Exploratory Analysis of Motor Carrier Accident Risk and Daily Driving Patterns

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Driving at different times of day within 1 day and over several days is associated with different levels of accident risk. Analyses of accident and nonaccident data from a less-than-truckload carrier representing 6 months of operation in 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 7-day period from a sample of 1,066 drivers (including those with accidents and nonaccidents on the eighth day). The analyses yielded clear interpretable driving patterns that could be associated with levels of relative accident risk. Higher risk was generally, but not exclusively, associated with extensive driving in the 2 to 3 days before the day of interest. The two patterns with the highest risk of an accident were those that contained heavy driving during the preceding 3 days and consisted of driving from 3:00 p.m. to 3:00 a.m. (Pattern 1) and from 10:00 p.m. to 10:00 a.m. (Pattern 8). The lowest risk was associated with driving from 8:00 p.m. to 6:00 a.m. but with limited driving on the preceding 3 days. Given the virtually limitless possible combinations of driving schedules, it is encouraging that interpretable distinct multiday patterns could be extracted from a data base of more than 1,000 observations. Within each pattern, drivers experienced similar duty hours: cumulative driving during the 7 days ranged from 47 to 49 hr. Continuous driving (between mandatory 8-hr off-duty periods) ranged from 7.8 to 8.4 hr. Individual drivers also experienced a cycle of on-duty and off-duty time that ranged from 22.3 to 23 hr, closer to the 24-hr period that is desirable from the perspective of human performance theories. The findings suggest that it is possible to identify and extract patterns of multiday driving and that these patterns are associated with different levels of accident risk. Additional empirical tests and the development of refined accident risk models are suggested for future research.

Interstate motor carriers are subject to limitations on the hours that their drivers may be on duty and driving. The regulations require that a driver be off duty for a minimum of 8 hr after driving for 10 hr or being on duty for 15 hr. There are also cumulative restrictions for on-duty time over several days: 70 hr on duty in 8 days for carriers operating 7 days a week and 60 hr in 7 days for those operating 5 days a week. These limitations, referred to as the hours of service regulations, were initiated in the 1930s. 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 the changes, attempts to assess the safety implications of the hours of service for contemporary conditions have been limited.

One of the difficulties in assessing the safety implications of hours of service policies is in understanding how accident risk varies with continuous hours driven and multiday driving.

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Whereas accident risk variation within a day has received limited study, multiday assessments were extremely limited in the literature. This paper focuses on variations in accident risk with alternative driving schedules and over several days. A companion paper (*1*) assesses multiday driving risk along with the risk due to continuous driving.

In a major book on fatigue, safety, and the truck driver, MacDonald (*2*) discusses the inconsistency and vagueness in how researchers have defined and used the concept of fatigue. For some researchers 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 (*3*).

There also appears to be confusion in some studies about 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-hr period, so there is a point of low rhythm that 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 declines in 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 1970s as part of a series of studies sponsored by the National Highway Traffic Safety Administration (*4–7*). The studies included analyses of retrospective accident data and field tests, with an instrumented cab, of drivers asked to drive particular schedules. The effects of heat, noise, vibration, and cargo-loading activities were also assessed.

The 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 to be "dozing at the wheel" indicated a particularly strong increase in accident risk as continuous hours of driving increased. Circadian effects were significant for the dozing drivers; the accident risk was highest from 2 to 6 a.m. Some studies included a separate collection of exposure data, but most of the analyses with accident data compared the actual number of accidents with those expected if there were no increased risk due to hours driven. This method is based on the assumption 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 the 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.

The 1978 report by Mackie and Miller (*7*) describes the findings of a series of field experiments. 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, particulary during the fifth and sixth days on duty, particularly for drivers who undertook moderate cargo loading, and particularly for rotating rather than fixed schedules. Unfortunately, the schedules assigned to all drivers exceeded the U.S. Department of Transportation (DOT) maximums established for interstate operations. It is problematic that performance reduction manifested itself most often during these illegal hours. Furthermore, the number of alternative driving schedules 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 stands as a classic work in the field of accident risk and hours of service.

Several recent studies have explored aspects of accident risk and driving hours. The Insurance Institute for Highway Safety recently completed a study of drivers in sleeper berth operations (*8*). It was found that regularity of schedule was an important predictor of road safety. In another study (*9*), a nonrandom set of accidents (primarily in the western United States) was 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 before 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. The findings are of interest, but the study suffers from methodological shortcomings: the criteria for selection of crashes appear to be biased toward severe outcomes, and the method used to determine the contribution of fatigue to accident occurrence appears subjective.

