S**	M*	S**	M*	S**
1	42.86	0.89	3.57	0.42	46.43	0.28
2	44.85	0.79	2.71	0.32	47.56	0.75
3	45.48	0.72	3.97	0.38	49.45	0.65
4	44.67	0.67	3.55	0.43	48.22	0.56
5	43.72	0.79	4.83	0.54	48.55	0.65
6	19.00	0.97	1.42	0.16	20.42	1.02
7	44.78	0.73	2.31	0.24	47.08	0.71
8	43.2	0.71	4.09	0.34	47.29	0.71
9	45.69	0.64	3.58	0.27	49.27	0.63

KEY
* M = mean
** S = standard deviation

Table 3 Cumulative On-Duty Hours for Each Pattern

less driving is less safe, however, because the higher cumulative driving hours results from more duty hours on days 1-4 for the low risk patterns. They are more completely filling their limit of US DOT cumulative hours during the first few days of the pattern. Those patterns with higher risk have more driving on days 5-7 but not enough to near the DOT cumulative maximum, which is more likely to be reached on the eighth day which is not shown. The conclusion is that these statistics support and are consistent with the presence of an increased accident risk with more recent extensive duty time.

A third indicator of individual driving within each pattern is the driving cycle, defined as the sum of consecutive driving and on-duty times and the subsequent off-duty time of eight hours or more. The driving cycle is thus intended to estimate the periodicity of driving. In order to screen cycles which include one or more full days off-duty (due to lack of freight or being "out of hours") a maximum of 24 hours off-duty is allowed for a driving cycle. The result is a variable that describes the period of duty when the driver is regularly scheduled. The concern is that the aggregate behavior displayed in Figures 1-10 is almost too good. There is a nearly 24 hour period despite the fact that drivers may be scheduled with an 18 hour period (i.e. 10 hours driving and 8 hours off duty). The driving cycle variable is intended to check if individual drivers actually are scheduled with a nearly 24 hour period, which would be clearly beneficial with respect to circadian rhythms. If the actual period is significantly less than 24 hours, then the driver's time on the road will not be stable with respect to time of day and, theory argues, additional decrements in performance can be expected (Mackie and Miller, 1978).

Table 4 summarizes the driving cycle data for each of the 9 patterns. The mean and standard deviation of the driving cycle are reported in the sixth set of columns (labeled "Driving Cycle"). Columns 1-5 report the same statistics for the duty hours that make up the driving cycle: these components include the time on-duty and driving; the time on-duty and not driving (e.g. time for pre-trip inspection); time on-duty and not driving during the trip for short rest breaks (e.g. meals); the total on-duty time (the total time in activities represented in columns 1-3; and subsequent off-duty time of at least 8 hours. While pattern 6 is again somewhat anomalous, all other patterns have mean driving cycles from 22.08 to 23.03 with most in the range of 22.7 to 22.9. There appears to be substantial evidence that the driving cycle, as defined, is much closer to 24 hours than the minimum driving times might suggest. This can be due to one of two reasons or some combination of the two. First, as Table 4 indicates,

	ONDUTY-DRIVE		ONDUTY-NOT DRIVE		ONDUTY-SHORT REST		ONDUTY-TOTAL		OFFDUTY TIME		DRIVING CYCLE	
	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV
PATTERN 1	8.05	1.62	0.53	1.10	0.96	0.79	9.55	1.83	13.18	3.90	22.73	4.32
PATTERN 2	8.40	1.62	0.42	1.00	1.04	0.89	9.86	2.20	12.92	3.60	22.79	4.21
PATTERN 3	8.32	1.46	0.49	1.00	1.04	0.70	9.84	1.77	13.03	3.69	22.88	4.12
PATTERN 4	8.25	1.35	0.42	0.96	0.91	0.74	9.58	1.62	12.73	3.74	22.31	4.00
PATTERN 5	8.12	1.56	0.64	1.12	1.03	0.80	9.78	2.02	13.06	3.67	22.84	4.21
PATTERN 6	7.88	1.34	0.28	0.58	0.94	0.76	9.10	1.93	11.98	3.64	21.08	4.22
PATTERN 7	8.13	1.37	0.37	0.81	0.95	0.80	9.45	1.92	12.63	3.66	22.08	4.13
PATTERN 8	8.18	1.57	0.63	0.99	1.05	0.89	9.86	2.06	12.95	3.46	22.81	3.93
PATTERN 9	8.43	2.49	0.49	0.84	0.97	0.91	9.89	2.95	13.14	3.70	23.03	4.63

