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Human error taxonomies applied to driving: A generic driver error taxonomy and its implications for intelligent transport systems

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ABSTRACT

Recent research indicates that driver error contributes to up to 75% of all roadway crashes. Despite this, only relatively little is currently known about the types of errors that drivers make and of the causal factors that contribute to these errors being made. This article presents an overview of the literature on human error in road transport. In particular, the work of three pioneers of human error research, Norman, Reason and Rasmussen, is scrutinised. An overview of the research on driver error follows, to consider the different types of errors that drivers make. It was found that all but one of these does not use a human error taxonomy. A generic driver error taxonomy is therefore proposed based upon the dominant psychological mechanisms thought to be involved. These mechanisms are: perception, attention, situation assessment, planning and intention, memory and recall, and action execution. In addition, a taxonomy of road transport error causing factors, derived from the review of the driver error literature, is also presented. In conclusion to this article, a range of potential technological solutions that could be used to either prevent, or mitigate, the consequences of the driver errors identified are specified.

1. Introduction to human error

It has been argued that driver-centred approaches to the introduction of new technology in vehicles should be based upon identifying driver needs. One such approach might be to consider the potential for errors during the driving task. Driver needs potentially involve integration into the vehicle of technology that prevents or reduces driver errors (Stanton and Marsden, 1996). This requires an in-depth understanding of the types of errors that drivers currently make, and of their causal factors.

The role of human error in accidents in most safety critical systems is well known. For example, within civil aviation human error has been identified as a causal factor in around 75% of all accidents, and is now seen as the primary risk to flight safety (Civil Aviation Authority, 1998). Investigation into the construct has led to the development of error focused accident investigation and analysis techniques, such as the human factors analysis and classification system (HFACS; Wiegmann and Shappell, 2003), human error identification techniques, such as the human error template (HET; Stanton et al., 2006) and various human error data collection procedures, such as incident reporting systems (e.g. the Aviation Safety Reporting System).

Recent research suggests that human or driver error contributes to as much as 75% of all roadway crashes (Hankey et al., 1999; cited in Medina et al., 2004). Despite this, compared to other domains in which human error has been identified as a major problem (e.g. aviation), there has been only limited investigation focusing on the types of human errors that drivers make. Consequently, relatively little is currently known about the different errors that drivers make, or about the causal factors that contribute to these errors being made. This is due in part to a lack of structured methods available for collecting human error data within road transport and also, in instances when data does exist, an absence of valid taxonomic systems for accurately classifying driver errors and their causal factors.

This article attempts to construct a generic taxonomy of driver errors and driver error causal factors, based on a synthesis of the available literature on human error and its causal factors. In proposing these taxonomies, this article considers both the form which errors take in general and also the different types of causal factors that lead to these errors being made. In conclusion to this article a range of intelligent transport systems (ITS) that could potentially be used to either prevent these errors from being made or to mitigate their consequences is specified.

Chapanis (1999) first wrote, back in the 1940s, that 'pilot error' was really 'designer error'. This was a challenge to contemporary thinking, and highlights the importance of design in human error reduction. He became interested in why pilots often retracted the landing gear instead of the landing flaps after landing the aircraft. He identified the problems as designer error rather than pilot error, since the designer had put two identical toggle switches

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side-by-side, one for the landing gear and one for the flaps. As a remedial measure, Chapanis proposed that the controls be separated and coded, a practice that is now standard human factors practice. Half a century after Chapanis's original observations, the idea that one can design error-tolerant devices is beginning to gain credence (e.g. Baber and Stanton, 1994). One can argue that human error is not a simple matter of one individual making one mistake, so much as the product of a design or system which has permitted the existence and continuation of specific activities which could lead to errors (e.g. Reason, 1990). A systems analysis of human error requires that all of the systemic elements be considered, such as the driver, the behaviour of the car, other road users and the road environment. The analysis of errors can be used to inform design activity. Ideally, any new system should be designed to be as error-tolerant as is practicable.

2. Human error classification

The use of formal human error classification schemes is widespread throughout most complex safety critical systems. Human error classification schemes are used both pro-actively, to anticipate errors that might occur, and retrospectively, to classify and analyse errors that have occurred during accidents and incidents. The prediction of human error is achieved through the use of formal human error identification (HEI) techniques, such as the systematic human error reduction approach (SHERPA; Embrey, 1986), which uses a taxonomy of external error modes (EEMs) to identify errors that could potentially occur during task performance. The retrospective analysis of human error is assisted by taxonomic systems and interpretation of underlying psychological mechanisms. Various taxonomies of human error have been proposed. Within the literature on human error, three perspectives currently dominate. These are Norman's (1981) error categorisation, Reason's (1990) slips, lapses, mistakes and violations classification and Rasmussen's skill, rule and knowledge error classification (1986). A brief summary of each approach is given below.

