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MODELS OF DRIVING BEHAVIOR: A REVIEW OF THEIR EVOLUTION

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Abstract—This paper reviews models that emphasize the cognitive components of driving behavior. Studies of individual differences have sought predictors of accident histories. Typically low correlations and reliance on post hoc explanations reflect theoretical deficiencies and problems with the use of accident measures. Motivational models emphasize transient, situation-specific factors rather than stable, individual predictors. However, neither testable hypotheses nor suitable methods have been developed to study situational factors and motives that influence driving. More recent models have incorporated a hierarchical control structure, which assumes concurrent activity at strategic, maneuvering, and operational levels of control. At the same time, automaticity has emerged as a central construct in cognitive psychology. All activities are assumed to combine fast, automatic components with slower, more deliberate, controlled processing. It is argued that identifying the situational factors that increase drivers' uncertainty and thus trigger a shift in attention from automatic to controlled processing will help integrate concepts of automaticity and motivational models. Finally, recent theorizing has suggested that errors associated with the inherent variability of human behavior may be more important to roadway crash causation than systematic errors, which are attributable to the known limits of the human information-processing system. Drivers' abilities to recover from errors may also be important to crash causation. It is concluded that the hierarchical control structure and theories of automaticity and errors provide the potential tools for defining alternative criterion measures, such as safety margins, and developing testable theories of driving behavior and crash causation. Two examples of models that integrate information-processing mechanisms within a motivational framework are described.

Keywords—Driving behavior, Accident prediction, Motivational models, Cognition, Errors

INTRODUCTION

Contemporary theorists have noted the lack of progress in developing a comprehensive model of driving behavior (cf. Michon 1985; Huguenin 1988). A number of reasons have been proposed for this stalemate. These include a preoccupation in the highway safety field with accidents and accident-causing behaviors. As a result, it has never been clear whether theories should explain everyday driving, or accident-causing behaviors, or both. Secondly, motivational models, which emerged in the 1960s and 1970s as alternatives to skill-based models of driving (e.g. Naatanen and Summala 1976), have failed to generate testable hypotheses necessary for developing a body of empirical findings. Finally, as noted by Michon (1985), the cognitive revolution in psychology has failed to influence driving theory.

Recently, there has been a resurgence of activity in driving theory, with major published discussions of risk-based theories (Brown and Janssen 1988) and more recently theories of errors in transport systems (Brown and Groeger 1990; see also, Rothengatter and de Bruin 1988). Perhaps the most significant development is the emergence of a hierarchical control structure, which represents driving as concurrent activity at strategic, maneuvering, and operational levels of control (Michon 1985; Molen and Botticher 1987). This framework has influenced both motivational models and theories of errors. In addition, cognitive psychology has now moved beyond the paradigm shift that occurred during the 1970s. Automaticity has emerged as a central construct, and its characteristics are now sufficiently well-established to be incorporated into models of driving behavior.

The objective of this paper is to explore these trends and speculate on the future of modeling driving behavior. The first section will review studies that have attempted to find predictors of accident involvement. The emphasis is on recent attempts to relate performance-based measures of complex cognitive processes, such as attention, to accident

involvement. Methodological problems associated with the use of accidents as criterion measures of safety will be discussed.

The second section will consider two categories of functional models, including motivational models and information-processing models. We will explore reasons why motivational models have failed to generate experimental programs and the appropriateness of existing research paradigms. We will discuss the new impetus to driver behavior modeling provided by the hierarchical control model and recent advances concerning the characteristics of automaticity. This will be followed by a discussion of theories of errors. Finally, two examples of models that have integrated information-processing mechanisms within a motivational framework will be presented.

The final section will summarize the current state of affairs in driving behavior and attempt to delineate a direction for future work. It will be argued, on both theoretical and methodological grounds, that we must go beyond accidents if we are to understand driving behavior. Furthermore, it will be argued that if motivational models are to be taken seriously, researchers may need to develop methods to characterize the essential components of various driving situations and research paradigms that allow exploration of the effects of situational factors on driving behavior.

INDIVIDUAL DIFFERENCES IN ACCIDENT CAUSATION

In the highway safety field, priority has generally been given to identifying risk factors through epidemiological studies of accident causation. The result has been an overreliance on accidents and accident-causing behaviors, and a failure to consider driving behavior within the broader context of transportation for a particular purpose (e.g. to get from home to work). Much experimental work has attempted to identify individual differences in basic capabilities that predict accident involvement, for the purpose of selecting drivers with above-average crash risk. This research has been referred to as the study of differential accident involvement (McKenna 1982) or the individual differences or selection approach (Barrett, Alexander, and Forbes 1973). The emphasis has been on identifying relatively stable traits, as opposed to the more transient states emphasized by motivational models of driving (Johnston and Perry 1980). Accident proneness was the focus of much of the early work in this area, although this concept offered little in the way of explanatory potential. McKenna (1982) considered the prediction of accident involvement on the basis of psychological tests to be an improvement over statistical attempts to identify accident-prone individuals, because it offers the potential for a theoretical understanding of the psychological abilities and characteristics associated with the errors involved in crash causation.

Early attempts using simple visual attributes and simple reaction time as predictors found weak or no relationships with accidents, presumably because drivers can compensate for deficiencies in these abilities (Hills 1980; McKenna 1982; Summala 1988). Burg's finding (cited in Hills 1980) that dynamic visual acuity was the best predictor of accident involvement motivated more recent attempts to relate complex visual and attentional skills to accident rates (e.g. Ball et al. 1993; Owsley et al. 1991). Hills (1980), however, concluded that tests of vision and perception may never satisfactorily identify high-risk drivers.

Harano, Peck, and McBride (1975) combined biographical (age, sex, occupation), overt behaviors (prior violations, annual mileage) and psychological attributes (perceptual style, attitudes) in predicting previous accidents. They used a total of 337 predictor variables, of which 140 were significant. Psychomotor and perceptual variables were considerably less important than biographical and exposure factors in predicting accident involvement. Marital status, mileage, traffic conviction record, and socioeconomic status were among the more significant predictors. Barrett et al. (1973) suggested that combining different categories of constructs could lead to conceptual confusion, due to the possibility of complex interactions between constructs at different levels of measurement. While this study was clearly conducted without concern for the processes underlying the identified predictive factors, it is worth noting that the objective was to improve driver-screening procedures and not to provide an understanding of accident causation.

Perhaps the most important work relating to the identification of predictors of accident experience was done by Barrett et al. (1973), who presented a conceptual analysis based on accident-cause data supporting their conclusion that three categories of information-processing measures were relevant for predicting accidents. These included perceptual style, selective attention, and perceptual-motor reaction time. A later analysis by Panek et al. (1977), focusing on the effects of aging on driving, provided rationale for adding vision, vigilance, and decision making, thus broadening their model to cover driving behavior rather than just accident causation.

The three constructs of the original model have been the basis for considerable research activity.