Studies have also been conducted in Europe. Hamelin (*10*), in an analsyis of professional and nonprofessional drivers, found that professionals had lower accident rates than nonprofessionals, particularly during extended driving. He concluded that the professionals could better cope with the rigors of on-road performance. Fuller reached similar conclusions in his study of driving performance in Ireland (*11*). 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 could take any of several paths. Detailed physiological and perceptual data could be sought from drivers undertaking truck-driving tasks. This approach, best exemplified by Mackie and Miller (*7*) is both costly and subject to criticism because it is not representative of actual driving conditions. An alternative is in-depth study of selected accidents (*9*). The generalizability of this approach can also be questioned. A third approach is to analyze accident data from actual truck operations, make comparisons with nonaccident events, and seek to identify accident patterns that support or refute a relationship with time of day and driver hours regulations [much in the spirit of the research by Harris in 1972 and 1977 (*4,5*)]. Each approach has its strengths and weaknesses, and a decision must be made on the approach to use in any particular study.

The approach taken in this research is to follow the lead of Harris and his colleagues and to seek to identify relationships between accident risk and driving hours. In particular, an attempt is made to identify changes in accident risk with time of day as well as over a multiday period. The multiday pattern 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 a primary concern is the effect of driving patterns on performance (i.e., a safely completed trip or an accident-producing trip). Whereas driver health and welfare issues are also important considerations, the focus of this study is on driving patterns and accident outcomes. Instead of relying on information from accident reports or driver interviews that attempt to attribute causality to factors such as fatigue, the approach in this research is more empirical. 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.

OBJECTIVES

The review of the literature suggests that there is a clear need to develop a method to analyze the effect of different daily driving patterns on accident risk. 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 is to test the method with data from trucking company operations. Data from accident reports as well as comparable nonaccident data should be included so that relative accident risk can be assessed.

METHODOLOGY

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 DOT). A driver's status is typically recorded for each of every 15 min throughout the day. If a driver is involved in an accident, the pattern is interrupted while forms are completed, repairs are 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. Obviously, a large number of driving patterns are possible over multiple days. For this research to succeed, a statistical method to identify drivers with similar driving patterns is needed so the effect of the pattern on risk can be assessed.

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 the time of day of their occurrence. To provide a measure of exposure to risk, a sample of nonaccident trips is analyzed. The nonaccident data include the beginning and ending time of each trip; the driver is assumed to be exposed to the risk of an accident throughout this time. Though drivers take breaks for meals and other purposes, this appeared to be a reasonable starting point for these exploratory studies.

Second, a method to extract similar driving patterns from a large pool is needed. It is important that the 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 for 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. To avoid these biases the following approach is adopted. Driving patterns are described for the 7 days preceding the accident or comparable exposure trip. This approach simplifies the statistical treatment of the data but is based on 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 assumption does not appear to be unreasonable. 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 7 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 is considered as the object; each driver is assigned to a cluster on the basis of the similarity of the driving pattern over 7 days with that of other drivers in the cluster. The driving patterns provide important information, including (*a*) hours on and off duty over 7 days, (*b*) the time of day that the on-duty and off-duty hours occurred, and (*c*) 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 selects 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 a 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 five to nine; the maximum number of clusters was determined by a rule of thumb that approximately 100 observations be contained in each cluster. Furthermore, limitations on computer memory precluded testing more than nine clusters. Because the driving patterns that were derived from the nine clusters were interpretable, the pattern search was stopped.

Data Used To Identify Driving Patterns

All data are obtained from a national less-than-truckload (LTL) 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. Because the carrier takes reasonable steps to adhere to DOT service hour regulations, most drivers in the study can be assumed to operate 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 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 nonaccident data from 1984 and 1985 are used. The accidents include all those experienced by the carrier for the 2 years in question (independent of DOT reportability thresholds). Nonaccident data were determined by obtaining a random sample of two nonaccident trips for every accident that occurred. Whereas the sample was obtained at random, it does not represent the true probability of an accident. Detailed analysis of data from one terminal (*12*) indicates that accidents occur approximately once in every 3,000 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. Because the primary concern is the relative probability with respect to a set of predictor variables, this appears to be a reasonable approach.

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

Multiday analyses required additional data. For the accident data, the first through the seventh days 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 the prior driving pattern over 7 days on accident risk for the eighth day. Similarly, for the nonaccident data, by defining the date of the nonaccident trip as the eighth day, the first through the seventh days are used to characterize the effect of the prior driving pattern.

Data from January through June 1984 are used to determine driving patterns and include 1,066 observations of accident- and non-accident-involved drivers.

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

- If both 15-min intervals have the same working status, the new variable (30-min interval) has the same working status.
- On duty and driving and on duty and not driving are treated as one working status, on duty (this is consistent with DOT cumulative hours regulations).
- If one of two 15-min intervals is off duty and another is on duty, the entire 30-min interval is treated as off duty.

The last transformation may cause an underestimate of hours on duty, but, if typical hours on duty last for 3 to 5 hr continuously, this approximation will not cause substantial error. Furthermore, the transformed data are only used as input to the cluster analysis, not in subsequent tabulations. Because most driving trips in the data include consecutive driving times of greater than 3 hr, the approximation appeared reasonable.

