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Towards a general theory of driver behaviour

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Abstract

Taylor [Taylor, D.H., 1964. Drivers' galvanic skin response and the risk of accident. Ergonomics 7, 439–451] argued that drivers attempt to maintain a constant level of anxiety when driving which Wilde [Wilde, G.J.S., 1982. The theory of risk homeostasis: implications for safety and health. Risk Anal. 2, 209–225] interpreted to be coupled to subjective estimates of the probability of collision. This theoretical paper argues that what drivers attempt to maintain is a level of task difficulty. Näätänen and Summala [Näätänen, R., Summala, H., 1976. Road User Behaviour and Traffic Accidents. North Holland/Elsevier, Amsterdam, New York] similarly rejected the concept of statistical risk as a determinant of driver behaviour, but in so doing fell back on the learning process to generate a largely automatised selection of appropriate safety margins. However it is argued here that driver behaviour cannot be acquired and executed principally in such S-R terms. The concept of task difficulty is elaborated within the framework of the task–capability interface (TCI) model, which describes the dynamic interaction between the determinants of task demand and driver capability. It is this interaction which produces different levels of task difficulty. Implications of the model are discussed regarding variation in performance, resource allocation, hierarchical decision-making and the interdependence of demand and capability. Task difficulty homeostasis is proposed as a key sub-goal in driving and speed choice is argued to be the primary solution to the problem of keeping task difficulty within selected boundaries. The relationship between task difficulty and mental workload and calibration is clarified. Evidence is cited in support of the TCI model, which clearly distinguishes task difficulty from estimates of statistical risk. However, contrary to expectation, ratings of perceived risk depart from ratings of statistical risk but track difficulty ratings almost perfectly. It now appears that feelings of risk may inform driver decision making, as Taylor originally suggested, but not in terms of risk of collision, but rather in terms of task difficulty. Finally risk homeostasis is presented as a special case of task difficulty homeostasis.

Keywords: Driving behaviour; Driver capability; Task demand; Task–capability interface; Mental effort; Risk perception

1. Introduction

Reaching a destination is usually the main goal of driving. In the decision-making process to achieve this goal, feedback is usually self-evident as the driver navigates towards and approaches her or his destination. Subsumed under this goal are a variety of secondary goals among which there has been a lasting controversy regarding the role played by risk of collision. In several formulations (e.g., Näätänen and Summala, 1976) this risk has been assumed to be predominantly a zero risk of collision, in others (e.g., Gibson and Crooks, 1938; Wilde, 1982; Adams, 1985) a target level of risk has been proposed. This paper will argue that risk of collision is generally not relevant in the decision-making loop. What is relevant is feedback regarding the difficulty of the driving task.

From the outset, however, it is important to distinguish between three basic uses of the term risk: objective risk, subjective risk estimate and the feeling of risk. In the first usage, objective risk may be defined as the objective probability of being involved in an accident. This is usually determined in a post hoc way from analysis of accident data. This concept of risk has been referred to elsewhere as 'statistical risk' (Grayson et al., 2003). Subjective risk estimate refers to the driver's own estimate of the (objective) probability of collision. Such estimates of risk represent the output of a cognitive process, while the feeling of risk represents an emotional response to a threat, a distinction previously clarified, for example, by Haight (1986) and Summala (1986). Under certain conditions, subjective estimate of risk and feelings of risk

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may be closely associated, such as when a driver has lost control of a vehicle on an icy road and is about to collide with another road user. However, this association may apply only after subjective estimates of risk have exceeded some critical value.

Once a motor vehicle begins to move, collision (or veering off the roadway) is not a matter of some refined estimate of a very low probability: it is inevitable. The probability of crashing is one, unless, of course, the driver more-or-less continuously makes direction and speed adjustments to avoid this otherwise certain outcome. For this reason, an earlier conceptualization of key elements of the driving task focused on avoidance of potential aversive consequences and the conditions for delaying an avoidance response, which had implications for safety (see Fuller, 1984). In that conceptualization, objective risk of collision was assumed to be related to the extent of delay of an avoidance response, once a critical threshold had been passed. An example of a delayed avoidance response might be not slowing down when approaching a turning vehicle, which was expected to be out of the driver's path by the time it was reached. This perspective on driver behaviour was subsequently elaborated into a comprehensive behaviour-analytic model, enabling detailed consideration of the role of antecedent events and consequences in the determination of driver behaviour (see Fuller, 1991a,b).

In that model, subjective risk estimates were not a determinant of driver decision making, except in the profound sense of motivating the continuous avoidance of certain catastrophe, and this distinguished the approach in a fundamental way from that of the Risk Homeostasis theory of Wilde (1994, 2001). As is well known, Wilde argued that through weighing up the costs and benefits of alternative actions, drivers arrive at an accepted level of risk which they actively target (target risk), ultimately yielding the road accident toll in the drivers' jurisdiction over a period of time. Thus, subjective risk estimates and objective risk are coupled in Wilde's theory. But further than this, Wilde also coupled subjective risk estimates and feelings of risk (fear). The experience of fear on the roadway informs estimates of subjective risk and behaviour adjustments are made so as to match these estimates with target risk.

Wilde's coupling of objective risk, subjective risk estimate and feelings of risk is clearly illustrated in his interpretation of a finding reported by Taylor (1964). Taylor found that measures of driver arousal (GSR), associated with particular roadway segments, were correlated with accident probabilities and inversely related to driver speed in those segments. He suggested that drivers were able to maintain GSR levels *per unit time* approximately constant by adjusting speed over different road segments. GSR rate, he proposed, was the feedback information drivers used to regulate speed. Wilde interpreted this to mean that drivers' assessments of subjective risk were accurately reflecting objective risk in those segments and were determining their fear response (i.e., GSR) and behavioural adjustment, as represented in heightened arousal and choice of speed. Thus, all three 'risk' elements covaried in the theory.