Table 4. Summary of Driving Cycles for Each Pattern

there is a mean of approximately 1 hour off duty and 0.50 hours on duty and not driving for each driving cycle. This pushes total on-duty time (with some short off-duty periods) to close to 10 hours. Consecutive off-duty time, however has a mean of 12 hours or more (even when excluding off-duty times beyond 24 hours). The extreme values of DOT regulations do not appear to be operative, particularly for off-duty time. One explanation could be that the schedules are determined partially by freight demand as well as DOT regulations. Because most businesses served by LTL operators open and close with a 24 hour period, freight movement demand may coincide (somewhat serendipitously) more closely with driver circadian rhythms, contributing positively to road safety.

IV. SUMMARY

Driving at different times of day within one day, and over several days, are associated with different levels of accident risk. Analysis of carrier-supplied accident and non-accident data for 6 months of 1984 are used to explore changes in daily and multiday accident risk. Cluster analysis is used to extract a distinct pattern of driving over a seven day period from a sample of 1600 drivers (including those with accidents and non-accidents on the eighth day).

The analysis revealed that the pattern of driving over 7 days that posed the highest accident risk was daytime and early evening driving. Night and early morning driving over 7 days posed the least risk. Drivers did appear to be directly affected by cumulative driving over several days: for each of 4 pairs of similar driving patterns the ones that contained driving on the sixth or seventh day had a consistently higher accident risk on the eighth day than those with day 6 and 7 off-duty.

Within each pattern, drivers experience very similar duty hours: cumulative driving over the seven days ranges from 47 to 49 hours. Continuous driving (between mandatory 8 hours off-duty periods) ranges from 7.8 to 8.4 hours. Individual drivers also experience a cycle of on-duty and off-duty time which ranges from 22.3 to 23 hours, chosen to the 24 hour period that is desirable from the perspective of human performance theories.

The findings reveal that it is possible to quantitatively account for both of hours driving over a seven day period as well as the time of day when the driving occurred. Numerous additional analyses are possible with the existing data set or with enhancements made to the existing data. The following paragraphs summarize areas for fruitful future research.

There is a need explore additional driving patterns and their effect on accident risk. While the 9 clusters in this study yielded very interpretable results, additional insights may be gained by trying to develop a larger number of clusters that are more precise in their driving patterns. This analysis requires additional data, beyond the 1600 cases used in this study. It is very difficult to determine when the "optimal" number of clusters has been identified as the statistical method, cluster analysis, is heuristic. Analyses of additional driver variables such as age and experience have been reported elsewhere (Kaneko and Jovanis, 1990) as has additional accident risk modeling using a logit formulation. Descriptors of the routes used by the drivers: the road design, traffic level and terrain, would be useful additional information Individual driver socio-demographic characteristics such as marital status and family structure may also help explain accident risk.

It is hoped that the use of cluster analysis in identifying multiday driving patterns will encourage similar studies with this methodology. Disaggregate analyses are becoming much more common in the truck safety literature (e.g. Stein, and Jones, 1988; Leigh-Gosselin, et. al., 1990) and offer the prospect of more accurate identification of relative accident risk as well as the absolute probability of accident occurrence (Chang, 1987). It is hoped that this paper contributes positively to this trend.

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