RESULTS OF DATA ANALYSIS

Accident Risk and Time of Day

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-hr period. The second row is a count of the number of non-accident-involved trucks on the road during the same 2 hr. The risk is the ratio of the number of accidents to the number of exposure units (i.e., the sum of accidents and nonaccidents).

It is clear that elevated accident risk occurs from midnight to 8 a.m. The highest risk occurs from 4 to 6 a.m. These findings are consistent with the theory of circadian rhythms, which anticipates a diurnal drop in arousal typically from 4 to 6 a.m. each day. The table is also generally consistent with results reported by Harris (*5*) for drivers diagnosed as dozing at the wheel compared with a sample of nonaccident driving times obtained by interviews at truck stops.

The findings are interesting but of limited utility. They are for only 1 day (the accident day or a randomly selected nonaccident day) and are not related to driving schedule. They are more related to times of truck movement than an analysis of driver policies such as hours of service. Additional insights can be obtained by examining multiday driving patterns.

Overview of Multiday Driving Patterns

After experimenting with five to nine clusters to describe driving patterns, the cluster analysis with nine homogeneous driving patterns was used for further modeling. A 2×9 contingency table was constructed from the nine patterns and the two levels of trip status (i.e., accident or nonaccident). Each of the 1,066 observations fell into 1 of the 18 cells, allowing the test of the null hypothesis that trip status is independent of cluster number. This hypothesis was rejected at $\alpha = .10$ but accepted at $\alpha = 0.5$, a mixed result (*1*).

The nine cluster patterns appeared to be the most distinct. Cluster analysis allocates observations to clusters on the basis of their statistical distance from cluster centroids; as each observation is added to a cluster, the centroid can shift slightly in reponse. The shift in centroid location can result in misclassifications of previously assigned observations. The clustering algorithm used in this study (BMDP) accounts for this by automatically reassigning observations and calculating centroids until no misclassifications occur. In the five to eight cluster analyses, reassignment and reallocation were necessary. The nine cluster patterns exhibited more stability by not requiring any reassignment of observations or recalculation of centroids.

Figure 1 shows the overall average driving pattern, and Figures 2 through 10 represent individual clusters. The horizontal scale represents the elapsed time for each of the seven 24-hr periods. The time scale starts at midnight (Point 0) and runs to 24 hr for the first day; 24–48 represents the second driving day, and so on; 144–168 represents the seventh driving day, just preceding the accident day. The vertical scale represents the proportion of drivers within the pattern that were driving or on duty at that time. For example, in Figure 2, about 30 percent of drivers in Pattern 1 are on duty at midnight at the end of the first day (Hour 24). The percentage of drivers on duty then drops to about 10 percent at 6:00 a.m. 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) with the individual clusters. Figure 1 merely

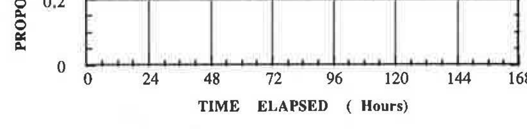

FIGURE 1 Aggregate pattern of driving over 7 days.

TABLE 1 RELATIVE ACCIDENT RISK BY TIME OF DAY

	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
Accident Count (A)	344	292	322	279	240	228	203	194	213	212	245	242	3014
Non-Accident Count (E)	2406	2269	2072	2044	1930	1861	1798	1628	1693	1952	2167	2337	24157
Relative Risk (A/[A+E])	.125	.114	.134	.120	.111	.109	.101	.106	.112	.098	.102	.094	.111

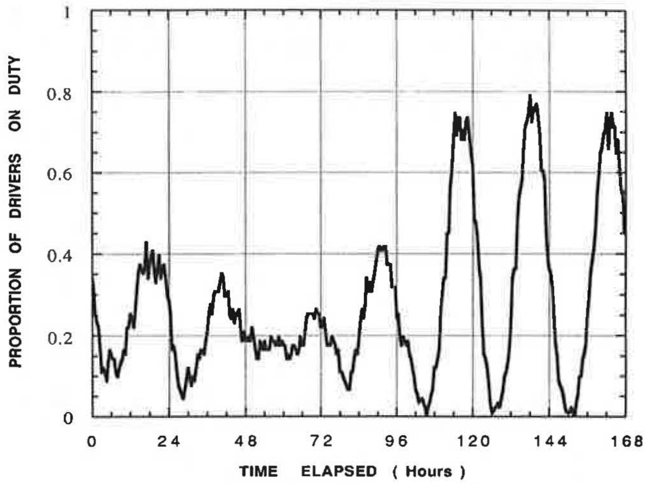

FIGURE 2 Proportion of drivers on duty, Pattern 1.