There are a number of problems with this interpretation of Taylor's results, however. The first is to assume that GSR is a measure of fear or of feelings of risk. As mentioned above, and admitted also by Wilde (1994), GSR is also a generalized measure of arousal (specifically as expressed through the sympathetic ANS). Consistent with this is the later finding by Heino et al. (1994) that electrodermal activity was not very specific to changes in perceived level of risk.

Furthermore, GSR reflects both orientation responses and adjustments to temperature fluctuations. Thus, it will covary with attentional demands of a situation as well as motor activity (see, for example, Heino et al., 1994). A related problem has to do with the suggestion that GSR responses provide feedback information since, except in extreme situations, we are typically unaware of the level of activity of our sweat glands. What Taylor showed was that at certain locations historically associated with a higher probability of accident and also associated in his study with observable 'traffic events' (by which I presume he means potential conflicts), drivers showed increased electrodermal activity (EDA) and slowed down. By slowing down they spread the EDA over a longer time-base and therefore lowered its level per unit time. Taylor concluded that 'drivers adopt a level of anxiety that they wish to experience when driving, and then drive so as to maintain it'. Wilde interpreted 'level of anxiety' here to mean a fear state coupled to subjective estimates of the probability of collision estimates, which are in turn linked to the objective probability.

An equally plausible explanation of Taylor's observations as that of risk-homeostasis, however, is the proposition that drivers respond to variations in *task difficulty* rather than feelings of risk and that they respond to these variations both in terms of autonomic arousal and adjustments in speed. EDA then becomes a correlate of task difficulty, an epiphenomenon that may play only an indirect role in mediating driver behaviour. If we replace 'anxiety' in Taylor's conclusion with 'task difficulty', then we get: 'drivers adopt a level of *task difficulty* that they wish to experience when driving, and then drive so as to maintain it'. Taylor indeed found strong evidence in support of this revised conclusion. He showed that the GSR, expressed as a rate per unit time, was negatively correlated with driving experience, providing quite a good fit to a negative exponential function. Taylor tried to argue that over the same route the less experienced drivers must have perceived more risk than the more experienced drivers. But not only is there accumulating evidence to show that inexperienced drivers typically underestimate risk compared with more experienced drivers (e.g., Finn and Bragg, 1986; Del homme and Meyer, 1998), but surely it is just as likely, if not much more so, that the less experienced drivers would simply have found the task of driving under the same conditions more difficult.

Given that crashing is more-or-less continuously inevitable unless a driver does something about it, it is not surprising that Taylor and subsequently Wilde should have made subjective risk estimate and fear so central to their thesis. However, what I want to propose here is that drivers adjust their speed to deal *more easily* with some hazard or potential difficulty. Thus, risk estimates linked to risk feelings are not ongoing determinants of driver decision making.

This view is largely concordant with that proposed by Näätänen and Summala (1976), McKenna (1988), and Wagenaar (1992), summarized by Summala (1986), who rejects the concept of risk as a determinant of driver behaviour. Summala argues that in most situations drivers know what they should do or not do to avoid a certain or almost certain accident. Driver behaviour is determined by the maintenance of safety margins, operationalized in his terms as the distance of the driver from a hazard. In a more recent formulation, Summala (1996, 1997) describes a ‘lane-tube’, formed by the roadway and lane markings painted on it. If a driver maintains speed and direction, it is the time to crossing the boundaries of the tube (time-to-line-crossing) which provides the control measure for lane-keeping and similarly time-to-collision provides the control measure for headway selection and approach to stationary obstructions. No concern is normally given to risks. As Wagenaar (1992) succinctly states: “. . . people . . . run risks, but they do not take them”. What undermines the maintenance of safety margins, however, are motivating conditions which push drivers to higher speeds, an insensitivity to low probability events on the roadway and a growing desensitization to potential threats (because the threats are not realized). Given Summala’s position on the determination of driver behaviour, the question then arises as to how drivers determine what is a safe margin in any given driving situation. Summala suggests that estimate of time-to-collision, for example, is a very basic human skill, for which computations can be carried out without cognitive computational processes (by which I presume is meant conscious processing). Safe margins are learned through experience and so most of driving ‘becomes a habitual activity which is based on largely automatized control of safety margins in partial tasks’ (Summala, 1986, p. 10).

Attractive as this model is, being situated firmly in a well-established behavioural paradigm, it is nevertheless vulnerable to the implausible requirement to recognize, and learn how to respond safely to, what is a virtually infinite number of roads and traffic scenarios. A learning model can provide a powerful explanation for which behaviours become established, once emitted. But it is unable to specify with any degree of precision which behaviour will be emitted in the first instance. What is needed is a heuristic, which goes beyond avoidance learning as a means of determining driver decision-making and therefore behaviour. One such heuristic is *perceived task difficulty*. If we agree that the driver’s task is to attain mobility goals while avoiding collision, then most relevant to driver decision-making is the driver’s perception of the difficulty of meeting those demands. Given this proposition, the question then arises as to what determines driving task difficulty.

2. The task–capability interface model

A recent conceptualization of what determines driving task difficulty has been presented in the task–capability interface (TCI) model (see Fuller, 2000 for the initial version of this model and Fuller and Santos, 2002 for a more developed version). In this model, task difficulty arises out of the dynamic interface between the demands of the driving task and the capability of the driver. Where capability exceeds demand, the task is easy; where capability equals demand the driver is operating at the limits of his/her capability and the task is very difficult. Where demand exceeds capability, then the task is by definition just too difficult and the driver fails at the task, loss of control occurs, and this perhaps leads to a collision or the vehicle careering off the roadway. Thus in essence, task difficulty is inversely proportional to the difference between task demand and driver capability. With a static level of capability, any event that pushes up task demand will therefore reduce this critical difference, increase task difficulty and potentially challenge safety. For instance, the use of a mobile phone can be an additional task, which pushes demand beyond driver capability. Violanti and Marshall (1996) report that cellular phone use while driving increases the probability of collision by 500%. Note that in this formulation task difficulty is independent of task complexity. If the driver’s capability far exceeds the demands of a complex task, the task is perceived as relatively easy. Similarly, a simple task will be challenging if the demands exceed the driver’s available capability.

