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FORMULATING ACCIDENT OCCURRENCE AS A SURVIVAL PROCESS

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Abstract—A conceptual framework for accident occurrence is developed based on the principle of the driver as an information processor. The framework underlies the development of a modeling approach that is consistent with the definition of exposure to risk as a repeated trial. Survival theory is proposed as a statistical technique that is consistent with the conceptual structure and allows the exploration of a wide range of factors that contribute to highway operating risk. This survival model of accident occurrence is developed at a disaggregate level, allowing safety researchers to broaden the scope of studies which may be limited by the use of traditional aggregate approaches. An application of the approach to motor carrier safety is discussed as are potential applications to a variety of transportation industries. Lastly, a typology of highway safety research methodologies is developed to compare the properties of four safety methodologies: laboratory experiments, on-the-road studies, multidisciplinary accident investigations, and correlational studies. The survival theory formulation has a mathematical structure that is compatible with each safety methodology, so it may facilitate the integration of findings across methodologies.

1. INTRODUCTION

The occurrence of accidents is often compared to the number of opportunities available for involvement in an accident. Some representation of these opportunities is commonly referred to as exposure to accident risk. Hauer develops a definition of a unit of exposure as a trial in which the outcomes are an accident (possibly of several types) or a nonaccident (Hauer 1982). Safety (as measured by accident occurrence) is the product of the probability of having an accident (also called risk) and the number of exposure units. Factors contributing to accident risk are thus conceptualized as affecting the probability of an accident.

The major problem in combining accident data with exposure is that accidents are discrete events. Data describing accidents routinely come from reports describing accident outcome and characteristics such as driver, vehicle, roadway, and environment at the time of the accident. Exposure data are much more aggregate, typically based upon measured or estimated daily, weekly, monthly, or often yearly travel. A fundamental dilemma in studies of accident occurrence is how to combine exposure and accident data in a meaningful and consistent way so that the contribution of individual factors to accident risk can be identified.

Accident prediction models have typically been developed using aggregate exposure data. The use of aggregate data can result in the loss of information, obscuring the relationship between risk factor and accident occurrence. Disaggregate data have been commonly used in travel demand research because of their improved explanatory capabilities, but they have not been commonly used in safety research.

While a disaggregate analysis approach has clear statistical advantages, it will lead to more meaningful safety research findings only if it is solidly based in theory and concept. The theoretical link provides the basis from which analysis results may be interpreted. A conceptual structure is needed to help assure that a comprehensive model framework has been developed. Accident occurrence is a complex as well as rare evént. Both of these attributes argue for a clear conceptual approach to the model structure.

The driver (or pedestrian) is the principal decisionmaking unit in the highway system, hence, in a commonly used safety theory the driver is considered an information processor (Shinar 1978). This representation allows the safety researcher to consider how a driver's physical and psychological condition influence performance. Characteristics of the roadway system, traffic levels, and environmental conditions can be used to define a risk system within which the driver operates.

The representation of the driver as an information processor is an important starting point for our conceptualization. It is equally important that the conceptualization allow for the clear identification of exposure to accident risk. While this may seem straightforward, Hauer has illustrated that the many potential applications for exposure require a generic and flexible definition (Hauer 1982). He uses the notion of the "chance setup" or trial to identify a unit of exposure. It would thus be advantageous for our model formulation to contain the concept of a trial, perhaps one that leads to either an accident or nonaccident after some set of events that depend on the design of the experiment. Following this reasoning, it is particularly advantageous for the mathematical formulation to be consistent with both the information processing definition and the concept of exposure as a repeated trial.

Section 2 of this paper describes the conceptual structure of the survival theory model in a way that is consistent with human information processing theories and Hauer's definition of exposure. Section 3 provides an overview of the mathematical formulation that is described in greater detail elsewhere (Jovanis and Chang 1989). Section 4 presents a typology of methodologies used to study accident occurrence with the aim of describing the advantages of survival theory compared to findings in the extant literature. The paper concludes with a summary of findings and discusses challenges remaining for future research.

2. A CONCEPTUAL FRAMEWORK FOR THE PROCESS OF ACCIDENT OCCURRENCE

The driver as an information processor

Though driving has been modeled as information processing for some time (Shinar 1978), there have been only limited attempts to use these concepts to develop a feasible quantitative model for highway safety research. In order to quantify this conception, there is a need to precisely describe how the information comes to a driver, how the driver responds to it, and how the model is able to mathematically structure these events.

Figure 1 illustrates how risk factors provide information to the driver. At this stage, a risk factor can be thought of as a collection of more precisely defined attributes that influence accident occurrence. This hypothetical structure formalizes the conceptualization of the driving task and helps to identify possible interrelationships between the attributes of the risk factors that may affect accident risk. Examples of the interrelationships as well as direct effects of risk factor attributes on accident risk are described in the following paragraphs. The reader may refer to Fig. 1 to identify information paths.