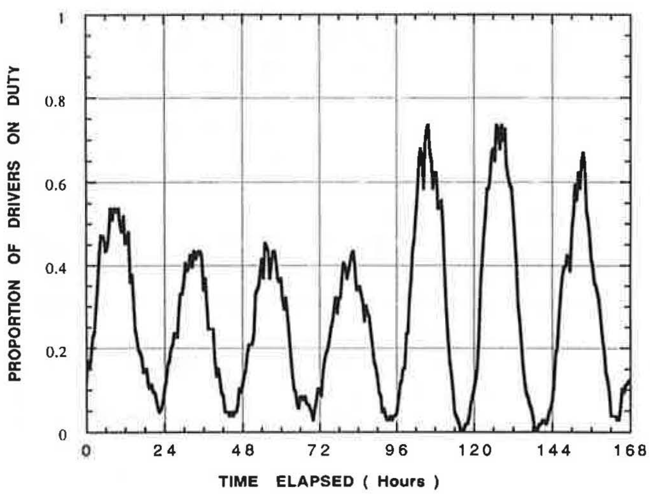

FIGURE 3 Proportion of drivers on duty, Pattern 2.

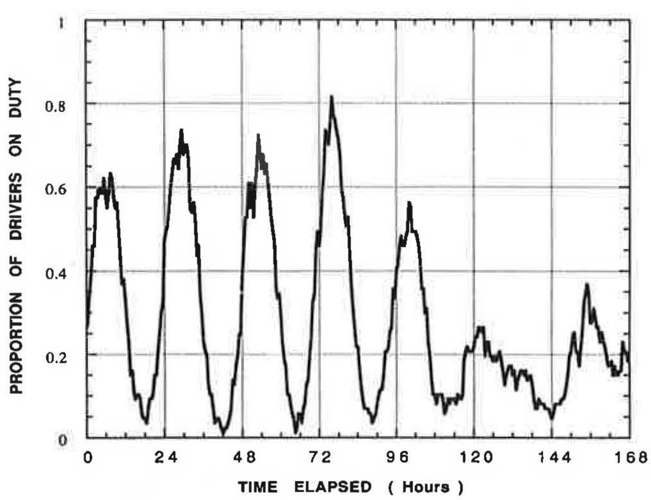

FIGURE 4 Proportion of drivers on duty, Pattern 3.

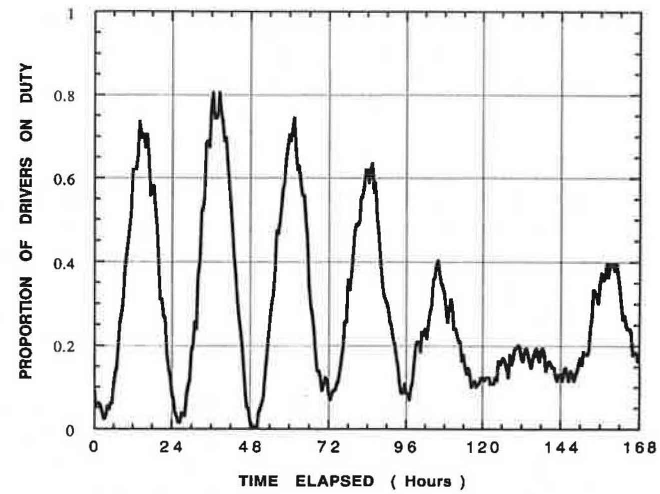

FIGURE 5 Proportion of drivers on duty, Pattern 4.

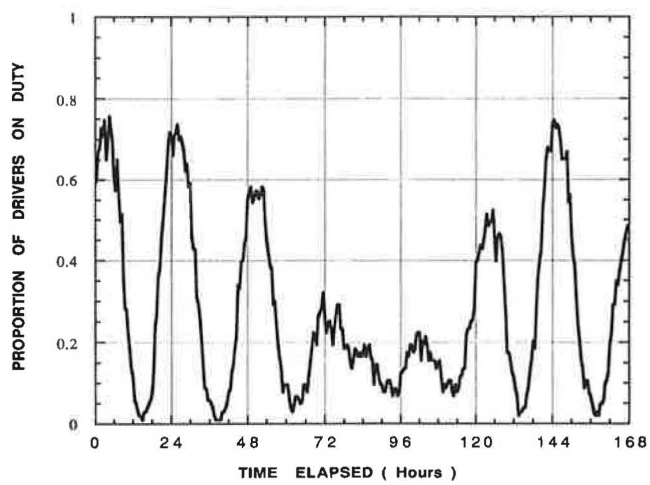

FIGURE 6 Proportion of drivers on duty, Pattern 5.

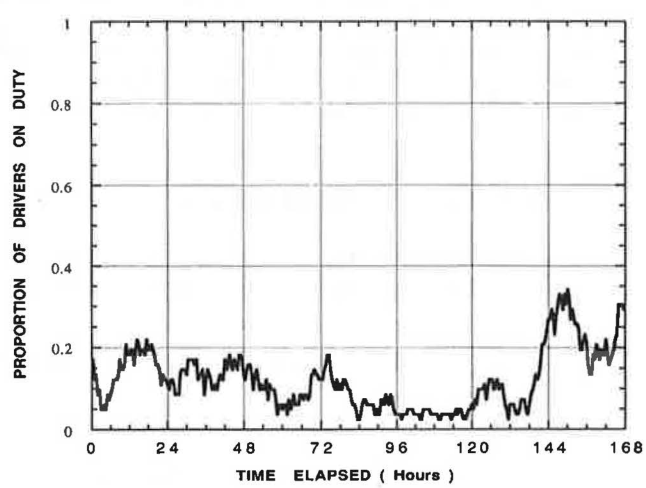

FIGURE 7 Proportion of drivers on duty, Pattern 6.