Sometimes the actions of another road user can rescue the situation from imminent catastrophe, such as a pedestrian leaping out of the path of an out-of-control vehicle. In such an instance the pedestrian effectively changes task demand at the very last moment (see Fig. 1). Alternatively, the driver may be able to recover from the loss-of-control situation and avoid an impending collision or road run-off.

At the threshold where task demand begins to exceed capability, we need not necessarily expect a sudden and catastrophic breakdown of control but rather a more fragmented degradation. As suggested by Wickens and Hollands (2000), quality of performance may deteriorate (such as the driver losing tight control of lane positioning or situation awareness; see, for example, the simulator study by van der Hulst et al., 2001), or low priority task elements may be dumped (such as mirror checking). In more extreme cases, high priority tasks may suffer a similar fate (such as looking ahead). However, in many instances where demand exceeds capability, the increased demands are such that the driver is simply unable to maintain the desired trajectory, avoid an obstacle or stop in time.

2.1. Elements of driver capability and task demand

Let us explore this model further by unpacking the elements of driver capability on the one hand and task demand on the other. Driver capability is initially constrained by bio-

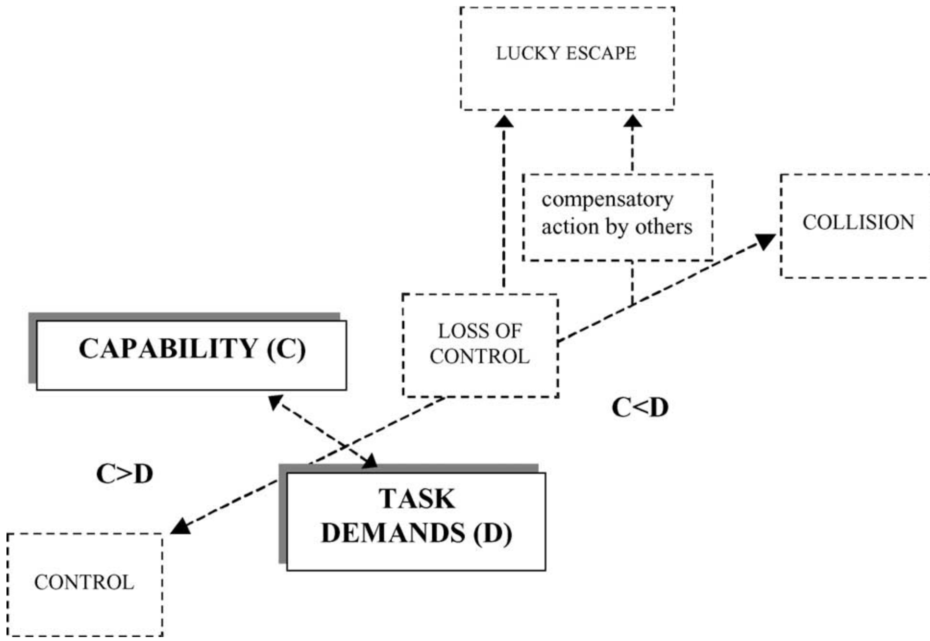

Fig. 1. Outcomes of the dynamic interface between task demand and capability.

logical characteristics of the driver, such as information processing capacity and speed, reaction time, physical reach, motor coordination and perhaps flexibility and strength. Built on top of these characteristics are knowledge and skills arising out of training and experience. Such knowledge includes formal elements such as rules of the road, procedural knowledge defining what to do under what circumstances (conditional rules) and a representation of the dynamics of road and traffic scenarios which enable prediction of how those scenarios will develop, like an internalized mental video which runs on ahead of the immediately observed situation (Kaempf and Klein, 1994). Skills include control skills associated with basic vehicle control as well as handling skills in challenging circumstances (such as a skid). Together these biological characteristics and acquired characteristics through training and experience determine the upper limit of competence of the driver. However, this competence is not necessarily what is delivered at any moment of time because capability is vulnerable to a host of human factor variables. These include factors of attitude, motivation, effort, fatigue, drowsiness, time-of-day, drugs, distraction, emotion and stress. Any of these can detract from driver competence to yield a somewhat lower level of capability.

Part of the motivational variable contributing to the determination of driver capability is resource allocation—the extent to which the driver is motivated to allocate the resources needed to carry out the task so that capability is maintained well above task demand. Brookhuis and De Waard (2001) recognize that driver capability can vary both between drivers and within the same driver at different times, partly as a result of the energetic state of the operator. Thus, although stepping on the accelerator may increase task demand by increasing speed, stepping on the accelerator of mental (and physical) effort may correspondingly increase available capability.

Mulder (1986) distinguishes this ‘computational’ effort from that arising when fatigued or bored (such as the effort to stay alert), which he calls ‘compensatory’ effort. Since there is a utility associated with high capability and also a utility of effort conservation (Wickens and Hollands, 2000), some trade-off between capability and effort may emerge. This is presumably related both to the driver’s attitude towards maintaining a wide safety margin between demand and capability (Delhomme and Meyer, 1998) and to the driver’s competence in determining what the task demand actually is. Thus, at risk in the traffic environment is not just the intentionally risky driver, but also the incompetent one and the lazy one.

Driving task demands are determined by a plethora of interacting elements. There are environmental factors such as visibility, road alignment, road marking, road signs and signals, road surfaces and curve radii, camber angles and so on. There are other road users with various properties occupying or with the potential to occupy critical areas in the projected path of the driver. There are the operational features of the vehicle being driven, such as its information display and control characteristics and its capability to provide roadway illumination in dark conditions. And then added to all of this are elements of task demand over which the driver has immediate and direct control, namely the vehicle’s trajectory and speed. Of these speed is clearly the most significant factor: it is self-evident that the faster a driver travels, the less time is available to take information in, process it and respond to it. Because the driving task is a self-paced task, driving task demand is in a very real and fundamental way under the control of the driver through speed selection. Importantly, choice of speed, like driver competence, is subject to the influence of human factor variables.