Mihal and Barrett (1976) examined the correlations between these measures and accident involvement over a five-year period for 75 commercial drivers. Field dependence and selective attention were positively correlated with accidents, while reaction time measures were not. Subsequent research focused on field dependence and selective attention as the main predictors of accident involvement. Perceptual style, defined as the ability to overcome embedding contexts in perceptual functioning (Goodenough 1976), is measured by the Rod and Frame Test (RFT) and the Embedded Figures Test (EFT). Results of studies using these measures, summarized by Goodenough (1976) and McKenna, Duncan, and Brown (1986), are mixed. The strongest relationship was observed between perceptual style and performance in a driving simulator (Barrett and Thornton 1968). The relatively high correlations were attributed to restricting the focus to one type of accident, the use of surrogate performance measures, and the strong logical relationship between perceptual style and the performance measure, which required identifying and responding to an emergency situation. Alternatively, based on a significant correlation between EFT scores and intelligence, McKenna et al. (1986) suggested that individual differences in the ability to learn how to operate a driving simulator, reflected by general intelligence, could have contributed to these results. Although earlier work generally exhibited positive correlations between perceptual style and accident measures, more recent work has failed to find a strong relationship (Avolio, Kroeck, and Panek 1985; Lim and Dewar 1988; McKenna et al. 1986; Clement and Jonah 1984).

The strongest and most consistent predictor, deriving from the work of Barrett and colleagues (1968; 1973), is selective attention. Based on the assumption that rapid switching of attention is required for complex task performance, such as driving and flying, numerous studies have found significant correlations between measures of selective attention and accident involvement (Kahneman, Ben-Ishai, and Lotan 1973; Mihal and Barrett 1976; Avolio et al. 1985). The majority of these studies have used a dichotic listening task [(DLT) also referred to as the Auditory Selective Attention Task (ASAT)], developed by Gopher and Kahneman (1971). The test requires subjects to respond to strings of letters presented simultaneously to each channel (ear). Each message has two parts, so that on some trials the instructions change between parts and require a rapid switch of attention from one channel to the other. The number of omissions, intrusions, and switching errors are recorded. A visual analogue was developed by Avolio et al. (1981). Switching errors have generally been found to correlate better with criterion measures than omissions or intrusions, which has been interpreted to suggest that rapid switching of attention is critical to safe driving (Avolio et al. 1985).

Arthur, Barrett, and Alexander (1992) conducted a meta-analysis to examine the generalizeability of four classes of predictors of accident involvement. They conducted separate analyses for three types of information-processing variables including selective attention, perceptual style, and choice/complex reaction time, as well as for measures of cognitive ability, personality factors, and demographic and biographical variables. Although none of the results was consistent with the authors' criterion for generalizeability, the strongest results were observed for measures of selective attention. Favorable results were also observed with two personality factors (regard for authority and locus of control). Marginally favorable results were observed for cognitive ability (intelligence). Demographic/biographical variables showed no effects. The results suggested that better selective attention, higher regard for authority, an internal locus of control, and higher cognitive ability were associated with lower levels of accident involvement. However, the authors suggested caution in interpreting the results, because meta-analysis results obtained from a small sample of studies are biased in favor of type I errors.

Most recently, Owsley et al. (1991) have found visual attention to be a significant predictor of retrospective accidents for older subjects. Their measure of attention, referred to as the useful field of view (UFOV), is a composite measure of preattentive (parallel) processing, incorporating speed of visual information processing, ability to ignore distractors (selective attention), and ability to divide attention. Their work was based on a hierarchical model of vision and information processing in driving, which included factors at the following levels: ophthalmological (eye health), functional vision, preattentive (UFOV), and cognitive function (mental status). An important feature of this work is the use of disaggregated accident data. Specifically, strong associations were found between the UFOV and culpability in intersection accidents. In a subsequent larger-sample study, significant correlations were observed between UFOV and all types of accidents (Ball et al. 1993). The relatively high r values observed by Owsley et al. (1991) may reflect their use of selected samples, for which correlations are generally expected to be larger than would be found in the general population (Harano et al. 1975).

Lim and Dewar (1988) combined a tracking task, a modified DLT, and a response-time task in

a time-sharing paradigm to more closely reflect the demands of driving. They also gave the EFT and measured mental workload. From a modeling perspective, the combination of component tests and driving dynamics represents a mixture of a trait and process modeling (Michon 1985). Seventy-two commercial drivers were separated into two groups, one accident-free, the other having had three or more accidents within the past five years. Tracking, response-time errors, and switching errors in the DLT were useful in discriminating past accident experience. The effects were obtained for all task combinations, indicating that the combination of tasks did not improve the relation with accident history. Response time was correlated with tracking performance and switching errors in the DLT. No relation was found between the EFT and accident experience.

What do tests really measure?

The use of simple correlational methods without multifactoral structural models raises questions about the meaning of significant correlations (Kenny 1979). In the absence of underlying theoretical models, post-hoc explanations have been proposed to explain the relationships between predictors and criterion measures. For example, it is often cited that "driver inattention" is responsible for a large percentage of accidents (Zaidel, Paarlberg, and Shinar 1979). This finding, based on police officers' judgments, is used to justify efforts to find correlations between laboratory measures of attention and accident measures (e.g. Parasuraman and Nestor 1991). This analysis mixes scientific with everyday concepts of attention and serves to reduce the construct to the most basic common denominator used in everyday language, as in "paying attention." Although this would appear to restrict researchers from taking advantage of theoretical distinctions between mechanisms of sustained, selective, and divided attention, in practice it has had the effect of allowing researchers to claim generality based on successes of different measures of attention. For example, the dichotic listening task (DLT) and the useful field of view (UFOV) are both tests of attention. Positive correlations between both tests and accident measures have been observed, however, the two tests evaluate different mechanisms. Both tasks involve specification of targets and the individual's ability to distinguish targets from distractors. However, the UFOV uses very brief exposure durations and is thus concerned with preattentive or the earliest stage of visual processing in which attention is captured and directed to salient visual events. Deficits of information-processing speed, which are evident among older individuals, can contribute significantly to performance on this task (Ball et al. 1990). In contrast to this bottom-up (data-driven) processing, the DLT emphasizes the strategic control of selection and switching between channels, and thus reflects top-down (memory-driven) processing. Furthermore, it is questionable whether either test addresses the same mechanisms cited as inattention on police accident reports. Poor operational definitions of attentional mechanisms have been identified as a shortcoming of test-based research in the highway safety field by Sivak (1981).

Avolio et al. (1985) compared the visual and auditory tests of selective attention. They found significant correlations between respective parts of the two tests; however, the relatively low percentage of common variance is not consistent with the conclusion that both tests evaluate the same processes. McKenna et al. (1986) questioned the interpretation of the DLT as a measure of the ability to switch attention. They compared DLT performance with an original timed paper-and-pencil task requiring rapid responses to geometric shapes. The task had control conditions under which subjects applied consistent stimulus-mapping rules and switch conditions under which rules changed during the trials. The switch condition was hypothesized to relate to the switching component of the DLT. Correlations between the DLT and shapes task components were significant, although weaker than would be expected from measures of the same abilities. The respective switch conditions of the two tasks did not correlate strongly, which led the authors to conclude that the DLT does not appear to measure ability to switch cognitive set. However, they allowed the possibility that their measure may have involved a different level of switching than required by the DLT. Uncertainty about the specific mechanisms involved in the DLT is reflected in the conclusion of a survey of studies that the theory of selective attention has not been developed sufficiently to allow determination of whether the different types of errors that compose the ASAT (DLT) should be highly correlated (Doverspike, Cellar, and Barrett 1986).