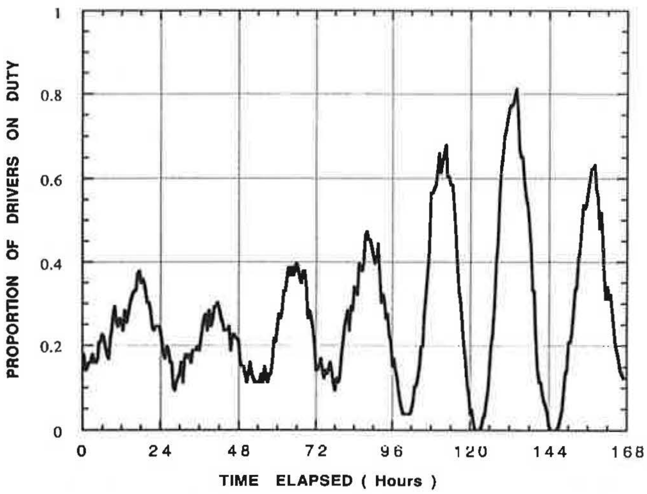

FIGURE 8 Proportion of drivers on duty, Pattern 7.

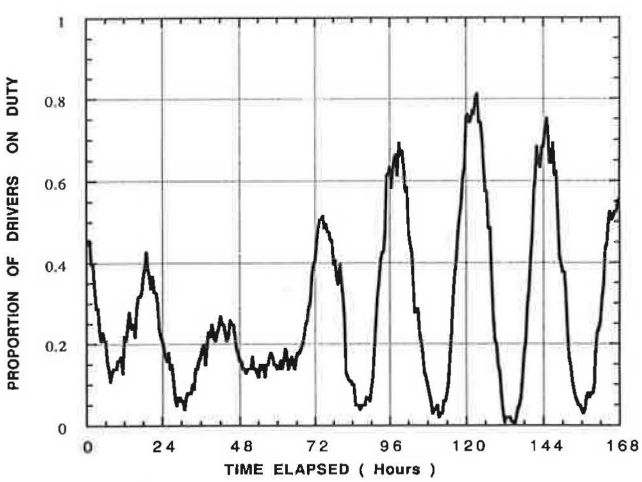

FIGURE 9 Proportion of drivers on duty, Pattern 8.

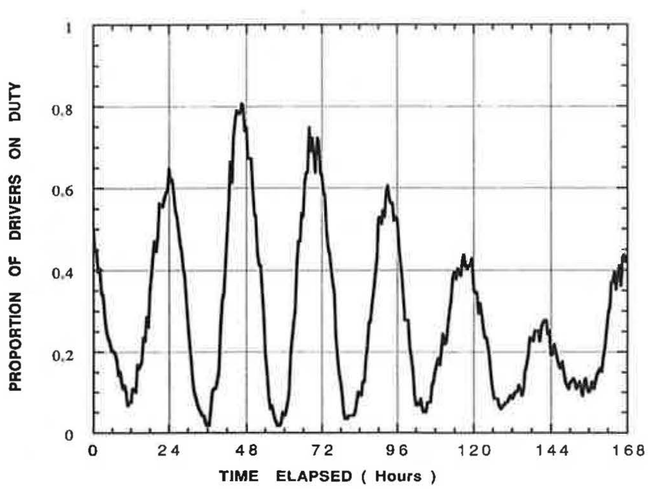

FIGURE 10 Proportion of drivers on duty, Pattern 9.

reflects for this firm what has been commonly reported elsewhere for the industry as a whole. Truck drivers are on duty throughout the 24 hr day for all 7 days, but there is a slight increase in the percentage of drivers on duty in the evening and early morning hours from about 6 p.m. until 8 a.m.). Overall, the change in drivers on duty is from slightly more than 30 percent at midnight of the seventh day to a low of about 22 percent around noon of Days 3, 4, 5, and 6.

Individual driving patterns are 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 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 in Cluster n,
e_n = number of trips resulting in no accident in Cluster n, and
n = the cluster number.

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 hr (consistent with DOT regulations). The rationale is that the driving and on-duty time dictates (causally) the requisite hours off duty. Drivers with off-duty times in excess of 24 hr (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 hr are probably caused by reaching the limit of DOT cumulative hours levels. When a driver is off-duty in excess of 24 hr, 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 through 10.