2.2. Hierarchical nature of driver decision making

Some authors (such as Allen et al., 1971; Michon, 1985; van der Molen and Botticher, 1988; Hollnagel et al., 2004) have emphasized the hierarchical nature of driver decision-making, pointing out the distinctions between strategic decisions (route and timing of journey), tactical decisions (manouvering) and operational decisions (executive acts). More recently, Laapotti et al. (2001) have added an even higher level, which pertains to 'goals for life and skills for living'. These distinctions are retained in the TCI model where drivers can influence task demand by making choices in relation to each of the factors, which influence it as well as their own speed. Thus, they can make purchase or hire decisions so as to drive a vehicle with particular features (such as ABS), they can select a particular route to a destination (avoiding high density or high speed motorways, for example) and a particular time-of-day (avoiding periods of congestion or driving in darkness—see, for example, Rimmo and Hakamies-Blomqvist, 2002). They can shift towards serial as opposed to parallel use of vehicle controls (Hakamies-Blomqvist et al., 1999) and they can also influence task demand by using directional indicators (and other signals) to affect the behaviour of other road users. Drivers also have some control over their capability, and decisions here also have a hierarchical structure. Remotest from real-time decisions on the roadway are decisions regarding type, amount and level of training and about the kinds of driving experienced. Closer to real-time driving are decisions about exposure to a range of human factor variables such as fatigue, stress and the effects of alcohol and of other drugs. And on an ongoing basis, drivers can vary their level of effort.

Putting all of these general features of the determinants of driver capability and task demand together, we arrive at the model presented in Fig. 2. The elements of the model interact to determine task difficulty and the outcome for the driver in terms of whether or not control is maintained or lost.

2.3. The interaction between task demand and capability

The TCI model as presented in Fig. 2 gives the impression that task demand and capability are independent elements. However, it must be recognized that this is not necessarily, or even usually, the case. Capability is determined by many variables and one of these is the driver's level of arousal or activation. The relationship between these two is traditionally described by an inverted U curve, with relatively lower levels of capability associated with both very low and very high levels of arousal. Arousal is partly determined by en-

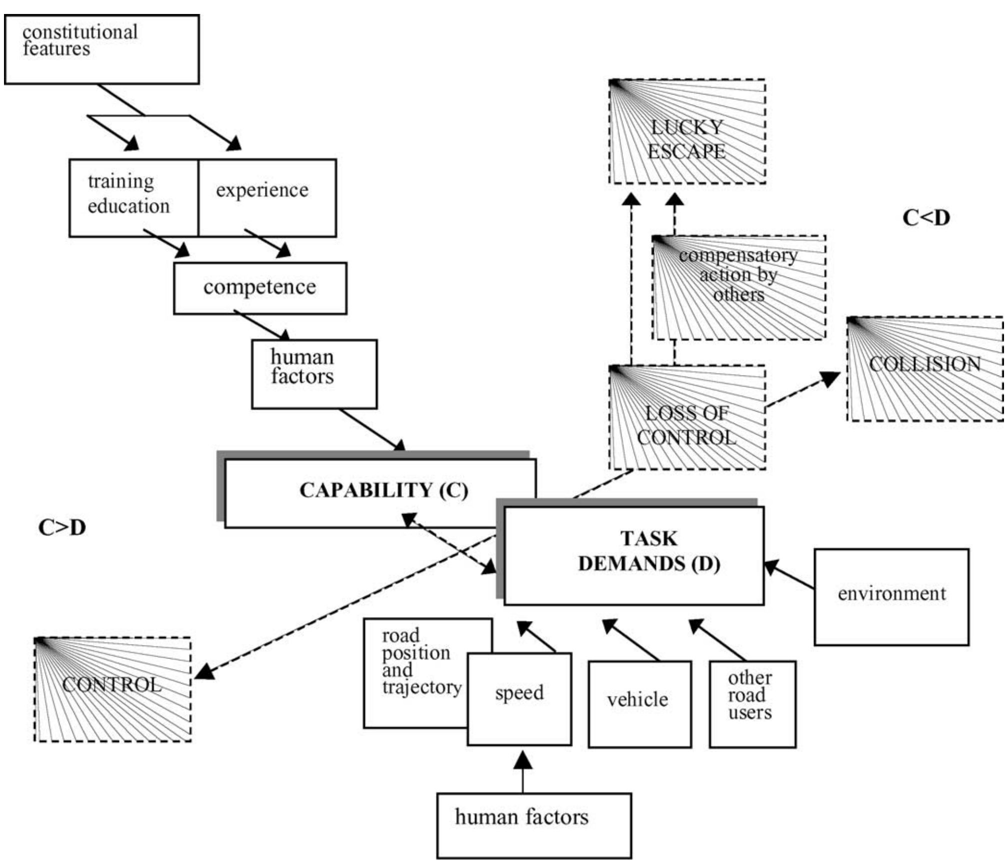

Fig. 2. The task–capability interface model.

dogenous factors such as the individual's circadian rhythm, but it can also be affected by external stimulation. Indeed extraverted individuals, who are characterized as having relatively low levels of endogenous arousal, actively seek external stimulation in order to drive their arousal levels up. The important point here is that driving-task demand provides an external stimulus, which can affect level of arousal, which in turn can affect capability. This relationship has earlier been recognized by Brown (1994), who pointed out that a drowsy driver may increase speed (and therefore task demand) in order to be shaken out of the drowsy state. This is precisely the interpretation given by Brookhuis et al. (1991) who found that the standard deviation of lateral position decreased under conditions of dual task performance, when the opposite effect might have been expected. However, this interdependence of task demand and capability raises further issues.