The interpretation of perceptual style, as measured by the Embedded Figures Test (EFT) and the Rod-and-Frame Test (RFT) has also been questioned. Concern that the two measures may be measuring different abilities was raised by low correlations between the two measures and different correlations with accident measures. Mihal and Barrett (1976) reported a significant correlation between the EFT and RFT; however, the magnitude was below what one would expect for measures of the same ability. Avolio et al. (1985) found a very small

relationship between the Group Embedded Figures Test and accident involvement and concluded, on the basis of previous work by Mihal and Barrett (1976), that the Rod-and-Frame Test may be expected to demonstrate higher correlations with accident rates.

Uncertainty also exists concerning the psychological construct tapped by these tests. Originally, according to Avolio et al. (1981), the RFT was developed to measure spatial orientation. It was later used as a measure of personality and finally to measure perceptual style. This latter interpretation was evaluated by McKenna et al. (1986), who compared EFT performance with a Stroop task. In this task, subjects name the color of the ink used to spell words and a strong distraction is provided by the fact that the words may spell inappropriate color names. The pattern of correlations was not consistent with the definition of the EFT as a measure of perceptual style and led the authors to conclude that the EFT does not measure a general ability to resist distraction from dominant stimuli.

The finding by Lim and Dewar (1988) that the combined administration of tracking, response time, and selective-attention tasks did not provide better prediction of accident histories than separate administrations can also be used to question the reliance on logical relations between tests and criterion measures. Specifically, the argument that combined administration more closely resembles the demands of driving and would thus be more likely to exhibit a significant correlation with accident measures appears as plausible as arguments proposed to support the EFT or measures of selective attention. The failure of these intuitively plausible arguments to explain findings of correlational studies underscores the need for use of theoretical models and experimental methods to establish relationships between basic capabilities and driving behavior.

Different correlations for different groups

Correlations between lab tests and previous accidents have generally been low, reflecting, according to McKenna et al. (1986), the complexity of roadway accident causes. Alternatively, Sivak (1981) suggested that fundamental differences between the stable traits measured by lab tests and the transient factors involved in accident causation are primarily responsible for low observed correlations. As a result, studies of this type that obtain correlations at or near $r = .5$ have been considered to be very successful. However, methodological differences between studies could help explain differences in the magnitude of observed correlations. For example, constructing a sample to include a disproportionate number of high-accident subjects can inflate the r value (Harano et al. 1975).

Parasuraman and Nestor (1991) hypothesized that measures of attention may be better predictors for older drivers, since a greater proportion of older drivers can be presumed to have attentional deficits. These deficits can thus be expected to play a bigger role in the causation of accidents of this group of drivers, relative to younger drivers, for whom accident causes have been associated with life events such as divorce or loss of employment. Larger correlations between measures of selective attention and accidents were found for older than for younger drivers in several studies (Mihal and Barrett 1976; Ranney and Pulling 1989; Parasuraman and Nestor 1991). In the Mihal and Barrett (1976) study, when age was taken into consideration, the correlations were observed to increase for the older subgroup, while disappearing for the younger group. Differences between the groups in the number of accidents were suggested as an explanation for this difference.

Methodological considerations

Barrett et al. (1973) identified several potential problems with the "unusual" postdictive research design that appears to be unique to the field of accident analysis. These include: (i) restricted range of criterion and/or predictor variables, for example as might be due to the death of the worst drivers before they can be tested; (ii) the potential effect on motivation or test performance of knowledge by the driver of having been placed in a special category due to accident involvement, and (iii) the questionable assumption that skills or attributes measured by the individual variables are highly reliable and do not change over time. They also pointed out that product moment correlation is not appropriate for accident frequencies that follow a skewed Poisson distribution. Concerns about the use of certain predictors in retrospective designs are also discussed by Arthur and Doverspike (1991).

Rabbitt (1981) criticized psychometric research for undue emphasis on the development of reliable predictors, without concern for the underlying psychological processes. Kenny (1979) argues that correlational methods can help answer questions concerning causation, if they are used in the context of a multifactoral model. The major developments in this field have both been based on such models (Owsley et al. 1991; Barrett et al. 1973); however, these models are what Rabbitt refers to as "linear sequences of independent successive processes" and as such do not capture the dynamics of control involved in driving.

Accidents as a criterion

Potential problems with the use of accidents as a basis for evaluating individual drivers include their lack of stability, the lack of statistical power due to their infrequency, and the lack of reliability of state accident records. The stability of accident data has been considered in several studies. Burg (1970) computed correlations between successive three-year records for 7,841 California drivers and found that conviction experience was more stable than accident experience. As a result, he recommended against trying to identify accident repeaters since the vast majority of accidents in one time period involve previously accident-free drivers. Similar results were reported by Peck, McBride, and Coppin (1971); Stewart and Campbell (1972), and more recently by Miller and Schuster (1983). Most recently, in a small sample study, Arthur and Doverspike (1991) found different predictors of retrospective and prospective accidents, indicating a lack of stability of accident involvement. These results raise the question of the validity of the retrospective studies, and support the conclusion that prospective data are preferable for this type of study (Ranney and Pulling 1989; Owsley et al. 1991; Arthur et al. 1992).

Because accidents are relatively infrequent events, data from a number of years must be combined to obtain sufficient statistical power. However, Evans (1991) has demonstrated that the extremely low likelihood of accident involvement for ordinary drivers creates significant difficulties in detecting drivers with above-average crash likelihood, even when periods of up to seven years are used. Use of longer periods is not recommended due to the instability of accident records, discussed above. This is another possible explanation for the relatively low correlations normally found in studies of retrospective accident prediction.

An important exception to this trend is the study of 1,000 Helsinki bus and streetcar drivers conducted using data from 1947–1954, in which accidents showed unusually high reliability, based on correlations between two successive time periods (Hakkinen 1979). In this study, the reliability was found to increase as the exposure duration was increased. The relatively high and consistent exposure of commercial drivers was undoubtedly responsible for the unusually high reliabilities observed in this study.

The reliability of accident records has been questioned in a study conducted by the Insurance Research Council (1991). Insurance claim files from 61 companies were compared with state accident records in the 40 states where such information is publicly available. Over 27,000 accidents from 1990, serious enough to meet the respective state reporting requirements, were included in the sample. It was found that only 40% of these accidents appeared on official state records. Individual states varied widely with a range between 1% and 71%, reflecting different statutory requirements for reporting and administrative procedures, especially damage thresholds. When compared with an earlier study, it was found that the reporting percentage had dropped from 48% in 1983 to the 40% in 1990. The adequacy of public records has been questioned by Klein and Waller (1970), based on the argument that data collected for administrative purposes generally do not adhere to standards necessary for research.

The shortcomings of accident data are well known, and it is not uncommon for researchers to recommend use of alternative criterion measures (Johnston and Perry 1980; Sivak 1981; McKenna et al. 1986). However this is considerably easier said than done, based in part on the conclusion that such measures would necessarily require validation against accidents (Ball and Owsley 1991). Alternative criterion measures include driving-simulator performance, closed-course performance, on-road driving tests, and unobtrusive observational studies of driving behavior (Johnston and Perry 1980; Allen and Weir 1984; Ranney, Pulling, and Roush 1986; Ball and Owsley 1991). Limitations of experimental methods include questions of required fidelity in driving simulators, inability to create realistic critical situations involving other traffic on closed courses, and lack of control in on-road methods.