Pattern 1

The most frequent driving periods in this pattern occur from early afternoon (about 3 p.m.) until about midnight but frequently extend until 3 to 4 a.m. Off-duty hours are thus most frequent from 4 a.m. until noon. Driving is irregular for the first 4 days of the pattern but regular for the last 3 days; for example, more than 80 percent of the drivers are on duty at 10 p.m. of the sixth day. This 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 irregular during the first 4 days of this pattern but highly regular for the last 3 days with steep peaks; for example, nearly 75 percent of the drivers are on duty at 11 a.m. on the sixth day. This driving pattern is associated with a low level of accident risk, a relative accident risk of 0.307.

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 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 percent 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.

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 regular for the first 3 days but somewhat less so during the fourth and even less so during the fifth. Driving is 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 percent of the drivers in this group are on duty at noon on the first and second days. This pattern is associated with a 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. This pattern is highly regular during the first 2 days (more than 80 percent 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 the fourth and fifth. This pattern 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 percent of the drivers in this pattern are on duty from midnight until about 6 a.m. This pattern is associated with moderate accident risk, a relative accident risk of 0.370.

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 regular on the last 3 days of the 7-day period, with nearly 80 percent of the drivers on-duty during Day 6, and somewhat less regular during Days 5 and 7. The first 4 days of the pattern demonstrate more variability, but there is a pronounced peak period; typically 40 percent 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 pattern is highly regular during the last 4 days, with a peak of 70 percent 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 in the data set, a relative accident risk of 0.442.

Pattern 9

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

Comparisons Between Patterns

Several trends emerge from an inspection of the clusters. Patterns 1, 2, 7, and 8 all contain infrequent, irregular driving during the first 3 to 4 days but highly regular driving thereafter. This is derived from, for example, the observation that 40 percent or fewer of the drivers in Pattern 1 are on duty or driving from about noon to midnight on Days 1 through 4, but this percentage rises to 70 percent on Days 5 and 7 and 80 percent on Day 6. On the other hand, Patterns 3, 4, and 9 have regular driving during Days 1 though 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 of the 7-day period have irregular duty hours. For example, both Patterns 1 and 9 contain peak driving from early afternoon (e.g., 3 p.m.) until early morning (e.g., 3 a.m.). The major difference is that Pattern 1 has irregular duty hours on the first 4 days, whereas Pattern 9 has irregular duty hours on Days 5 though 7. This "phase shift" is also apparent in comparisons of Patterns 2 and 3, 4 and 7, and 5 and 8.

Additional insight is obtained by comparing the accident risk of the pairs of patterns that appear similar except for the phase shift of 3 to 4 days. Recall that these phase shift pairs are Patterns 1 and 9, 2 and 3, 4 and 7, and 5 and 8. Examination of the relative accident risks indicates that patterns containing signficant on-duty time during Days 5 through 7 (Patterns 1, 2, 7, and 8) have a consistently higher accident risk than the comparable paired patterns (i.e., Patterns 9, 3, 4, and 5), which have off-duty time during Days 5 through 7 with one exception. Pattern 2 has a lower risk than Pattern 3 (0.307 versus 0.398) even though Pattern 2 contains frequent driving on Days 5 through 7. Thus there appears to be increased risk due to cumulative driving that occurs over several driving days, even for similar times of day. It is clear, however, that this effect is not consistent across all pairs: Patterns 4 and 7 show small accident risk differences, whereas Patterns 1 and 9 and 5 and 8 have large differences; Patterns 2 and 3 show an opposite trend.

A detailed comparison of the accident risk of the phase shift pairs provides additional insights into 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 the same except for the day within the driving pattern that the observation is initiated. For example, the drivers in Pattern 8 drive infrequently during the first 2 days of observation. Drivers in Pattern 5 drive infrequently during Days 3 and 4. It can thus be hypothesized that Patterns 5 and 8 represent two similar driving patterns over an 8-day period; the primary difference is when within the 8-day period the accident occurred or the nonaccident trip is sampled. 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. Comparisons of Patterns 1 and 9 yield similar findings: Pattern 1 drivers have much higher relative risk than Pattern 9 drivers, the principal difference being the amount of driving during Days 5, 6, and 7. It can be concluded that drivers who complete their trip during early morning 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 only slightly when driving is conducted during Days 1, 2, 3, and 4 (relative risk = 0.322) rather than Days 5, 6, and 7 (relative risk = 0.370). Thus, for drivers on a fairly regular daytime schedule (i.e., 10 a.m. to 6 p.m.), there is evidence of a much smaller risk increase due to cumulative driving than for late-night and early-morning drivers.

The pair consisting of Patterns 2 and 3 illustrates a reversal in accident risk associated with the combination of frequent driving. It appears that drivers who start their trips around midnight have a higher risk when initiating a driving cycle than when driving frequently. This may be because of difficulties in transitioning from off-duty days that are "normal" (wake during day, sleep at night) to working days that are the opposite.

Measures of Individual Driver Duty Hours Within and Across Patterns

Figures 1 through 10 provide useful information about driving patterns as a description of the aggregate behavior of sets of individuals. The duty hours of individual drivers within each pattern and how they compare across patterns are also of interest. 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. Whether daily driving really has a 24-hr cycle, as is apparent from Figures 1 through 10, is important to circadian rhythms. 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 and their implications for safety are discussed.