Let us first consider the effect of environmental attributes. There are three paths by which environmental factors provide information about the risk system to the driver. *First*, the environment can directly pass its information to the driver and affect driver performance. The driver's vision, for example, will be hindered when driving during adverse weather such as fog or snow. *Second*, the environment affects roadway conditions and then this joint information is delivered to the driver. An example is the presence of snow on an unplowed roadway: obliterated pavement markings make it more difficult to position the vehicle on the roadway. *Third*, the environment can affect vehicle performance; for example, strong wind conditions can make small vehicles unstable, requiring more careful driving and greater levels of driver arousal.

The roadway has two ways to transmit its information to drivers. Different roadway designs and markings provide information to the driver about the correct choice of speed and path. The driver also receives information about the roadway through the vehicle

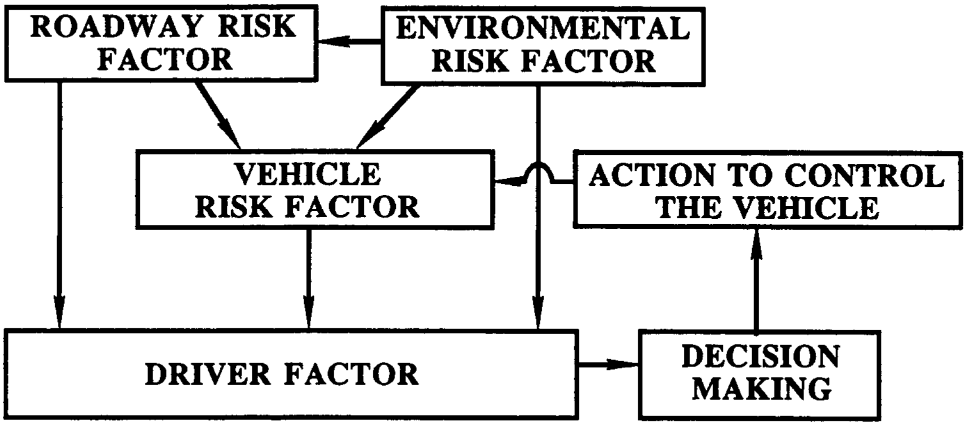


Fig. 1. A conceptual framework for information processing by driver (modified from Shinar 1978).

steering mechanism (e.g. super elevated curve); this allows the driver to properly position and steer the vehicle.

The vehicle is the element of contact closest to the driver. The vehicle passes its information directly to the driver through his sensory mechanisms. Most of this information is initiated with the environment and roadway and is processed by the driver as described in the preceding paragraphs. Some information is, however, provided by the vehicle itself, such as speedometer readings or indications of mechanical defects.

A driver bases his decisions on the information received. Different drivers may make their decisions in different ways, and the same driver may act differently at different times. Driver attributes and feedback received by taking actions are, thus, important determinants of driver performance. The driver controls the vehicle and receives continuous feedback for subsequent decisions from a variety of environmental, roadway, and vehicle conditions.

Conceptualized Accident Occurrence Process

Conceptualization of accident occurrence starts with observation of individual vehicles, from the start to end of their movement. The interest of this observation centers on how, if at all, an accident is initiated, what the contributing risk factor attributes are, and how those attributes work together. This conceptualization of individual vehicle movement is entirely consistent with the information processing framework illustrated in Fig. 1 and described in the previous section. Figure 2 illustrates how this concept can be extended to include the outcome of the travel: either an accident or a successfully completed trial. Using the disaggregate perspective of individual vehicle movement and driver information processing allows us to formulate a conceptual structure of accident occurrence (Fig. 2) that is consistent with Hauer's definition of exposure as a repeated trial.

The conceptualization is illustrated as a flow chart, because an important aspect of the structure is the repetition of trials. Once each trial is initiated, the risk system is entered and driver information processing begins (as in Fig. 1). Accident occurrence is modeled in two stages within the risk system: generation and patterning, as described in subsequent sections. Once a trial is completed, a new trial is begun.

In order to realistically describe the risk of highway operation the selection of the time frame which defines the "trial" is an important decision. The choice of time frame can vary widely, depending on the nature of the safety system to be investigated and the hypotheses to be tested. For example, in order to explore accident risk for automobile drivers, we may choose a 24-hour or longer observation period in order to capture the