Several researchers have proposed that alternative criterion measures be developed without the requirement of validation against accident measures. Sivak (1981) proposed that skills with high face validity to driving be selected and evaluated by examining the effects of transient human states (fatigue, alcohol intoxication, stress). Skills sensitive to the effects of transient factors would thus be considered most critical for driving. Following their difficulty interpreting correlations between different laboratory measures, McKenna et al. (1986) concluded that identifying causes of error would be a better research focus than trying to predict past accidents. Similarly, based on positive correlations between observed errors, their level of danger, and accident incidence, Brown (1990) concluded that field-testing of hypotheses developed from theories of driver error is a more valid approach to highway safety than the reliance on post-hoc subjective assessments of error contributions to accident statistics.

The available evidence clearly supports the use of alternative criterion measures, yet surrogate mea-

sures are not widely used. This reflects both the failure of existing theoretical models to provide such measures and the uncertainty associated with interpreting such measures if there is no connection to safety.

FUNCTIONAL MODELS OF DRIVING BEHAVIOR

Michon (1985) distinguished between taxonomic and functional models of driving behavior. Trait or test-based models, which underlie most of the individual differences research discussed above, are taxonomic, and thus involve no dynamic relations among components. In contrast, functional models, which include motivational models and information-processing models, have greater potential for helping to understand complex tasks such as driving (Michon 1985).

Motivational models of driving

Motivational models of driving emerged in the 1960s and 1970s as alternatives to the skill-based models that had existed prior to that time (Summala 1985). The main assumptions of these models are that driving is self-paced and that drivers select the amount of risk they are willing to tolerate in any given situation. The emphasis on transient or situation-specific factors came about in response to the lack of success of earlier attempts to relate stable personality traits to accident causation (Johnston and Perry 1980). The risk associated with possible outcomes is seen as the main factor influencing behavior; however, these models also assume that drivers do not generally make a conscious analysis of the risks associated with alternative outcomes (Wagenaar 1992).

The importance of motivation in driving was demonstrated in a series of studies originated in Sweden. In the first studies (Johansson and Rumar 1966; Johansson and Backlund 1970), drivers were stopped immediately after they passed a sign and asked to identify the last sign they saw. Accuracy of reporting the sign under these conditions ranged between 17% and 78%, depending upon the "subjective importance" of the sign, that is, the amount of risk involved in ignoring the sign. In a subsequent study (Summala and Naatanen 1974), an experimenter inside the vehicle asked drivers to recall all signs (581) over a distance of 257 km with heavy traffic. Only 3% of the signs were ignored. Although methodological differences between the two studies preclude strong conclusions about their differences, the results have been cited repeatedly as evidence that on-road driving differs considerably from drivers' capabilities, which in turn supports the conclusion that motivation is an important determinant of on-road driving. (Naatanen and Summala 1976).

Examples of motivational models include risk compensation models (Wilde 1982), risk threshold models (Naatanen and Summala 1976) and risk-avoidance models (Fuller 1984). Risk compensation models propose a general compensatory mechanism whereby drivers adjust their driving (e.g. speed) to establish a balance between what happens on the road and their level of acceptable subjective risk. Wilde's risk homeostasis theory (RHT) is based on the assumption that the level of accepted subjective risk is a relatively stable personal parameter. An important implication of this model is that drivers will compensate for traffic safety improvements by faster and/or less cautious driving to reestablish a constant level of risk. As a result, changes to the roadway or vehicle or even improvements to driving competency will not have a lasting safety impact. This implication has created considerable controversy (see McKenna 1988; Wilde 1988; Evans 1991, for recent summaries of respective positions).

Risk-threshold models propose the existence of a control process by which drivers attempt to maintain a stable balance between subjective, perceived risk and objective risk. The motivational model of Naatanen and Summala (1976), later renamed the zero-risk model (Summala 1985; 1988) is of this type. According to their model, the perceived risk (R) in traffic is the product of the level of subjective probability of a hazardous event and the subjective importance of the consequences of the event. Behavior is assumed to be directly related to the level of R. In most circumstances, R is perceived to equal zero, that is, drivers generally feel and act as if there is no real risk at all. If a threshold is exceeded, risk-compensation mechanisms are activated in an attempt to lower the risk level. The main differences between this and the previous category of models is the existence of a threshold and the operation of safety margins (Summala 1988). Whereas according to the risk compensation models, drivers are always adjusting their performance, the risk-threshold model assumes that compensation begins only when the perceived risk exceeds a threshold. Safety margins, defined in terms of the spatial or temporal distance between the driver's vehicle and a hazard, are proposed as alternatives to the stable-risk parameter proposed by Wilde (Summala 1988).

The risk-avoidance model (Fuller 1988) is based on the assumption that making progress toward a destination and avoiding hazards are the two predominant driver motivations. The conflict between these two motivations forms the conceptual basis

for this model. Focusing on avoidance of threats derives from the fact that we cannot drive unimpeded in a straight line to our destination, but must repeatedly avoid obstacles and potential hazards along the way. Repeated exposure to obstacles is our basis for learning how to identify risks on the road.

Motivational models have been criticized for lacking specificity regarding their internal mechanisms, which precludes validation (Michon 1985; Molen and Botticher 1988). In an attempt to overcome this problem, Molen and Botticher (1988) developed a hierarchical risk model, which they argue is both fully specified to allow quantitative calculations and flexible enough to be consistent with the three main models considered above. However, this model has been criticized for failing to distinguish between the aggregate and individual levels of analysis, a problem that according to Michon (1989) will lead to "vicious circles and pernicious homunculi," among other theoretical problems. Wilde's RHT model suffers from the same problem, as evidenced by the need to assert that all drivers have homeostatic mechanisms to explain homeostatic behavior at the aggregate level of analysis. Fuller's threat-avoidance model does not suffer from this problem; however, as with all behaviorist models, it cannot handle embedded or nested behavior, e.g. a problem arises while the driver is dealing with another problem. Fuller's model is applicable only to single-instance situations (Michon 1989).

The emphasis on risk has been criticized by those who argue that motivation is multifactoral. Rothengatter (1988) identified four different motives for speed selection, including pleasure in driving, traffic risks, driving time, and expenses. Summala (1988) identified a tendency toward higher speeds, reluctance to reduce speed, conservation of effort, and habit as motives in driving. He cited the example of a driver who passes another just before exiting a road. Drivers may actually attempt to minimize their allocation of attention to driving, to free up resources for non-driving-related activities. The recent proliferation of in-vehicle distractions, including entertainment systems, communications systems, and even the increased incidence of reading while driving provide support for operation of this motive.

Recently Janssen and Tenkink (1988) attempted to facilitate a reconciliation between the RHT and its opponents by suggesting three modifications to the assumptions of that model. First, to address concerns over the existence of a very specific target level of accident risk, they argue that risk taking must be considered as part of a more general utility-maximizing process. They also suggest softening the strong requirement of RHT that compensation need be complete. Finally, they argue that risk taking must be modeled at different levels, including the trip and particular situations. This reflects the emergence of hierarchical control, which will be discussed in the next section.