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-hr off-duty periods mandated by DOT regulations. There is remarkable consistency in mean driving hours across all patterns. The range is from 8.38 to 7.73 hr, a mean difference of only about ½ hr. The standard deviation values are more dispersed, particularly for Pattern 6 (a value of 3.57 hr), which is the "odd" pattern with infrequent driving. Apparently Pattern 6 also contains more short driving trips than other patterns. Whereas there is some variability, the remaining standard deviations range from 0.91 to 1.47. More important, 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 appear to apply uniformly across the patterns, so, aside from Pattern 6, there are only small differences across patterns.

Data on cumulative driving and on-duty (not driving) time for each driver during the 7 days are summarized in Table 3. 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 the two (total time on duty). As in Table 2, 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 the phase shift pairs discussed previously are considered, an interesting pattern appears. For each pair, except Patterns 2 and 3, the pattern with the higher relative accident rate also has the lower cumulative driving hours over the 7 days. It is erroneous to conclude that less driving is less safe, however, because the higher cumulative driving hours result from more duty hours on Days 1 through 4 for the low-risk patterns. They are more completely filling their limit of DOT cumulative hours during the first few days of the pattern. Those

TABLE 2 CONTINUOUS DRIVING HOURS FOR EACH PATTERN

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	8.00	1.47
6	7.73	3.57
7	8.01	1.01
8	7.90	1.18
9	8.06	1.43

TABLE 3 CUMULATIVE ON-DUTY 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	43.20	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

patterns with higher risk have more driving on Days 5 through 7 but not enough to approach 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 8 hr or more. The driving cycle is thus intended to estimate the periodicity of driving. To screen cycles that include 1 or more full days off duty (due to lack of freight or being "out of hours"), a maximum of 24 hr 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 through 10 is almost too good. There is a nearly 24-hr period despite the fact that drivers may be scheduled with an 18-hr period (i.e., 10 hr driving and 8 hr off duty). The driving cycle variable is intended to check whether individual drivers actually are scheduled with a nearly 24-hr period, which would clearly be beneficial with respect to circadian rhythms. If the actual period is significantly less than 24 hr, the driver's time on the road will not be stable with respect to time of day, and, according to theory, additional decrements in performance can be expected (7).

Table 4 summarizes the driving cycle data for each of the nine patterns. The mean and standard deviation of the driving cycle are reported in the sixth set of columns (labeled Driving Cycle). Columns 1 through 5 report the same statistics for the duty hours that make up the driving cycle: the time on duty and driving; the time on duty and not driving (e.g., time for pretrip inspection); time on duty and not driving during the trip because of short rest breaks (e.g., meals), the total on-duty time (the total time in activities represented in Columns 1 through 3), and subsequent off-duty time of at least 8 hr. Whereas Pattern 6 is again anomalous, all other patterns have mean driving cycles from 22.08 to 23.03 hr, with most in the range 22.7 to 22.9 hr. There appears to be substantial evidence that the driving cycle, as defined, is much closer to 24 hr than the minimum driving times might suggest. This could be due to one of two reasons or a combination of the two. First, as Table 4 indicates, there is a mean of approximately 1 hr on duty with short rest and 0.50 hr on duty and not driving for each driving cycle. This pushes total on-duty time to close to 10 hr. Consecutive off-duty time, however, has a mean of 12 hr or more (even when excluding off-duty times beyond 24 hr). Drivers thus do not appear to be scheduled for maximum driving time and minimum off-duty time (on the basis of DOT regulations). 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-hr period, freight movement demand may coincide (somewhat serendipitously) more closely with driver circadian rhythms, contributing to road safety.

SUMMARY

Driving at different times of day within 1 day, and over several days, is associated with different levels of accident risk. Analysis of accident and nonaccident data from an LTL carrier

TABLE 4 SUMMARY OF DRIVING CYCLES FOR EACH PATTERN

	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

representing 6 months of operation in 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 7-day period from a sample of 1,066 drivers (including those with accidents and nonaccidents on the eighth day).

The analyses yielded clear interpretable driving patterns that could be associated with levels of relative accident risk. Higher risk was generally, but not exclusively, associated with extensive driving in the 2 to 3 days preceding the day of interest. The two patterns with the highest risk of an accident were those that contained heavy driving during the preceding 3 days and consisted of driving from 3:00 p.m.to 3:00 a.m. (Pattern 1) and from 10:00 p.m. to 10:00 a.m. (Pattern 8). The lowest risk was associated with driving from 8:00 p.m. to 6:00 a.m. but with limited driving on the preceding 3 days.

With the exception of a pattern representing infrequently scheduled drivers (Pattern 6), the remaining 8 patterns are classified into 4 pairs identified by common times of driving within a day. The differentiating feature is whether driving occurs in the first 3 to 4 days of the driving period or the last 2 to 3 days before the day of interest. Given the virtually limitless possible combinations of driving schedules, it is encouraging that interpretable distinct multiday patterns could be extracted from a data base of more than 1,000 observations.