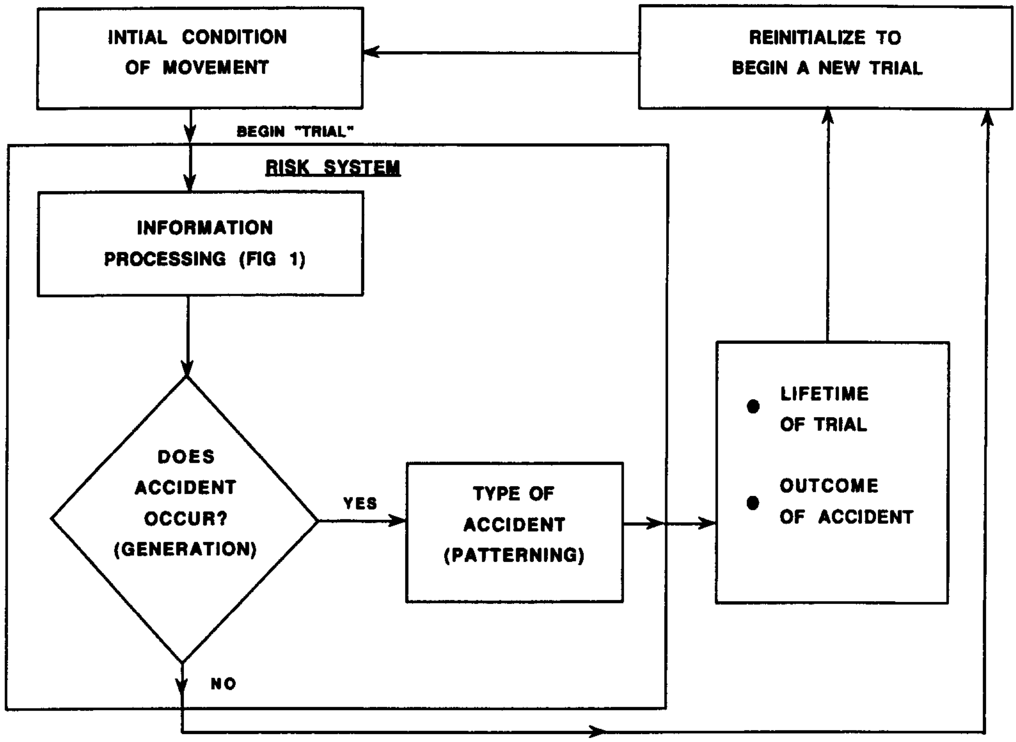


Fig. 2. Conceptual framework for accident occurrence.

effect of periodic travel due to patterns of activities. An origin-to-destination observation may be undertaken for truck safety studies, because we may want to test specific hypotheses about dispatching policies or the relative safety of particular truck configurations, e.g. twin trailers.

The time frame should be selected with recognition that some attributes of risk factors may change with time. In the example of personal travel, the individual may make trips for several purposes, perhaps in different vehicles, throughout the day or week. The analyst, basing his decisions on the hypotheses of interest, must conceptualize the "trials" in his particular case. In the mathematical formulation of this conceptualization, the time frame is a critical variable, which the analyst must select carefully. Although the mathematical formulation (summarized in Section 3) is quite flexible, compromises in model structure may have to be made, as with any other model.

Accident generating process

An initial set of driver, vehicle, and trip characteristics are given before the vehicle enters the risk system. These characteristics are the initial conditions of movement (see Fig. 2). In terms of accident risk, these initial conditions imply some potential risk for accident involvement. For example, the lack of enough rest before starting one trip will affect a driver's arousal and can increase accident risk. With these initial conditions, the driver starts to undertake the information processing task and seeks to attain the required performance in order to maintain accident-free vehicle operation.

The driver ends the exposure with a stop. Stops can be classified into two categories—accident involvement or nonaccident stop—according to the definition of the chance set up. An accident occurrence will always end our observation of that individual trial. A nonaccident stop results in an interruption before the driver starts another continuous movement. Depending on the criteria chosen to define the trial, the nonaccident stop may be either the end of one trial or a temporary interruption. Movement following the interruption results in continued information processing until a stop occurs that is consistent with the defined trial. This trial is then recorded, with its risk factors, as a unit of exposure.

The microscopic observation of individual drivers terminates with the successful completion of one trial or involvement in an accident. The accident generating process is defined as the process that the driver experiences in seeking to survive in the risk system from the start to the end of one trial. For accident-involved trials, the observation includes the lifetimes of the trips, the associated attributes, and the outcomes of the accidents. For nonaccident trips, in addition to a comparable set of trial attributes, the only information available is survival after a given amount of time in the risk system. In terms of the survival analysis models in the next section, these nonaccident trials are statistically treated as censored (i.e. one does not observe their failure time).

Accident patterning process

In the accident generating process, the interest is to determine how the risk system affects whether or not an accident will occur. However, when an accident is initiated, the risk system will affect the specific accident outcome. This outcome includes the number of involved vehicles, type of collision, severity of injury, and so on. Accident patterning is the process by which the risk system determines the type of accident outcome. Therefore, the risk system will determine the accident generating process, as well as the accident patterning process. The risk components for the accident generating process operate during the entire trial, but accident patterning is primarily determined by instantaneous risk factors (those at or near the accident scene).