Motivational models focus on "what the driver actually does" in a given traffic situation rather than on the level of driving skill. The driver is seen as an active decision maker or information seeker (Gibson 1966), rather than the passive responder implicit in many information-processing models. A related distinction has been made between performance and behavior (Naatanen and Summala 1976; Shinar 1978; Evans 1991), where performance refers to what drivers are capable of doing, while behavior refers to what drivers actually do on the road. This distinction helps clarify differences between the major research paradigms used to study driving behavior. Individual-differences research has focused almost entirely on predicting accident rates. To the extent that this research has used performance limits on information-processing tasks as predictors, it implicitly assumes that precrash behaviors represent the limiting capabilities of drivers. The questionable validity of this assumption and the restricted focus on the set of behaviors that precipitate crashes are likely reasons for the lack of success of efforts to identify predictors of safe driving. In contrast, motivational models address driving in its entirety and emphasize the inherent variability in driving. The importance of crashes is replaced by situational variables, such as safety margins, which by definition reflect a difference between on-road driving and performance limits.

Despite their appeal and promise, motivational models have failed to generate a significant body of research findings. Several possible reasons exist. First, the confusion between individual and aggregate levels of analysis has plagued some of these models (Michon 1989). The result is an inability to generate testable predictions. Second, the protracted debate concerning the validity of the theory of risk homeostasis (Janssen and Tenkink 1988) has stalled progress. Finally, empiricists have failed to come to grips with the implication of these models that if driving is determined largely by motives, goals, and expectations, it may be irrelevant to study driving in the laboratory, driving simulator, or closed course, where the fundamental element of the goal of the trip is removed (Duncan 1990). One recent exception is a study of driver behavior on curves conducted by Wong and Nicholson (1992), which combines motivational theorizing with an observational methodology.

Information-processing models

Information-processing models began to emerge in the 1950s (e.g. Broadbent 1958) in response to the discovery of air-traffic controllers' limitations in handling simultaneous messages (Kahneman and Treisman 1984). These models are typically represented as a sequence of stages, which include perception, decision and response selection, and response execution. Each stage is assumed to perform some transformation of data and to take some time for its completion (Wickens 1992). Much experimentation has been directed at determining which types of processing can occur simultaneously and which must occur sequentially.

With several exceptions (Rockwell 1972; Shinar 1978), models of driving behavior have failed to incorporate theoretical advances in cognition (Michon 1985). In contrast to Michon's suggestion that human factors curricula are to blame, it is proposed that early information-processing models and their associated experimental techniques were incompatible with the requirements of complex tasks such as driving. Specifically, in a deliberate attempt to isolate perceptual processes from memory, psychologists created experimental techniques using stimuli that were abstract, discontinuous, and only marginally real (Neisser 1976). As a result, the spatial and temporal continuities of real objects, essential for describing continuous tasks such as driving, were eliminated. During the 1970s, a pardigm shift (Kuhn 1962) took place in the study of attention (Kahneman and Treisman 1984). The shift involved a move away from determining the limits of processing and locus of the attentional bottleneck. More recently, based in large part on theoretical advances by Schneider and Shiffrin (1977; Shiffrin and Schneider 1977), research has been directed at determining the characteristics and conditions under which automaticity develops. This work has influenced research in human factors (Fisk, Ackerman and Schneider 1987), and is beginning to influence theory in driving behavior.

Automaticity. The importance of automaticity to driving is not a new idea, having been identified by Gibson and Crooks (1938) as a worthy research endeavor. Automaticity is characterized as fast, effortless processing, which develops following extended consistent practice (Schneider and Shiffrin 1977; Shiffrin and Schneider 1977). It is contrasted with controlled processing, which refers to slow, serial, and effortful processing. Although early experimentation used very simple stimulus material and examined elementary processes such as detection and memory search (Schneider and Shiffrin 1977), recent work has extended the automatic/controlled distinction, although not the explanatory mechanisms, to more complex behaviors (Fisk and Schneider 1983). Schneider and Shiffrin's (1977) theory suggests that virtually all behaviors include components of controlled and automatic processing and that the relationship between the various components is constantly changing according to the type and quantity of practice.

Because driving involves a seemingly endless variety of situations, a model of driving behavior must allow for the development of automaticity in the absence of the highly consistent stimulus conditions that can be presented in laboratory settings. Several studies have explored the development of automaticity in situations that are not entirely consistent. Fisk and Schneider (1984) found that automatic processing was not limited to tasks that are consistent from input to output. They varied the consistency of attending and the consistency of motor responding factorially in a multiple-frame detection paradigm and found that consistent attending produced a substantial improvement in search performance regardless of the consistency of the response component. Automatic component processing can thus improve total task performance, despite inconsistencies among other task components. In the context of driving, this suggests, for example, that braking and steering patterns may become automatized despite differences in the characteristics of precipitating situations, such as obstacles or hazards.

Fisk, Oransky, and Skedsvold (1988) examined the relationship between higher and lower level consistency. Using a magnitude-judgment task they found that stimulus-based consistency is not necessary for automatic process development if higher order consistencies can be identified and used by subjects. Specifically, when the task was to identify the largest digit in a display, there would be no consistent relationship between any single digit and response. However, subjects were able to take advantage of the consistent higher level relationships among digits, (e.g. 7 is always greater than 6) for development of automaticity. Applied to driving, this may suggest that consistent practice following the same route to a destination can result in automaticity with regard to route selection, independent of day-to-day variations in weather, visibility or traffic conditions. Alternatively, the similarities among curves or intersections may be sufficient for development of automatic action patterns, despite geometric differences between individual intersections or curves.

Automaticity has also been used to refer to the detection of objects that can occur preattentively, without repeated exposure to consistent stimuli.

Treisman (e.g. Treisman and Gelade 1980) has proposed that features such as color, orientation, size, and direction of movement are coded automatically, without attention. Furthermore, the relation between a target and its surroundings determines the ease of object detection. If an object differs from its background by the presence of a unique feature, it can be detected preattentively and the object appears to "pop out" of the background automatically. However if the object differs by more than one feature, focused attention, which requires conscious effort, is necessary for detection. This model has not been applied to driving, in which the relationship between objects and their background is constantly changing, however Rumar (1990) has suggested that the artificiality of the driving environment and the unnatural speeds prevent drivers from taking full advantage of automatic detection capabilities that allow for efficient visual search in natural environments.

While motivational models of driving have been criticized for lacking detail concerning mechanisms, information-processing models have generally been criticized for not incorporating motivational or emotional components (Eysenck 1982). Modeling the driving task would thus appear to offer an ideal forum for combining concepts from these two areas. For example, it is of interest to determine the relation between the various motives that influence driving and the development of automaticity. Summala (1988) discusses the relationship between uncertainty and the development of automaticity in driving, suggesting that novice drivers initially feel a sense of uncertainty in most situations. With practice, skills become automatized and self-confidence replaces uncertainty. In driving, novel or hazardous situations evoke uncertainty, which, according to Summala (1988), causes control to shift from automatic to controlled, conscious processing.