It is generally accepted that there is an arousal level or range that is optimal, both for sustaining performance and as being rewarding to the individual. This implies that drivers may modify task demand in order to reach and sustain this level, making level of arousal a criterion that feeds into the determination of their target task difficulty. And given that extraverted individuals are more likely to seek enhanced external stimulation, they may be more likely to accept higher levels of task demand and, OTRE, because of this be more likely to be involved in loss of control and collisions. Research on individual differences and accident involvement tends to support this prediction (Loo, 1979). Related to this is the dimension of sensation-seeking which is also argued to be a constitutional characteristic of individuals (Zuckerman, 1979) and again the evidence supports the prediction that individuals high in sensation-seeking are more likely to speed, overtake more and adopt shorter headways and are over-represented in traffic crashes (Jonah, 1997). They are also more likely to report an intention to compensate for active safety interventions such as ABS by driving faster (Jonah et al., 2001). Finally in this context it should be recognized that some drivers may elect for a high task difficulty in order to induce a related arousal boost: the phenomenon of getting 'high' on speed.

Thus, a preferred level of arousal may play a role in the determination of task demand. But apart from this, the relationship between task demand and capability implies that at very high and very low levels of task demand, capability (to the extent that it is influenced by task demand) may begin to decline and approach or even fall below the level of task demand. An example under low task demand conditions would be the driver becoming drowsy and falling asleep at the wheel. As described earlier, de Waard (2002) and Mulder (1986) argue that under these conditions people can actively counteract their state for some time by investing effort.

Capability and task demand interact in a further and potentially very important way for safety. One obvious characteristic of capability is the ability to predict correctly the im-

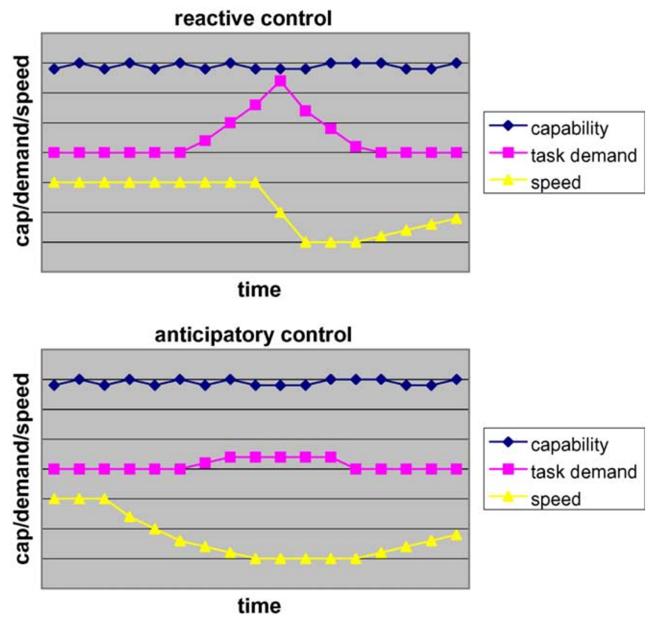

Fig. 3. Reactive and anticipated changes in task demand.

mediate future state of the unfolding road and road user scenario ahead, an ability sometimes referred to as 'reading the road'. Individuals differ in this ability as a function of experience (Quimby and Watts, 1981; Brown and Groeger, 1988), inexperienced drivers being more confined to a 'reactive' mode of dealing with hazards, producing the saw-toothed pattern of variations in task difficulty shown in Fig. 3 (reactive control). Experienced drivers, on the other hand, are more likely to show anticipatory avoidance of a hazard (by changing speed, direction, level of vigilance, focus of attention, information transmitted to other road users—see, for example, Saad et al., 1990) producing a relatively smooth pattern of task difficulty variation over time (Fig. 3—anticipatory control). This anticipatory responding alters the state of the system in such a way that potential threats are essentially neutralised before they are encountered (Fuller, 1984).

On the other side of the task–capability interface, a feature of task demand is the variable predictability of unfolding events, making some scenarios difficult to anticipate. A particular advantage of anticipatory responding is that if the driver makes an error or mistake, there is still the possibility of error correction (e.g., if the driver brakes and begins to slide). However if the driver is in 'reactive' mode, opportunities for error correction will be relatively limited (Brown, 1990).

So much, then, for the determinants of task difficulty. If it is the ongoing perception of this which determines driver behaviour, however, then we need to represent how this dynamic might work, to reassure ourselves that drivers are sensitive to task difficulty and to show that it is task difficulty and not some other variable, such as risk assessment, that is the key determinant of driver behaviour.

3. Task difficulty homeostasis

How might the perception of task difficulty determine driver behaviour? The proposition I want to suggest is that at the outset of a journey, and sometimes also during it, a driver will determine a range of task difficulty that she/he is prepared to accept, a kind of target margin or envelope of task difficulty. A key element of this is the upper boundary of difficulty beyond which the driver prefers not to go. That preference may influence in the first place both choice of route and time of journey and, on an ongoing basis, will influence speed choice. In fact, once the more strategic decisions have been made, it will be speed choice, which the driver will predominantly use to control the level of task difficulty experienced (see Fig. 4), although as suggested by Hakamies-Blomqvist et al. (1999), drivers may also change the 'architecture' of their performance. What determines the preferred level will be motivation for speed, perceived capability and effort motivation. Motivation for speed arises from variables such as available time for a journey, possible social forces relating to passengers (e.g., desire to 'show-off' to peers or to provide a comfortable ride for an elderly person). Perceived capability will be a function of estimates of competence and sensitivity to the effects of human factor variables. It is as if the driver asks herself/himself: what do I have to do here and what am I able to do? The result of this will be an acceptable, preferred range of task difficulty. This concept of task difficulty or workload homeostasis has been alluded to elsewhere in the context of industrial work. As stated by Wickens and Hollands (2000): "Given some flexibility, operators usually work homeostatically to achieve an 'optimal level' of workload by seeking tasks when workload is low and shedding them when workload is excessive" (p. 470). In a self-paced task like driving, modifications of speed provide a very flexible and fairly rapid means of control of workload level (see also next section).