Accident patterning may be studied without detailed travel exposure. The study can be easily undertaken by using the data already present in accident reports, obviating the difficult issue of proper use of exposure data. Accident report data can be used to associate attributes of risk factors to the accident outcomes; lack of use of exposure data will prohibit associating risk factor attributes with accident *rates*. It is possible, therefore, that lack of exposure data will result in identifying factors that may not be efficient in that they may not produce the largest reduction in accident rate.

Summary and discussion

This section contains a description of a conceptual framework of accident occurrence. The conceptualization begins by considering the driver as an information processor and, using principles from psychology, links the information processing to the vehicle, roadway, and environment through a series of direct and indirect channels. This information processing paradigm is then imbedded within a framework that explicitly considers travel as a trial that can result in an accident or nonaccident (exposure) outcome. This broader framework considers accident and exposure occurrences at the consistent disaggregate level and models accident occurrence as a sequential process: first, accident generation, which is an "accident—no accident" determination; then, accident patterning, which determines accident outcomes.

Alternatively, specific accident patterns may be thought of as having their own accident generating processes and then competing with each other to stop the continuation of a trial. Such an accident occurrence process is considered to be a competing risk formulation. Specific accident patterns can be classified by accident causes or accident outcomes; whenever one of the specified outcomes occurs, the trial is terminated and the other outcomes do not occur. In this way the outcomes are conceptualized as "competing" with each other. One of the possible outcomes is, of course, not having an accident.

It might be interesting to use a competing risks formulation to model the changes in accident patterns that are associated with changes in risk factor attributes. For example, one might like to identify the reduction in right-angle accidents and the likely increase in rear-end collisions that would occur with the conversion from two-way stop controls at an intersection to traffic signals.

Several issues must be carefully considered before the formulation of accident occurrence as a competing risk. The principal conceptual difficulty is that the competing outcomes are usually modeled as independent (Moeschberger and David 1978). A number of important attributes of accidents argue against their formulation as competing risks. One problem arises because some outcomes are not mutually exclusive. For example, an injury accident is virtually always associated with some property damage. Modeling competing outcomes classified by severity level is then inappropriate if the mathematical formulation does not allow for some association between outcomes. There is another form of association between competing outcomes that violates the independence assumption; in the traffic signal/stop sign example discussed earlier, appropriate roadway design, driver attributes, and weather conditions are common risk components that may affect the probability of both rear-end and right-angle accidents.

While the idea of modeling highway accident occurrence as competing risks is conceptually appealing, there is a very limited literature on ways to overcome the statistical challenges and estimation challenges posed by association between competing outcomes (Moeschberger and David 1978). The separate conceptualization of generation and patterning seems to be the most reasonable approach at this time.

3. MODELLING HIGHWAY ACCIDENT OCCURRENCE

Formulation of accident generation

According to the conceptual structure, the accident generating process possesses characteristics that critically affect the consideration of the appropriate mathematical approach for problem formulation. First, the occurrence of an accident can be thought of as the failure to successfully complete a trial, given a risk system defined by the attributes of the four principal factors. The system hazard (i.e. the probability of being involved in an accident) varies during the trial. An accident is the only event that can occur during a trial other than successful completion of the trial. These characteristics allow the accident generating process to be modelled as a survival process. The interest is to observe how long the vehicle can survive before an accident occurs (Jovanis and Chang 1989).

Let T be a nonnegative random variable representing the lifetimes of individual trials in some population. Let $f(t)$ denote the probability density function of t and let the distribution function be:

$$F(t) = Pr(T < t) = \int_0^t f(x)\,dx \tag{1}$$

The probability of a trial resulting in survival until time t is given by the survival function:

$$S(t) = Pr(T \geq t) = \int_t^\infty f(x)\,dx \tag{2}$$

Note that $S(t)$ is a monotone decreasing continuous function with $S(0) = 1$ and $S(\infty) = \mathrm{Lim}_{t\to\infty} S(t) = 0$. The hazard function, $h(t)$, is defined as:

$$h(t) = \lim_{\Delta t \to 0} \frac{Pr(t < T < t + \Delta t \mid T > t)}{\Delta t} = \frac{f(t)}{S(t)} \tag{3}$$

The hazard function specifies the probability density function of being involved in an accident at time t, given that the trial results in success up until t. The function of $f(t)$, $S(t)$, and $h(t)$ are the three basic functions of the survival theory. Expressions for $S(t)$ and $f(t)$ can be derived in terms of $h(t)$ as:

$$S(t) = \exp\left[-\int_0^t h(x)\,dx\right] \tag{4}$$

$$\text{and}\quad f(t) = h(t)\exp\left[-\int_0^t h(x)\,dx\right] \tag{5}$$

Because the functions of $f(t)$, $S(t)$ and $h(t)$ are mathematically equivalent specifications, the analysis can be undertaken in terms of any one of them. Cox and Oakes