2.1. Donald Norman on the categorisation of errors

Norman (1981) reported research on the categorisation of errors, in which he presented an analysis of 1000 incidents. Underpinning the analysis was a psychological theory of schema activation. He argued that action sequences are triggered by knowledge structures (organised as memory units and called schemas). The mind contains a hierarchy of schemas that are invoked (or triggered) if particular conditions are satisfied or events occur. The theory seems particularly pertinent as a description of skilled behaviour.

In Neisser's (1976) seminal work on 'cognition and reality' he puts forward a view of how human thought is closely coupled with a person's interaction with the world. He argued that knowledge of how the world works (e.g. mental models) leads to the anticipation of certain kinds of information, which in turn directs behaviour to seek out certain kinds of information and provide a ready means of interpretation. During the course of events, as the environment is sampled, the information serves to up date and modify the internal, cognitive, schema of the world, which will again direct further search.

The perceptual cycle can be used to explain human information processing in driving a car. For example (assuming that the individual has the correct knowledge of the car they are using), their mental model will enable them to anticipate events (such as whether they need to brake in order to avoid colliding with other vehicles), search for confirmatory evidence (e.g., the braking of their vehicle is in line with their expectations), direct a course of action (decide to depress the brake further if braking is not sufficient) and continually check that the outcome is as expected (e.g., that separation between their vehicle and other vehicles is maintained). If they uncover some data they do not expect (such as their car starts to lose grip and slide uncontrollably) they are required to source a wider knowledge of the world to consider possible explanations that will direct future search activities.

This interactive schema model works well for explaining how we act in the world. As Norman's (1981) research shows, it may also explain why errors occur as they do. If, as schema theory predicts, action is directed by schema, then faulty schemas or faulty activation of schemas will lead to erroneous performance. As Table 1 shows, this can occur in at least three ways. First, we can select the wrong schema due to misinterpretation of the situation. Second, we can activate the wrong schema because of similarities in the trigger conditions. Third, we can activate schemas too early or too late. Examples of these types of errors are presented in Table 1.

Of particular interest to this article is the problem of mode errors (see the first category in Table 1), because they are the result of people's interaction with technology. Norman (1981) singled this error type out as requiring special attention in the design of computing systems. He pointed out that the misclassification of the mode that the computing system was in could lead to input errors, which may have serious effect. In driving, mode awareness by the driver may be of utmost importance, particularly within vehicles that have automation systems such as adaptive cruise control. A mode error in this case would be when the driver wrongly assumes that the vehicle is in full adaptive cruise control mode (i.e. vehicle automatically maintains speed and a safe gap between itself and the vehicle in front), when it is in fact not. A measure of the success of the design will be the extent to which drivers are aware which mode the system is in and how that relates to the behaviour of the vehicle in any given situation.

2.2. James Reason on generic error modelling

Reason (1990) developed a higher-level error classification system also incorporating lapses, mistakes and violations, rather than just concentrating on slips. Slips and lapses are defined by attentional failures and memory failures respectively. Both slips and

Table 1
Error taxonomy with examples (adapted from Norman, 1981)

Taxonomy	Examples of error types
Errors in the formation of intention (misinterpretation of the situation)	Mode errors: erroneous classification of the situation
	Description errors: ambiguous or incomplete specification of intention
Errors that result from faulty activation of schemas (due to similar trigger conditions)	Capture errors: similar sequences of action, where stronger sequence takes control Data-driven activation errors: external events that cause the activation of schemas Association-activation errors: currently active schemas that activate other schemas with which they are associated Loss-of-activation errors: schemas that lose activation after they have been activated
Errors that result from faulty triggering of active schemas (too early or too late)	Blend errors: combination of components from competing schemas Premature activation errors: schemas that are activated too early Failure to activate errors: failure of the trigger condition or event to activate the schema

lapses are examples of where the action was unintended whereas mistakes are associated with intended action. In the driving context, an example of a slip would be when a driver who plans to push the brake pedal to slow down inadvertently pushes the accelerator pedal or when a driver intending to signal to take the next turning off the freeway turns on the windshield wipers instead of the direction-indicators. In both cases the intention was correct but the execution was erroneous. Examples of lapses include a person forgetting to turn off the lights when departing their car, even though they fully intended to do so and also forgetting to lock their car even though they fully intended to do so. A mistake occurs when an actor intentionally performs an action that is wrong. Therefore mistakes originate at the planning level, rather than the execution level, and can also be termed planning failures (Reason, 1990). For example, a mistake would be when a driver decides to accelerate when the appropriate action would have been to brake or slow down. Violations are more complex, and are categorised behaviours that deviate from accepted procedures, standards and rules. Violations can be either deliberate (i.e. knowingly speeding) or unintentional (i.e. unknowingly speeding) (Reason, 1997). Reason's taxonomy is presented in Table 2.