Task difficulty is an expression of the separation between task demand and driver capability. From a safety perspective, a key issue is their degree of separation. The closer capability is to task demand, the more difficult will be the task and the less reserve capability there will be to accommodate a sudden increase in task demand (such as a child dashing out from behind a parked vehicle). This problem may be particularly salient where journey time is limited, forcing a driver to drive faster than would otherwise be preferred (such as a truck driver attempting to make a just-in-time delivery). In such situations safety may be further challenged by the fact that capability may be simultaneously lowered by the stress of anticipated 'mission failure' and a state of heightened anxiety. But the general principle proposed here is that drivers are motivated to maintain a preferred level of task difficulty. Speed choice is the primary solution to the problem of keeping task difficulty within selected boundaries and, as described above, those boundaries are subject to motivational influences. This principle explains not only the continuous adjustment of speed to perceived hazards on the roadway (such as approaching a small radius bend) and the general phenomenon of behavioural adaptation (OECD, 1990) but also the effects on driver speed of traffic calming measures (such as throats, chicanes, lane narrowing and gateways).

Hoyos (1986), in discussing a study that measured driver estimates of task demand and their speed, reported that drivers used compensatory speed reductions as demand increased. In a study of the behaviour of older drivers, de Raedt and Ponjaert-Kristoffersen (2000) found that this kind of 'tactical' compensation was associated with better drivers, as rated by driving instructors and by number of accidents. They concluded that it would be advisable to evaluate compensatory abilities in fitness-to-drive assessments of older drivers and recommended that older drivers should learn such strategies, as well as more 'strategic' decisions, such as avoiding high demand situations (driving in dark, fog, etc.). They also suggested, in line with Hakamies-Blomqvist (1994) and the fundamental postulate of the TCI model, that "it is probable that the immediate goal of compensation behaviour of older drivers is to reduce mental load, with increased safety a by-product *rather than the main goal of the behaviour*" (italics mine). In an interesting technical development from this line

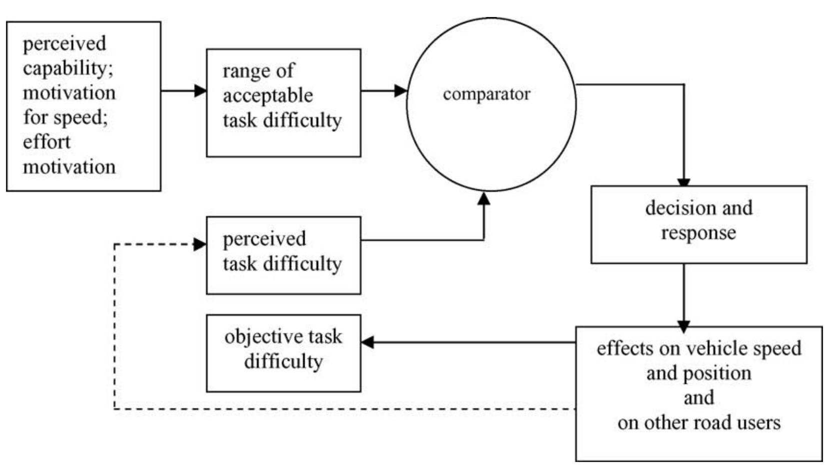

Fig. 4. Task difficulty homeostasis.

of research, Piechulla et al. (2003) report a pioneering attempt to measure driver workload automatically and to use an upper limit of workload to re-route incoming calls to a mailbox, thereby preventing driver overload.

Apart from speed adjustment, task difficulty can be modified in other ways: reference has already been made to the observation that older drivers may execute control movements in a serial manner. Brookhuis and de Waard (2001) found evidence to support the idea that drivers attempt to maintain a reasonably stable level of task difficulty on a journey by glancing fewer times in the rearview mirror under conditions of increased task demand (driving a busier road or when using a carphone). Research has also shown that when engaged in a telephone task, drivers slow down, increase time headway to a vehicle in front and reduce mirror and speedometer inspections (Brookhuis et al., 1991; Recarte and Nunes, 2003). Thus, there is convergent evidence to support the hypothesis of task difficulty homeostasis.

4. Sensitivity to task difficulty

The concept of task difficulty is not new in the driver behaviour research literature, but it has existed in a different guise, namely that of mental workload. Kahneman (1973) defines mental workload as being a specification of the capacity an operator spends on task performance (see also de Waard and Brookhuis, 1997; de Waard, 2002). As de Waard (2002) states: '... in particular the word *difficulty* reflects mental workload very well'. Brookhuis and de Waard (2001) define mental workload as the proportion of mental capacity that is required for task performance, determined by the interaction between the capability of the driver and the task itself (as for the concept of task difficulty in the TCI model). The fundamental importance of this interaction is similarly emphasized by Zijlstra (1993) and Wiethoff (1997).

This concept of mental workload needs to be differentiated from other definitions. According to de Waard and Brookhuis (1997), some authors have defined mental workload as the objective load of a task or task demand. Others define it as "the difference between cognitive demands of a particular job or task and the operator's attentional resources" (Rubio et al., 2004), a definition closer to spare capacity. In the conception preferred here, workload is inversely related to spare capacity. Since workload is the measure of capacity used, it should not be confused with *spare* capacity.

According to de Waard (2002) drivers can easily assess their workload and report it through measures such as the multidimensional NASA-TLX (Hart and Staveland, 1998) and the unidimensional rating scale mental effort (RSME) which measures invested effort (Zijlstra, 1993). As would be predicted from the TCI model, perceived increases in task demand, such as engaging in a telephone task, lead to compensatory reductions in that demand through downward adjustments in speed and increases in time headway (see, for example, Brookhuis et al., 1991). The corollary to this is that where compensatory adjustments cannot be made, performance suffers. In a simulator study in which drivers were instructed to maintain speed at 70 mph, it was found that as mental workload increased, situational awareness decreased (Stanton and Young, 2002).