(1984) raised a number of reasons why consideration of the hazard function may be a good idea. The hazard function, $h(t)$, is preferred to the other functions because the notion of failure rate is basic and conceptually simple. Presumably, the lifetime of an individual trial is affected by concomitant variables. Therefore, in general, the hazard function can be represented as $h(t|\mathbf{X})$, where $\mathbf{X}$ is a vector of explanatory variables, which are the risk factors and their attributes as identified in Section 2. The hazard function $h(t|\mathbf{X})$ indicates the probability to be involved in an accident at time t for a trial with risk attribute vector $\mathbf{X}$, given survival until t. The use of trial in this context is entirely consistent with the "trial" discussed in the conceptual formulation in Section 2 and is also consistent with the definition of exposure proposed by Hauer.

Model estimation may be conducted in a number of ways. An accident contributes a factor $f(t|\mathbf{X})$ to our model formulation, but a nonaccident contributes a factor $S(t|\mathbf{X})$ to the model. Therefore, the likelihood function for a set of observed data on n trials can be expressed as follows when the lifetime distribution of a trial is considered to be a function of regression vector $\mathbf{X}_i$:

$$L = \pi_{i=1}^{n} \{f(t_i|\mathbf{X}_i)\}^{\delta_i} \{S(t_i|\mathbf{X}_i)\}^{1-\delta_i} \tag{6}$$

where t_i is the lifetime or censoring time for the individual trial i and δ_i is the usual indicator variable taking on the value of 1 if t_i is a lifetime and 0 if t_i is the censoring time. Taking the logarithm of Eq. (6) one obtains the log-likelihood function as:

$$LL = \sum\{\delta_i \log[f(t_i|\mathbf{X}_i)] + (1 - \delta_i) \log[S(t_i|\mathbf{X}_i)]\} \tag{7}$$

Applying the assumed proportional hazards models like Eq. (8) (see below) with an appropriate nuisance hazard $h_0(t,C)$, the log-likelihood function of Eq. (7) is bounded and twice differentiable. The existence and uniqueness of the solution of estimated coefficient vectors which maximizes Eq. (7), can be obtained from the literature of survival analysis (Lawless 1982; Cox and Oakes 1984). A nonparametric approach is also available using the product limit method (Kaplan and Meier 1958). Further information about Cox's nonparametric method can be obtained from Cox (1972), Chang (1987), and Jovanis and Chang (1989).

Formulating the hazard function for highway accident occurrence

Several types of hazard models for suvival analysis have been introduced in the biomedical literature (e.g. Aranda-Ordaz 1983; Cox and Oakes 1984). They differ in the way in which the explanatory variables are assumed to influence the underlying hazard. Among those available models, the proportional hazards model proposed by Cox (1972) is commonly used in survival analysis. The proportional hazards model is expressed as:

$$h(t|\mathbf{X}) = h_0(t)\ \mathrm{Exp}(\mathbf{B}^*\mathbf{X}) \tag{8}$$

where $\mathbf{B}^*\mathbf{X} = b_1 x_1 + b_2 x_2 + \text{------} + b_p x_p$ and the b_p's are the unknown regression coefficients, and $h_0(t)$ is the hazard function when $\mathbf{X} = 0$. There are several reasons for considering the proportional hazards models (Cox and Oakes 1984). *First*, there is a simple easily understood interpretation to the idea that the effect of the risk components vector is to multiply the hazard by a constant factor. *Second*, censoring time and the occurrence of several types of failure are relatively easily accommodated within this formulation, and, in particular, the technical problems of statistical inference when $h_0(t)$ is arbitrary have a simple solution (Cox 1972). *Third*, the proportional hazards assumption appears to be reasonable in many situations. Some examples and references to this in the biomedical area are contained in works by Barlow and Proschan (1981) and by Prentice and Kalbfleisch (1979). In engineering contexts, proportional hazards are considered by Lawless (1982) and many others.

The proportional hazards model possesses the property that the increase in the system hazard due to the increased risk of one specific risk factor attribute depends on the values of all the other attributes. That is, when the risk component x_i increases Δx_i, the hazard function $h(t|\mathbf{X})$ will increase to $h_0(t)$ Exp($\mathbf{B}^*\mathbf{X}$) Exp($b_i^*\Delta x_i$). This characteristic explicitly recognizes that accident risk is a complex function of many components acting together. For example, the accident risk of a mechanical defect (e.g. brake failure or flat tire) might depend on vehicle speed and the level of surrounding traffic. Compared with other hazard functions (Chang 1987; Jovanis and Chang 1989), the proportional hazards model can capture a wide variety of the characteristics contributing to highway accident occurrence. Refinements in model specification can be used to represent the contribution to risk of an individual attribute or the interaction of attributes. Starting with a basic disaggregate formulation allows great flexibility in subsequent model formulation and testing. Much more research is needed in the safety field before we are to formulate mathematical models that can better represent attributes contributing to accident occurrence. For the present, the basic formulation, described by Eq. 8 is used.