Multiple resources. Because driving is a time-shared activity, a theory of driving behavior should provide some basis for determining which combinations of skills can and do become automatized with practice. For example, basic vehicle control activities (steering, acceleration, shifting, braking) can be combined with visual search, decision making at intersections, reading traffic signs, listening to the radio, and even talking with a passenger or operating a telephone. Wickens' (1984) multiple-resource theory may provide a framework for determining the degree of compatibility among various component tasks. He proposed the existence of several different supplies of resources, including the stage of processing (early, late), the modality (auditory, visual), and the processing code (spatial, verbal). Wickens has demonstrated that interference in a dual-task situation will be more likely when the individual tasks draw on the same pool of processing resources.

Hierarchical control models

Rasmussen (1987) differentiated among skill-based, rule-based, and knowledge-based behaviors. Skill-based behavior is the lowest level and involves automated schemata, consisting of well-learned procedures. Rule-based behavior involves automated activation of rules or productions. Knowledge-based behavior involves conscious problem solving and is generally invoked in novel situations for which no existing rules are applicable. Recently, Lehto (1991) proposed a fourth level, referred to as judgment-based behavior. This was added to reflect the importance of value judgments and affective reactions in determining behavior. Schneider and Shiffrin's (1977) distinction between automatic and controlled processing appears very similar to that between skill-based and knowledge-based processing (Rasmussen 1987); however, Rasmussen's taxonomy apparently intends no dynamic relations between the different types of processing. Reason's (1990) generic error modeling system (GEMS), described in detail in a subsequent section, has integrated processing mechanisms with Rasmussen's model, thereby extending its use beyond classification of errors.

A three-level hierarchy has also been proposed to underlie cognitive control of driving (Michon 1985; Molen and Botticher 1987). The three levels include the strategic, tactical or maneuvering, and operational or vehicle control (Michon 1985; Molen and Botticher 1987). The strategic level involves general trip planning, including setting trip goals (e.g. minimize time, avoid traffic), selecting routes, and evaluating the costs and risks associated with alternative trips. The maneuvering level involves negotiation of common driving situations such as curves and intersections, gap acceptance in overtaking or entering the traffic stream, and obstacle avoidance. The operational level consists of the immediate vehicle control inputs, which are largely automatic action patterns (e.g. steering, braking, shifting). This hierarchy assumes a dynamic relationship among concurrent activities at the three levels; however, control mechanisms have not been specified.

The different levels of decision making require different types of information. While strategic decision making can be largely memory-driven, requiring little if any new information, maneuvering and vehicle-control decisions are based on the immediate driving environment and can thus be considered

	Strategic	Tactical/ Maneuvering	Operational/ Control
Knowledge	Navigating in unfamiliar area	Controlling skid	Novice on first lesson
Rule	Choice between familiar routes	Passing other vehicles	Driving unfamiliar vehicle
Skill	Route used for daily commute	Negotiating familiar intersection	Vehicle handling on curves

Fig. 1. Classification of selected driving tasks by Michon's control hierarchy and Rasmussen's skill-rule-knowledge framework (adapted from A. R. Hale et al. 1990, Figure 1, p. 1383)

as mainly data-driven (Norman and Bobrow 1975). Another difference concerns the time available to make decisions. Decisions at the strategic level are generally not constrained by real time. General trip plans can be made in advance of a trip. More specific strategic decision making can generally be done while driving as time permits, often many minutes before execution. Maneuver-level decisions are considered to take place in seconds, while control decisions require only milliseconds to execute.

The control hierarchy of driving has been related to Rasmussen's taxonomy, as shown in Fig. 1 (Hale, Stoop, and Hommels 1990; Molen and Botticher 1987). For experienced drivers, most driving tasks cluster in the three cells on the diagonal that runs from the upper left to the lower right box in the figure. Skill-based behavior is involved at the operational level, rule-based behavior at the tactical level, and knowledge-based behavior at the strategical level. As shown by the examples in other matrix cells, exceptions reflect differences between skilled and novice performance, and between familiar and unfamiliar situations. For example, novice drivers initially use knowledge-based behavior to shift gears, while experienced drivers use skill-based, automatic action patterns. Experienced drivers can generally use skill-based behavior for navigating along highly familiar routes or for negotiating familiar intersections, reflecting the fact that automaticity can operate at all levels of control. However, rule-based behavior will predominate in unfamiliar situations, as long as previous experience is sufficient for selection of rules. Novel or unexpected situations, for which no applicable rules can be located, will disrupt skill-based (automatic) processing and necessitate knowledge-based (controlled) processing. In general, drivers operate more homogeneously and predictably at the skill-based and rule-based levels than at the knowledge-based level (Hale et al. 1990).

The incorporation of a hierarchical structure, together with the inclusion of mechanisms that enable control to switch between levels, which were proposed by Michon (1985) as criteria for a comprehensive model of driving behavior, have provided new impetus for modeling efforts. Specifically, the conceptualization of driving as concurrent activity at three different levels suggests that the driver's motivation may also have components relating to different levels of control. Motives concerning the purpose and importance of a trip may influence behavior throughout the trip; however, situations encountered en route may create shorter term goals that motivate tactical problem solving. For example, although a driver may have selected a route and departure time to ensure a leisurely, relatively uneventful drive, the presence of excessively slow traffic ahead may motivate the driver to speed up and pass. Compensatory behavior may also operate at different levels of control. For example, changes in trip plans, such as the avoidance of rush-hour or nighttime driving by older drivers (Planek and Fowler 1971), are examples of strategic-level compensations. Adjustments to safety margins, such as the rejection of a higher percentage of gaps during on-road merging by older drivers (Wolffelaar, Rothengatter, and Brouwer 1987), or during conditions of poor visibility, are maneuver-level compensations. Momentary adjustments to steering and acceleration in response to slippery roads are examples of compensation at the vehicle-control level.

Motivational models assume that drivers actively decide how to allocate processing resources among the concurrent activities at the strategic, tactical, and operational levels of control (Michon 1989). As shown above, behavior at all levels may become automatic in highly familiar situations. However, changes in motivation, created by unanticipated deviations from the driver's expectations, are likely to disrupt automatic processing. Uncertainty, created by an unexpected event or associated with a conflict between motives at different levels of control, has been proposed as the mechanism that triggers compensatory behavior, which leads to a reallocation of cognitive resources. However, the

extent to which such decision making occurs automatically, and thus outside the driver's awareness, is not known. Because the vast majority of behavior occurs at the skill-based and rule-based levels, it is likely that drivers are rarely conscious of their decision making until knowledge-based problem solving is required (Wagenaar 1992).

ERRORS

The contribution of errors to crash causation has been studied extensively. Perhaps the most widely referenced study is the Indiana University Study of Accident Causes (Treat et al. 1977). For this study, a taxonomy was developed allowing classification of causal factors as human, vehicular, or environmental. Human causes were further classified as either direct or indirect. Direct causes referred to errors that immediately precipitated a crash, while indirect causes referred to conditions such as fatigue, alcohol intoxication, or emotional upset. The results of this study have been cited extensively to support the importance of information-processing failure to crash causation, however it is important to note that the direct causes precipitating a crash do not necessarily implicate a particular information-processing mechanism (Shinar 1993). For example, a "decision error," which might be associated with passing or crossing a traffic stream, could represent the outcome of any of a number of problems, including sensory deficiencies, misperception of critical information, application of an inappropriate rule, lack of appropriate knowledge, or perhaps a deliberate attempt to accommodate an extreme motive such as being in a hurry. The limitations of taxonomic models in providing information concerning underlying behavioral mechanisms has been discussed by Michon (1985).