Kuiken and Twisk (2001) define the ability of drivers to recognize the relationship between the demands of the driving task and their own capability as 'calibration'. They stress the importance in driver training of putting less emphasis on specific skill training and more on developing a reliable evaluation of the relationship between task demand and capability; in other words, task difficulty. And consistent with this, Deery (1999) stresses the importance for safety of people evaluating their abilities as accurately as possible, citing Brown (1982), who is reported as suggesting that the overconfidence of young drivers explained completely their overrepresentation in crashes. Brown has long argued that drivers in general, and certain categories in particular, may drive with inadequate safety margins arising out of either underestimation of traffic hazards or overestimation of their own capability or both (Brown, 1990) and has signaled the need for accident countermeasures for young drivers aimed at improving self-knowledge as well as their assessment of danger (Brown and Groeger, 1988).

5. Task difficulty and risk assessment

The evidence reviewed above provides clear support for the notions that drivers are sensitive to task difficulty and attempt to maintain their experienced level of difficulty within a margin of acceptability. But the question remains as to the relationship between driver perceptions of task difficulty and their assessments of statistical risk. Perhaps task difficulty is really only a surrogate for risk assessment and the TDI model is the old wine of RHT relabeled in a new bottle.

In a recent study, we have been getting drivers to assess both task difficulty and statistical risk directly by asking them to view video sequences of roadway segments, filmed from the viewpoint of the driver, and travelled at different speeds (Fuller et al., in press). Participants were required to rate each sequence for task difficulty and for statistical risk of collision. They were also asked to rate their experience of risk (i.e. feeling of risk) for each sequence. On the basis of the TCI model, we predicted that task difficulty would be closely related to speed but that statistical risk would remain at zero at lower speeds but then increase rapidly after some critical threshold was reached, that is the point where task demand began to approach the boundary of capability.

We found strong evidence of a pattern in which ratings of task difficulty increased in the absence of any increase in the estimated likelihood of collision, a pattern, which was consistent across road types. The results for one type, the country road, are presented in Fig. 5, which shows the average collision risk estimate for the three speed levels above

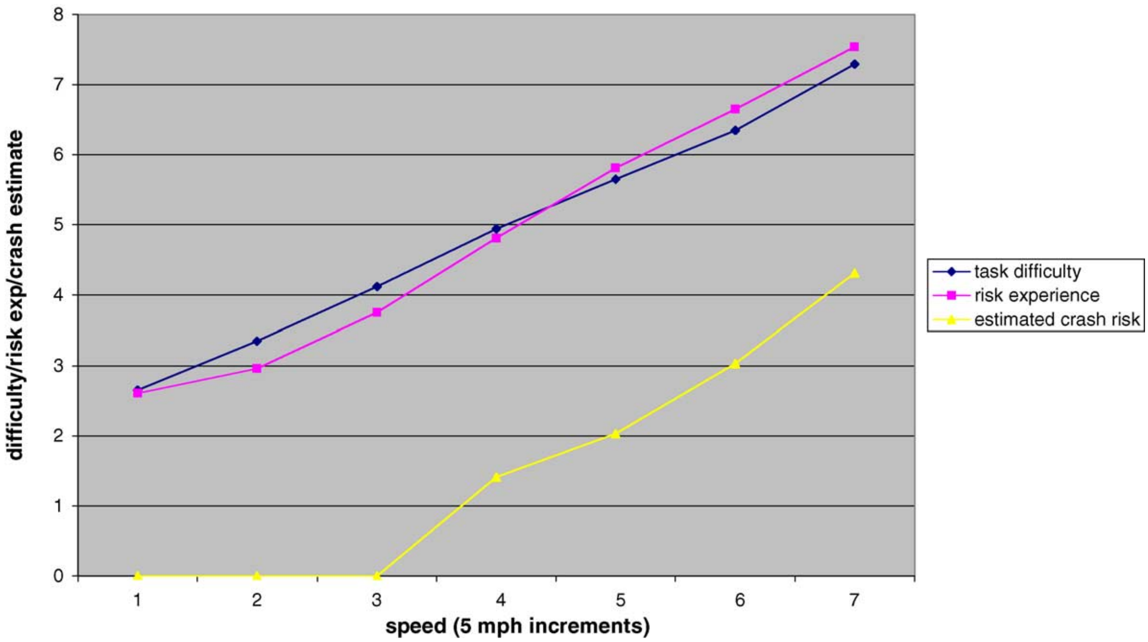

Fig. 5. Ratings of task difficulty, estimates of crash frequency and ratings of risk experience for the country road scenario.

the speed at which estimated collision risk first exceeded zero, and the average task difficulty and experienced risk rating for the three speeds below and above this point. (The point was determined for each individual separately. Mean speed at which the threshold for collision exceeded zero was 51.48 mph, S.D. = 12.15.)

As can be clearly seen and as predicted from the TDI model, task difficulty is closely related to speed, throughout the speed range, but ratings of statistical risk remain at zero at lower speeds but then increase fairly rapidly after the critical threshold is reached. What is also revealed in Fig. 5, however, is the remarkably close association between ratings of task difficulty and ratings of the experience of risk. The average correlation between these two variables, determined separately for each individual ($n = 30$), was Pearson $r = 0.972$, S.D. = 0.025.

Thus, task difficulty and feelings of risk appear to be very highly related to each other, but feelings of risk and ratings of statistical risk are completely unrelated until a critical speed is reached (presumably where task demand approaches capability). This was an unexpected but important finding. It implied that drivers might use feelings of risk as a measure of task difficulty; it implied that Taylor may have been correct in concluding that ‘drivers adopt a level of anxiety that they wish to experience when driving, and then drive so as to maintain it’ and it implied that Wilde was wrong in assuming that feelings of risk could be consistently mapped onto individual estimates of statistical risk.

To be more confident in these results, we replicated the study and included a request to participants to indicate the highest speed at which they would find driving comfortable. As a further test of RHT, we wanted to determine if this speed would be lower or higher than the speed at which drivers first rated the probability of collision as greater than zero (Pender, 2004, B.A. Thesis, University of Dublin, unpublished; Fuller et al., in press).