Formulating the hazard function of accident occurrence as a proportional hazards model, the hazard function is treated as the product of two factors—the nuisance hazard $h_0(t)$ and the multiplicative factor Exp($\mathbf{B}^*\mathbf{X}$). The nuisance hazard $h_0(t)$ can be thought of as the combined hazard due to the fatigue of driving (from continuous driving) and the risk components that are not included in the model. It can be specified as a time-independent function (i.e. constant hazard) or a time-dependent function of some specific parametric distribution family. Hence, in general, the nuisance hazard is usually represented as $h_0(t,\mathbf{C})$, where $\mathbf{C}$ is the vector of unknown parameters that specify the distribution of nuisance hazard. The multiplicative factor acts as an adjustment factor to the hazard function for the risk components included in the model. The multiplicative factor should be nonnegative, so it is natural to apply the exponential expression in the proportional hazards model.

Accident patterning

As currently formulated, accident patterning can be modelled within the estimation of the hazard function of Eq. 8. For example, different accident outcomes may be modeled as distinct segments of a larger accident data set. The approach was taken by Jovanis and Chang (1989) in a non-parametric estimation with accident data only. For some types of accident patterns, dummy variables may be used to distinguish accident outcomes. Whatever approach is taken to deal with accident outcomes, the pattern of accidents can be expressly and consistently modeled within the survival theory formulation. Even with the limitation on competing risk formulation that was discussed in the conceptual framework, significant flexibility is afforded the analyst in representing accident patterning.

Model applications

Data from trucking company operations were used to estimate hazard functions that included as covariates: driver risk factors such as age, experience, hours off duty just prior to the accident, and hours on duty and driving during last eight days; environmental risk factors such as season (winter or not) and time of day (night or not); and a vehicle risk factor, cargo weight. No roadway risk factors were explicitly included (Jovanis and Chang 1989). Additional models estimated with truck operations data are discussed in Chang (1987). Although these are the only known uses of survival theory in road safety studies, the next section discusses the model's potential utility to link findings from several existing methodologies.

4. TYPOLOGY OF SAFETY RESEARCH METHODOLOGIES APPLIED TO ACCIDENT OCCURRENCE

Overview

In developing a new method to analyze accident occurrence, it is useful to understand how the methodology compares to existing research techniques. It is also useful to identify, when possible, linkages between study methods. This is important, because the complex nature of accident occurrence requires that many different methodologies from different disciplines be applied to understand accident processes. If a method has utility in integrating findings across disciplines and study methodologies, it will be extremely useful.

A typology of traffic safety research methodologies is illustrated in Table 1. Four different methodologies are identified: laboratory experiment, on-the-road study, multidisciplinary accident investigations, and correlational studies (borrowed from Shinar 1978). Each of the categories are denoted by whether data are collected at the aggregate or disaggregate level and also whether these methodologies address three topics that are reflected in the conceptual structure and are, we believe, important in the identification of accident causality. The three topics are defined as follows:

Initial Conditions of Movement—These conditions include physical and psychological factors that are relatively invariant during the trial.

Definition of A Trial—The trial or chance setup was discussed in Section 1 of this paper; in this context it represents the concept that exposure to accident risk is explicitly considered as part of the methodology.

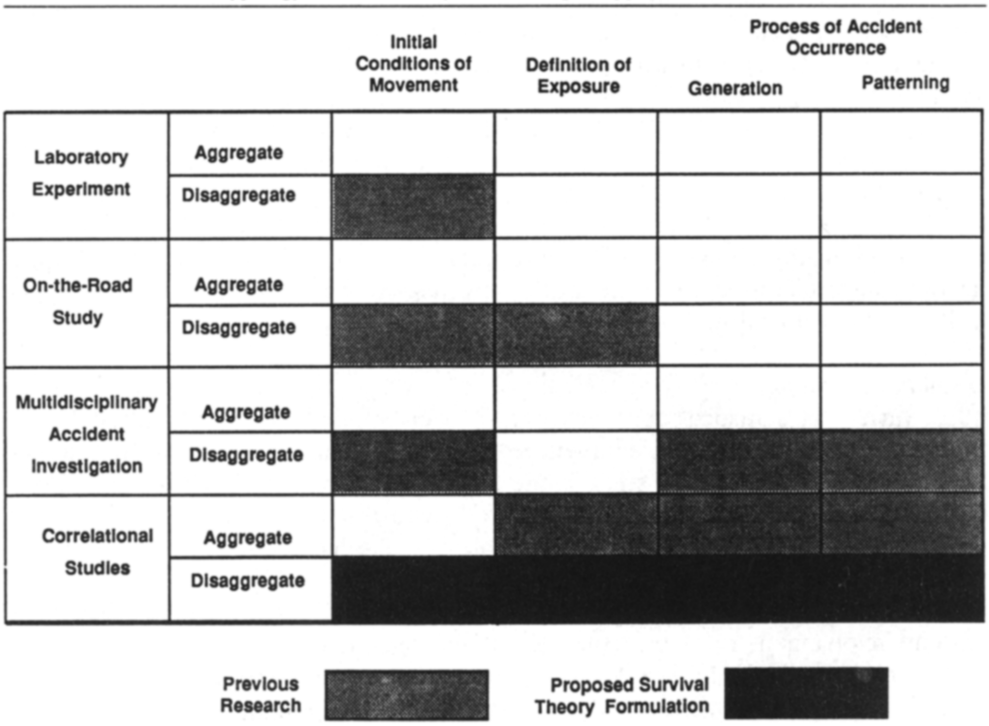
Process of Accident Occurrence—Both aspects of accident occurrence, generation and patterning, are considered in a methodology.