Within each pattern, drivers experienced similar duty hours: cumulative driving over the 7 days ranged from 47 to 49 hr. Continuous driving (between mandatory 8-hr off-duty periods) ranged from 7.8 to 8.4 hr. Individual drivers also experienced a cycle of on-duty and off-duty time that ranged from 22.3 to 23 hr, closer to the 24-hr period that is desirable from the perspective of human performance theories.

It is clear, however, that there are no simple explanations for multiday accident risk. Rather, drivers who drive at particular times of day appear to face changing accident risks within any 8-day driving period. The findings indicate that it is possible to quantitatively account for both hours of driving over a 7-day period and 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 to explore additional driving patterns and their effect on accident risk. Whereas the nine clusters in this study yielded interpretable results, additional insights may be gained by developing a larger number of clusters that are more precise in their driving patterns. This analysis requires additional data, beyond the 1,066 cases used in this study. It is difficult to determine when the optimal number of clusters has been identified because the statistical method, cluster analysis, is heuristic. Analyses of additional driver variables, such as age and experience, and descriptors of the routes used by the drivers (road design, traffic level, and terrain) would be useful additional information to include in subsequent analyses. Individual driver sociodemographic characteristics, such as marital status and family structure, may also help explain accident risk.

It is hoped that the use of cluster analysis to identify multiday driving patterns will encourage similar studies with this methodology. Disaggregate analyses are becoming much more common in the truck safety literature (*13,14*) and offer the prospect of more accurate identification of relative accident risk as well as the absolute probability of accident occurrence (*12*). It is hoped that this paper contributes to this trend.

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REFERENCES

1. T. Kaneko and P. P. Jovanis. Multiday Driving Patterns and Motor Carrier Accident Risk: A Disaggregate Analysis. *Transportation Research Group Research Report UCD-TRG-RR-90-9*. Department of Civil Engineering and Transportation Research Group, University of California, Davis, 1990, 32 pp.
2. N. MacDonald. *Fatigue, Safety and the Truck Driver*. Taylor and Francis, London, 1984, 218 pp.
3. N. L. Haworth, T. J. Triggs, and E. M. Grey. *Driver Fatigue: Concepts, Measurement and Crash Countermeasures*. Department of Transport and Communications, Federal Office of Road Safety, Canberra, Australia, 1988, 124 pp.
4. W. Harris and R. R. Mackie. *A Study of the Relationships Among Fatigue, Hours of Service, and Safety of Operations of Truck and Bus Drivers*. Final report. BMCS RD 71-2, FHWA, U.S. Department of Transportation, 1972.
5. W. Harris. Fatigue, Circadian Rhythm, and Truck Accidents. In *Vigilance: Theory, Operational Performance and Physiological Correlates*, Plenum Press, New York, 1977, pp. 133–146.
6. R. Mackie et al. *A Study of Heat, Noise and Vibration in Relation to Driver Performance and Physiological Status*. Technical Report 1735, Human Factors Research, Inc., Goleta, Calif., 1974.
7. R. Mackie and J. Miller. *Effects of Hours of Service, Regularity of Schedules and Cargo Loading on Truck and Bus Driver Fatigue*. Report DOT HS-803 799. Human Factors Research, Inc., Goleta, Calif., 1978.
8. R. Hertz. Tractor-Trailer Driver Fatality: The Role of Nonconsecutive Rest in a Sleeper Berth. *Accident Analysis and Prevention*, Vol. 20, No. 6, 1988, pp. 431–439.
9. Transportation Research and Marketing. *A Report on the Determination and Evalution of the Role of Fatigue in Heavy Truck Accidents*. AAA Foundation for Traffic Safety, Falls Church, Va., 1985, 76 pp.
10. P. Hamelin. Truck Driver Involvement in Traffic Accidents as Related to Their Shiftworks and Professional Features. *Symposium on Role of Heavy Freight Vehicles in Traffic Accidents*, Vol. 2. Roads and Transportation Authority of Canada, Ottawa, Canada, 1987.
11. R. Fuller. Determinants of Time Headway Adopted by Truck Drivers. *Ergonomics*, Vol. 24, 1981, pp. 463–474.
12. H. Chang. *A Disaggregate Survival Model of Motor Carrier Highway Accident Occurrence*. Ph.D. dissertation. Northwestern University, Evanston, Ill., 1987.
13. M. E. H. Lee-Gosselin, A. J. Richardson, and G. Taylor. Truck Accident Involvement With and Without Front-Axle Brakes: Application for Case-Control Methodology. In *Transportation Research Record 1270*, TRB, National Research Council, Washington, D.C., 1990.
14. P. P. Jovanis and H. Chang. Disaggregate Model of Highway Accident Occurrence Using Survival Theory. *Accident Analysis and Prevention*, Vol. 21, No. 5, 1989, pp. 445–458.

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