Of 120 separate analyses over three kinds of road condition, 95 (79%) confirmed the earlier result of task difficulty increases in the absence of any increase in the estimated likelihood of collision. Furthermore, there was again a very strong association between ratings of task difficulty and risk experience (average Pearson $r = 0.978$). Finally it may be noted that 38 of the sample of 40 drivers identified the highest speed at which they would be comfortable as *lower* than the speed at which they first rated the probability of collision as greater than zero. In other words 95% of the sample would be uncomfortable driving at a speed at which there was some estimated risk of crashing.

Thus, as in the first study, task difficulty and feelings of risk appear to be very highly related to each other, and feelings of risk and ratings of statistical risk are in a majority of cases unrelated until a critical speed is reached. In addition, drivers are typically uncomfortable at a speed at which they rate the probability of collision as greater than zero.

Why should feelings of risk and the perception of task difficulty be related to each other? The driving task continuously involves making decisions about how to avoid the certainty of collision if nothing is done. The more difficult this task becomes, as the margin between demand and capability shrinks, the closer the driver comes to losing control of the situation. It is hardly surprising, then, that this process should be linked to feelings of risk. Furthermore, feelings of risk may provide the motivational basis for avoiding taking on a level of task difficulty, which is too high to be accommodated. By providing feedback regarding the relationship between task demand and capability, feelings of risk enable the driver to maintain difficulty level within preferred boundaries.

This relationship between task difficulty and feelings of risk has also been reported by Grayson et al. (2003) in two rather different types of study. In one, 96 drivers rated 12 different sections of a test route (traveling in both directions) for difficulty and danger (I am presuming that ratings of danger are equivalent to feelings of risk). The correlation between these two measures was 0.63 ($p < 0.01$), a relationship that was stable across age and experience groups in their sample. In a separate study, 1340 persons responded to a questionnaire, which included amongst other features five driving scenarios. Participants were requested to provide ratings of their perceptions of danger and difficulty for each, as well as the extent to which they would feel in control. Again the correlation between ratings of difficulty and danger was 0.63 ($p < 0.05$).

6. Risk homeostasis a special case of task difficulty homeostasis

We can tentatively conclude from the above results that Taylor and Wilde were correct in exposing experienced risk (i.e., feelings of risk) as a critical determinant of driver behaviour, but that Wilde was wrong in assuming this was the same as drivers' estimates of the probability of crashing (or statistical risk) and therefore the fundamental determinant of the accident toll in a jurisdiction. The TDI model argues that experienced risk and subjective estimates of statistical risk will only begin to converge when task demand approaches capability and the driver gambles on there being no unexpected increase in demand (e.g., from the behaviour of other road users) and no unexpected decrease in capability (e.g., mistakes or errors). Under these conditions we can see a special case where RHT may be correct in its description of key processes and outcomes, where conscious risk-taking meets the criteria proposed by Wagenaar (1992): ". . . an investigation of the available choices, of their possible consequences, and of how these consequences are to be valued (and) following some decision rule, risks are compared, and accepted or rejected" (p. 274).

7. Conclusion and some further considerations

Driving task difficulty is inversely related to the difference between driver capability and driving task demand. Drivers appear to be able to make judgements of task difficulty easily and to behave in such a way as to keep the level of task difficulty within target boundaries. The feeling of risk may be an important source of information about task difficulty. However, this risk experience is not the same as the driver's rating of the risk of collision. Thus, although drivers may target a level of risk, this is not to say that they target a level of accident involvement. Consequently, aggregated levels of target risk are not predictive of the accident toll. Nevertheless, conditions may occasionally arise where the driver gambles that there will be no increase in task demand or decrease in capability, when she/he is operating close to the threshold where task demand equals capability. Under such conditions, ratings of task difficulty, of the probability of collision and of feelings of risk may all covary.

This TDI model is both descriptive of the interaction of key factors, which influence driver behaviour and provides a dynamic control–motivational framework for understanding driver action. It attempts to shift the focus on the driver in isolation to the interaction between the driver and driving situations, a change in focus recommended by Ranney (1994). We already know a little about self-assessment of capability (particularly in inter-individual comparisons, e.g., Svenson, 1981; Finn and Bragg, 1986;). Young drivers tend to overestimate their level of skill (Matthews and Moran, 1986; Gregersen, 1996) and Groeger and Grande (1996) have shown that self-assessments do not relate accurately to actual ability. But in very few areas of research have questions been asked about driver awareness of human factors in driving, and what to do about them.

Assessment by the driver of task demand involves access to a flow of information, which will vary in distribution, complexity, rate and certainty. This information flow will be channeled through processes of attention, perception, decision-making and prediction, processes, which have been fairly extensively researched (see, for example, Rumar, 1985; Wickens and Hollands, 2000). Some work has been published on aspects of the critical element of maintaining task difficulty within target boundaries (see, for example, Lee's account, 1976 of Spurr, 1969; Brehmer, 1990; Brown, 1990), although this seems to be an area ripe for further research (Ranney, 1994). The recent study by Grayson et al. (2003) suggests that the margins selected by a driver may be a stable individual characteristic.

The TCI model and associated hypothesis of task difficulty homeostasis are an attempt to move on from the stalemate posed by empirical and theoretical difficulties associated with the notion that drivers use estimates of statistical risk as a key component in the decision-making loop. They avoid the heavy dependence on automisation of the selection of safety margins and associated learning requirements of the Zero-risk model, whilst steadfastly supporting the key concept of zero-risk motivation for the general case. The TCI model readily incorporates and extends the principle of hierarchical (embedded) levels of decision-making, in terms both of controlling task demand and capability and provides a coherent framework for relating the mental workload concept to driver motivation and performance. It is also consistent with more generalised conceptualizations of human behaviour in the workplace (e.g., Wickens and Hollands, 2000) and the generic applied approach to investigations of human error in terms of a mismatch between task demands and available resources to deal with them (Dekker, 2002).

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