Laboratory experiment

Laboratory experiments or simulations can be used to study details of driver or vehicle actions which may be linked to accidents but are difficult to observe in the field. Laboratory experiments commonly study actions such as steering wheel movement (Crandall, Duggar, and Fox 1966), lateral and longitudinal position (Barrett, Kobayashi, and Fox 1968), velocity estimation (Salvatore 1969), breathing rate (Bears, Case, and Hulbert 1970), and vigilance (Heimstra 1970). In those experiments or simulations, the relationship between independent variables and these intermediate measures is applied directly and then inferences are made about the effect of these independent variables on highway accident risk.

The advantages of laboratory experiments include safety of the subjects, control of some confounding variables, and possibly reduced costs compared to field observation.

Table 1. A typology of traffic safety methodologies applied to accident occurrence



Foremost among the shortcomings of laboratory experiments is the difficulty of generalizing the laboratory findings to the actual highway environment (Shinar 1978).

Although laboratory experiments allow us to obtain individual disaggregate performance data, they are limited in their ability to provide insight in the process of accident occurrence and, obviously, do not contain data on actual involvements. Trials are conducted during the experiments, but they reflect "pseudo" exposure because no actual risk system exposure is undertaken.

On-the-road studies

Studies of drivers in actual conditions include application of the traffic conflicts technique (e.g. Perkins 1969; Oider and Spicer 1976), inobtrusive observation of individual drivers and vehicles (Shinar, Rockwell, and Malecki 1975) and on-road measurements of drivers in instrumented vehicles (e.g. Platt 1970; Helander 1976).

The major advantage of on-the-road research is that results obtained from it may be immediately applicable to the highway environment. Its major disadvantage is that many variables are not under strict experimental control, and the results may be due to uncontrolled variables and/or limited to the specific location where the study was conducted. While individual drivers are studied, it is not possible to directly relate these studies to outcomes (accidents). Exposure to the risks under study is limited because accidents are rarely observed during on-the-road studies. Although unit of exposure can be derived, their use in computing accident probability or risk is limited by the scope of road research that is possible given normal budget constraints. Because accidents are infrequently observed, data on accident occurrence are not generally used, but inferences about risk are made.

Multidisciplinary accident investigations

An accident results whenever one or more factors—labeled as the accident cause or causes—deviates from the norm to such an extent that the system cannot accommodate it (Shinar 1978). One of the most consistent findings in accident research is that accidents are caused by more than one factor. Each factor cited as causal may be a cause only in the context of the other causes.

The most prominent study for accident causal analysis is Indiana University's Trilevel Study of The Causes of Traffic Accidents (Treat et al. 1977). These three levels of accident investigation include: (i) routine police investigation, (ii) "on-site" investigation by specially trained technicians who rushed to the accident site immediately after notification by the police, and (iii) "in-depth" investigation by a multidisciplinary accident investigation (MDAI) team who examined and interviewed the driver, reconstructed a complete diagram of site and vehicles' paths, and examined the accident vehicle in a specially equipped garage. The study results show that human factors, identified as probable or definite causes, are related to approximately 91% of the traffic accidents.

This study has had a great influence on subsequent safety research, so it is obviously of major importance. The limitation of the methodology is the lack of exposure data, which argues against an even broader interpretation of the results. It may also be argued that the causal factors used in the study were heavily weighted toward driver factors, but it is difficult to substantiate this potential bias.

Correlational studies

A variety of statistical approaches have been applied to safety studies. Usually, analysts combine the accident data with controlled exposure and test the hypothesis of interest. The simplest type of study is the comparison of the mean and variance of the accident involvement rates, which is undertaken to test the equality of accident risks between different exposure groups. Examples of this technique include the work of Foldvary (1979), Meyers (1981), and Jovanis and Delleur (1984).