Because drivers commit many errors other than those that precipitate accidents (Brown 1990), it is clear that accident data alone do not provide appropriate information for the analysis of driving errors. In much the same way that motivational models have shifted the emphasis from accident-precipitating behaviors to all driving behavior, more recent theories have considered errors as a part of normal behavior. This alternative approach advocates studying errors within the larger context of all driving behavior, because they are inevitable in self-regulating systems (Rasmussen 1990).

Errors can be classified as either perceptual, which refer to mistakes in evaluating a situation, or as execution errors, or slips, which involve the inability to execute a planned response (Brehmer 1990). Slips refer to events in which the planned action would have achieved the desired goal, while mistakes reflect execution of plans that would not have achieved the desired goal. Within the context of the three-level control hierarchy of driving, perceptual errors are likely to precipitate inappropriate maneuvering decisions, e.g. a driver misperceives the speed of an oncoming vehicle and incorrectly concludes that sufficient time is available to enter or cross the traffic stream. Slips relate more directly to psychomotor components of driving at the operational level of control, e.g. the driver fails to turn or brake appropriately in a given situation. Of particular relevance to roadway accidents is the conclusion that lapses of attention reflect errors in skill-based or automatic behaviors (Reason et al. 1990).

Brehmer (1990) distinguished between systematic and variable errors. Systematic errors reflect the difference between some mean performance measure and a target value and are explained by the limitations of the human information-processing system. Variable errors, defined most precisely as within-subjects variability, represent the inherent variability of human behavior. According to Brehmer (1990), because systematic errors are predictable, they allow relatively complete compensation and therefore are likely to cause accidents only for inexperienced operators. In contrast, variable error is unpredictable and thus represents a significant obstacle to effective adaptation. Variable errors are therefore hypothesized to be a major cause of accidents (Brehmer 1990).

Drivers adopt safety margins to protect against the consequences of their errors. Effective safety margins require protection from the entire distribution of responses. The occurrence of accidents in relation to increasing speed and speed variability suggests that drivers' safety margins are inadequate (Brehmer 1990). Inadequate safety margins occur because drivers underestimate traffic hazards and overestimate their own driving skills (Brown 1990). This model leads to predictions concerning the types of errors to expect in various situations. For example, if drivers follow too closely, they will impose a time-stress on themselves and not allow sufficient time visually to sample the wide range of spatially distributed cues necessary for driving. A relatively high frequency of attentional and perceptual errors will likely occur as a result.

Brown (1990) distinguished between factors that influence the production of errors and those that constrain drivers' ability to recover from errors. Because of the potential for catastrophic consequences resulting from driver errors, the highway system has been designed to be tolerant of minor errors, such as deviations from the travel lane. The

absence of feedback concerning minor errors in driving can weaken associations between actions and their consequences, which can lead to overlearning of inappropriate behaviors. Drivers' adaptation to error is thus prone to distortion, which may affect the degree to which correct responses can be automatized (Groeger 1990). Instead, automatic action patterns may include a relatively wide range of both correct and incorrect responses. One implication is that drivers will be unaware of inappropriate speeds or inadequate safety margins. The inherent variability of human behavior combined with the variability of automatic patterns will inevitably lead to more serious errors. At this point, the driver's ability to recover from error may determine the likelihood of accident. This has led Brown (1990) to conclude that factors that influence drivers' ability to recover from errors may be more important to theories of driving behavior than factors that influence error production.

NEW DIRECTIONS IN MODELING DRIVER BEHAVIOR—TWO EXAMPLES

Visual search

Visual search in driving involves identifying salient information in a constantly changing, moving scene. Targets differ along dimensions of their familiarity, the predictability of their location, and their movement. For example, regulatory signs and signals occur in fairly predictable locations and contain information that is highly predictable. In contrast, dynamic information displays, such as changeable message signs, may be located at less predictable locations (e.g. construction zones) and may contain less predictable information (e.g. temporary speed limit, lane closed). Moving targets include other vehicles, pedestrians, and unexpected hazards, such as debris falling from a vehicle or a rolling ball (likely to be followed by a child).

Visual search in driving has been studied in a series of on-road and driving-simulation studies. These studies have generally examined patterns of eye movement in relation to the changing visual scene of the roadway. Mourant and Rockwell (1972) compared the visual search patterns of experienced and novice drivers. They found that novice drivers generally looked more closely in front of the vehicle and more to the right of the vehicle's direction of travel than experienced drivers. This pattern was interpreted to suggest that novice drivers must allocate more of their attention than experienced drivers to maintaining the vehicle's position on the road.

Visual search paradigms in the laboratory have been used to study mechanisms of selective attention (Shiffrin 1988). According to Theeuwes (1989), the essential difference between visual search as studied in the laboratory and in driving concerns the existence and nature of the search targets. In driving, the search targets may not be well defined and search is not top-down (Norman and Bobrow 1975) or target-driven, but rather bottom-up or data-driven. In other words, much of visual search in driving consists of drivers' waiting to notice a conspicuous target (Cole and Hughes 1990). In one sense, this may render much of the visual search literature not applicable, because most experimentation on selective attention has used top-down, target-specified search (Johnston and Dark 1986). Other differences between laboratory studies and on-road driving include the use of eye and head movements while driving and the constantly changing visual scene in the moving vehicle. The majority of laboratory studies use static displays with minimal content, to minimize the involvement of memory, and brief exposures to eliminate eye movements.

These differences are considered in a model of visual search in driving developed by Theeuwes (1989). According to this model, top-down regulated search during driving occurs only when several conditions are met. First, the driver can be in two possible states, a state of certainty or a state of uncertainty. This state is determined by the changing sensory input in relation to the immediate goals of the driver. For example, if the driver expects to stay on the same road for sometime, he/she will be in a state of certainty with regard to the question of, for example, where to turn. If the driver is near a point where a turn is required, in an unfamiliar area, then he/she may become uncertain. If there is no uncertainty, then no search target will be generated and the driver will be passively "noticing," rather than searching. However, when the driver becomes uncertain, an attempt will be made to reduce the uncertainty. The type of uncertainty, together with the outcome of a global analysis of the environment and the driver's experience with this type of uncertainty in this environment, will determine whether a search is initiated. If a search objective is defined, a subsequent process will determine whether an appropriate schema exists so that a learned stereotypic search pattern can be used. For example, the uncertain driver looking for a place to turn may activate a schema that directs his/her gaze to the location most likely to contain a street-name sign or a break in the pavement edgelines. The two-stage search model, in which an initial global search is followed either by a selected specific scanning pattern or a more general-purpose pattern, is based on Rabbitt's work (1981:1982).

This model applies the mechanisms of motivational models to visual search in driving. Specifically, the control of search by an uncertainty-reducing mechanism is consistent with the risk-threshold model (Naatanen and Summala 1976). Furthermore, the emphasis on conspicuity provides the framework for application of models of visual detection; however, additional theoretical work will be necessary to determine the extent to which the automatic detection of conspicuous targets in driving occurs as the result of extensive learning of consistently mapped relations (Schneider and Shiffrin 1977), or through the action of distinctive features (Treisman and Gelade 1980).

Cognitive processing and errors

Reason's (1990) generic error-modeling system (GEMS) has incorporated information-processing mechanisms into Rasmussen's taxonomy in an attempt to show how control shifts between levels. The model concerns two types of error, including monitoring failures, which precede the detection of a problem, and problem-solving failures, which follow such detection. Periodic attentional checks are an important part of well-practiced (skill-based) actions. These checks are intended to determine whether the actions are running according to plan and whether the plan is still adequate to achieve the desired outcome. The scheduling of attentional checks can be a critical factor contributing to the occurrence of a monitoring failure. Attentional checks should occur near critical choice points, particularly if the planned action is not the most frequently used choice. For example, if a driver selects a route that corresponds initially to a highly familiar and frequently used route, but later requires a change, the likelihood of an error may depend on whether an attentional check occurs slightly before the point at which the driver must deviate from the highly practiced route. Reason (1990) has identified two categories of monitoring failure, including inattention (distraction) and overattention (preoccupation).

Problem-solving failures result from attempts to apply inappropriate rules. This derives from the assumption that human problem-solvers are strongly biased toward looking for an existing solution at the rule-based level before resorting to the considerably more effortful knowledge-based solution. In fact, Reason suggests that even when an appropriate rule cannot be found, the bias toward finding an existing solution motivates continued attempts to identify similarities between the current and previous situations, even as knowledge-based problem-solving proceeds.

Consistent with Michon's (1985) criteria for a model of driving behavior, GEMS includes the provision for switching control among the various levels. Once an attentional check results in the detection of a problem, control will shift from the skill-based to rule-based level. This change can also be represented as a change from primarily automatic to controlled processing. If an applicable rule can be found, it will be activated; however, control will remain at the rule-based level until it has been decided that the new rule will resolve the problem. At that point, control will again shift to the skill-based level. However, if no applicable rule can be found to address the immediate problem, control will eventually shift from the rule-based to the knowledge-based level. According to Reason, this occurs when the problem solver becomes aware that none of the existing rules is applicable to the current problem.

This model represents a combination of cognitive processing mechanisms and hierarchical control theory. Specifically, automatic versus controlled processing is interpreted within the context of Rasmussen's three-level control hierarchy. This model is also consistent with motivational models in that subjective uncertainty is viewed as the mechanism that triggers a shift in the allocation of attentional resources.

SUMMARY AND CONCLUSIONS

No comprehensive model of driving behavior has been developed, and, given the wide variety of driving situations and associated combinations of component skills, it is unlikely that one will soon emerge. Recent psychometric research has used performance-based measures to predict individual accident histories. With several exceptions, it has been conducted without the benefit of a process model of driving; has focused primarily on accident-causing behaviors, not on everyday driving; and has relied heavily on post-hoc explanations. The general lack of success in identifying predictors of safe driving, together with methodological difficulties associated with the use of accident measures, lead to the conclusion that we should abandon the differential accident involvement paradigm and define alternative measures of safe driving.

Motivational models distinguish between drivers' performance limits and on-road driving. They emphasize transient, situation-specific factors, and suggest that it may be futile to search for stable predictors of alternative measures of driving. Taken to the extreme, this implies that there are no good or bad drivers as such, only dangerous situations. However, abandoning the concept of good and bad

drivers entirely is premature, for several reasons. First, because of theoretical and methodological problems, motivational models have not been fully specified, let alone thoroughly tested. Second, it is very unlikely that crash causation involves only transient factors. Nevertheless, moving the focus of research away from the driver in isolation and focusing more on the interaction of the driver and driving situations would improve the ecological validity of roadway safety research. It would better define the limits of its generalizeability by revealing the deficiencies of controlled research conducted in artificial settings, where there are no demonstrable connections to real-world driving. It would also move theory beyond artificial obstacles created by the idea that human errors contribute to an exceedingly high percentage of accidents and allow work to focus on identifying factors that create incompatibilities among the drivers, the vehicles, and roadway systems.

Second-generation motivational models have incorporated a hierarchical control structure and have given emphasis to motives other than risk. Driving is now seen as involving concurrent activity at the operational, maneuvering, and strategic levels of control. The driver's allocation of attention depends on the immediate driving situation and the driver's motives, which include the level of risk and other motives related to the purpose of the trip. This model provides the framework for a research paradigm in which the interest is in identifying factors that influence the driver's allocation of attention among the tasks at the different control levels. In this context, the generalizeability of research results can be operationally defined as the set of driving situations that involve the same combination of motives and allocation of component driving behaviors as the experimental situation.

Automaticity has emerged as a central construct in cognitive psychology. The distinction between automatic behavior, which is fast and effortless, and controlled processing, which is slow and demanding of attentional resources, is relevant to driving, since it is obvious that much of routine driving is done automatically. Consistency is essential for the development of automaticity, which can operate at all three levels of the control hierarchy. Automaticity is situation-specific, since the response to any driving situation depends on the relationship between that situation and all previously encountered situations. Novel or unexpected situations, or those that differ considerably from previous experience, may be expected to disrupt automatic processing and require deliberate controlled responses. Uncertainty is believed to trigger this disruption and the associated change in allocation of attention. One theory proposes that when uncertainty increases above a subjective threshold, a switch from passive noticing of unspecified stimuli to active goal-directed visual scanning occurs. Thresholds associated with the activation of the control mechanism are hypothesized to vary among individuals and driving situations, reflecting differences in driving experience and (route and/or vehicle) familiarity. Details of control mechanisms responsible for changing drivers' allocation of attention have generally not been specified. Determining the characteristics of situations that create uncertainty for drivers and trigger a shift in the allocation of attention among the various component behaviors is a potential research focus that would help integrate concepts of automaticity and motivational models.

Theories of errors have recently been applied to driving. Errors associated with the inherent variability of human information processing, referred to as lapses of attention, are thought to be important to roadway crash causation. Unlike systematic errors, attributable to known limits of the human information-processing system, variable error is unpredictable and thus creates significant difficulty for adaptation. With sufficient safety margins, minor lapses of attention are generally of little consequence. However, driving generally fails to provide feedback concerning minor errors, which results in automatic patterns with considerable variability, including a wide range of correct and incorrect responses. This suggests that inadequate safety margins and other unsafe behaviors, such as excessive speed, may develop gradually and outside the driver's awareness. Behaviors referred to as risk-taking may thus be highly learned and automatic and not deliberate. Furthermore, because of the tolerance of the roadway system for minor errors, drivers' abilities to recover from errors may also be important to crash causation. However, if drivers adopt inappropriate safety margins, lapses of attention may leave insufficient room for recovery. Identifying the situational determinants of safety margins is also a potential focus for roadway safety research.

Attentional mechanisms have been prominent in all approaches to understanding driving behavior. However, whether crashes are more often caused by systematic errors associated with drivers' performance limits, such as one's ability to switch attention rapidly among competing sources, or by variable errors of automatic processes, such as lapses of attention, is not well established. The complexity of attentional mechanisms and lack of operational definitions underscore the need for a common terminology for attentional and control mechanisms in

driving. The framework provided by the hierarchical control model, together with concepts derived from work in automaticity, appear to be suitable tools for this endeavor.

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