Linear regression models have been widely used in safety studies. Usually, the accident involvement rates are considered the dependent variables in most of linear regression analyses of safety study, and the risk components to be detected are assigned to the independent variables. Those risk components include travel speed (Hall and

Dickinson 1974; Lavette 1977), traffic volume (Oppe 1979; Ivey et al. 1981; Ceder and Livneh 1982), as well as weather and vehicle (Jovanis and Delleur 1984).

Some properties of accident occurrence argue against the application of linear regression analysis to highway safety studies (Jovanis and Chang 1986). In order to improve the shortcomings of linear regression analysis in safety study, one discrete model, the Poisson Regression Model, has been applied in the study of accident occurrence. Hamerslag, Roos, and Kwakernaak (1982) used it to detect the effects of road characteristics and traffic volume of the accident involvement rates. Jovanis and Chang (1986) described the accident occurrence on a closed highway system as a Poisson process in which the daily expected number of accidents is a function of daily traffic exposure and weather conditions.

Some multivariate analysis techniques other than regression analysis are also used in safety study. Those techniques include automatic interaction detection (AID) (Snyder 1974; Cleveland and Kitamura 1978), category analysis (Koornstra 1969), factor analysis (Häkkinen 1979), and generalized loglinear models (Chirachavala et al. 1984; Saccamano and Buyco 1988).

The common denominator of all above statistical or correlation analyses for traffic safety study is the absence of an explicit explanatory framework for accident occurrence. That is, those efforts emphasized the estimation of statistical relationships in the available data and attempted to interpret those relationships. A preferred approach is the development of an understanding of the underlying process that determined those relationships, and the development of an analysis framework that can capture those relationships. Furthermore, all exposure-based accident prediction models in previous literature were developed with aggregate data. The use of aggregate data to construct an accident prediction model will cloud the relationships between risk components and accident occurrence.

The relationship of the proposed survival theory model to previous methodologies

Examination of Table 1 leads one to discover that the first three methodologies used to explore accident causation are fundamentally disaggregate techniques: information of interest is obtained from a series of observations or experimental trials. It is principally when these observations are combined with exposure data (as in correlational studies) that this potentially powerful disaggregate information is lost. Data are then aggregated into cells in order to facilitate their combination with exposure data. In many cases it is not possible to include all explanatory variables, because exposure is not known for some factors of interest, for example, age, gender, income of drivers *not* involved in accidents.

By using the proposed survival theory formulated for accident occurrence, study findings regarding driver behavior can be directly analyzed with actual accident involvements. Findings from driving simulators, on-the-road tests, and MDAI studies can be explicitly included in a consistent quantitative framework. Trials that result in accidents are treated as "failed," and those that are successfully completed are treated as "censored." Hypotheses regarding the effect of a variety of factors can then be quantitatively tested. The capability of testing a broad range of factors and include disaggregate exposure is, we believe, a major advantage of the method.

It is hard to collect disaggregate exposure data, but it is even harder to collect disaggregate exposure data without a research framework to indicate how to collect it. The survival theory model is proposed as an example of how to fill the theoretical gaps between previous traffic safety studies. Survival theory allows the development of a research framework for disaggregate modeling in highway safety by combining elements of driver behavior with a conceptualized model of the accident occurrence process, exposure data, and data describing actual accident outcomes.

5. SUMMARY AND FUTURE RESEARCH CHALLENGES

A conceptual framework for accident occurrence based on the principle of the driver as an information processor is developed. The framework underlies the development of a new modelling approach. It supports the idea that theory and concept should be directly considered before statistical methods are used. Survival theory is proposed as an example of a statistical technique that is consistent with a conceptual structure and allows the exploration of a wide range of the components that contribute to highway operating risk.

This survival model of accident occurrence is developed at a disaggregate level, and, hence, allows highway safety researchers to broaden the scope of their research, which may be limited by the use of traditional aggregate approaches. Most of the transportation industries, such as trucking, aviation, rail, and public mass transportation, routinely keep the record for each individual trip for business purposes. With the availability of disaggregate data, the survival model can be readily applied to those transportation industries and provides a useful tool for predicting traffic accident risk under their operating policies. It can also be combined with the cost of accident loss to undertake operations planning, in terms of cost-benefit, for changing their policies to reduce accident involvement. The critical piece of information needed for the use of the model is the time to "failure" or "success."

Accidents are such rare events, however, that simple random sampling is unlikely to result in sufficient accident trips for model estimation. Enriched sampling, in which accident trips are over sampled, can be used to provide accident data, but a large number of nonaccident trips will be required for model estimation. In a study of interstate truck accidents, it is estimated (Chang 1987) that as many as 6,000 nonaccident trips are required in order to obtain a risk factor that significantly contributes to accident occurrence. Further studies are needed regarding optimal sample size requirements to achieve statistical significance in survival theory applications to different transportation modes. Findings in this area would help in planning future empirical studies and in allocating resources for data collection.

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