Full explanations of each of these types of errors are to be found in Reason (1990). Reason makes the point that slips and lapses are likely to result from either inattention (e.g., failing to monitor performance at critical moments in the task, especially when the person intends to do something out of the ordinary – such as deviating from the normal route on the way home from work) or over attention (e.g., monitoring performance at the wrong moments in the task). Whereas, Reason argues, mistakes are likely to result from either the misapplication of a good procedure (e.g., a method of performing a task that has been successful before in a particular context) or the application of a bad procedure (e.g., a method of performing a task that is "unsuitable, inelegant or inadvisable" (Reason, 1990, p. 79)) at the most basic level.

Wickens (1992) uses the information processing framework to consider the implication of psychological mechanisms in error formation. He argues that with mistakes the situation assessment and/or planning are poor whereas the retrieval action execution is good. With slips, the action execution is poor whereas the situation assessment and planning may be good. Finally, with lapses, the situation assessment and action execution may be good, but memory is poor.

Wickens (1992) was also concerned with mode errors, with particular reference to technological domains. He suggests that a pilot raising the landing gear whilst the aircraft is still on the runway is an example of a mode error. Wickens proposed that mode errors are a result of poorly conceived system design that allows the mode confusion to occur and allows the operation in an inappropriate mode. Chapanis (1999) argued back in the 1940s that the landing gear switch should be rendered inoperable if the landing gear detects weight on the wheels, as the aircraft would be on the ground.

Table 2
Basic error types with examples (adapted from Reason, 1990)

Basic error type	Example of error type
Slip (attentional failure)	Misperception Action intrusion Omission of action Reversal of action Misordering of action Mistiming of action
Lapse (memory failure)	Omitting of planned actions Losing place in action sequence Forgetting intended actions
Mistake (intention failure)	Misapplication of good procedure Application of a bad procedure Poor decision making Failure to consider alternatives Overconfidence
Violations	Intentional violation Unintentional violation

Mode errors are a continued source of concern for system designers. Whilst there may be valid technological reasons for multiple modes in system design, mode errors only occur in systems where there is more than one mode. One reason for mode errors is the failure of the human operator of the system to keep track of the mode changes (Woods, 1988); another reason is that the rules of interaction change with the mode changes (Norman, 1988). A classic mode error was committed on the flight deck of an A320 in the early 1990s at Strasbourg. As part of a planned descent, the pilot entered the digits 33 for a mean angle of descent of 3.3 degrees. Unfortunately, the autopilot was in another descent mode (feet per minute descent mode) and interpreted the entry as a descent of 3300 feet per minute. On the flight deck of the A320, there was little to distinguish between the two different modes, and data was input using the same data entry system. As a result of the mode error the A320 impacted Mont St Odile, killing 87 people. The catastrophe was attributed to pilot error caused by faulty design. The faulty design was the bimodal VS/FPA dial, which is used to enter both feet per minute descent rate and also flight path angle (Harris et al., 2005).

2.3. Jens Rasmussen on errors in levels of cognitive control

Errors are also affected by skill, experience and familiarity with the situation encountered. Experienced drivers do not tend to commit the same kinds of errors as novice drivers. Fig. 1 shows three levels of cognitive control, denoted as skill-based, rule-based, and knowledge-based, behaviour (Rasmussen, 1986). At the bottom of the figure is a simplistic representation of the world, where the effects of human actions are to input data to change the state of the world and receive data about the state of the world via sensory systems. Human action can be highly automatic (i.e. skill-based), associative (i.e. rule-based), and analogous or exploratory (i.e. knowledge-based). In complex tasks like driving, action can be directed at all of these levels simultaneously. The model of cognitive control is intended to represent the level of skill present in the driver and has implications for the attentional demand of the driving tasks. Aspects of the task that are very familiar and routine will be largely automatic (i.e. skill-based behaviour). Aspects of the task that are unfamiliar and rarely encountered will require effort and conscious attention (i.e. knowledge-based behaviour). In between these extremes are aspects of the task that require identification and recall of the appropriate response which is stored in memory (i.e. rule-based behaviour). In learning to drive, the individual progresses from knowledge-based, through rule-based, to skill-based behaviour in the vehicle control tasks. Despite the fact that vehicle control might be a highly developed skill in normal operation of the car, the driver might still be operating at higher levels of cognitive control in unfamiliar situations, for tasks like navigation in an unfamiliar route or hazard avoidance in poor weather conditions or particularly heavy traffic.

The research evidence on cognitive control suggests that different kinds of errors occur at different levels. Reason (1990) argues that slips and lapses occur at the skill-based level, whereas mistakes occur at the rule-based and knowledge-based levels. Thus, increased skill does not guarantee error-free performance, just different types of error.

The review of the three dominant research perspectives on human error reveals a high degree of concordance. All of the researchers propose classification schemes that draw on each other's work.

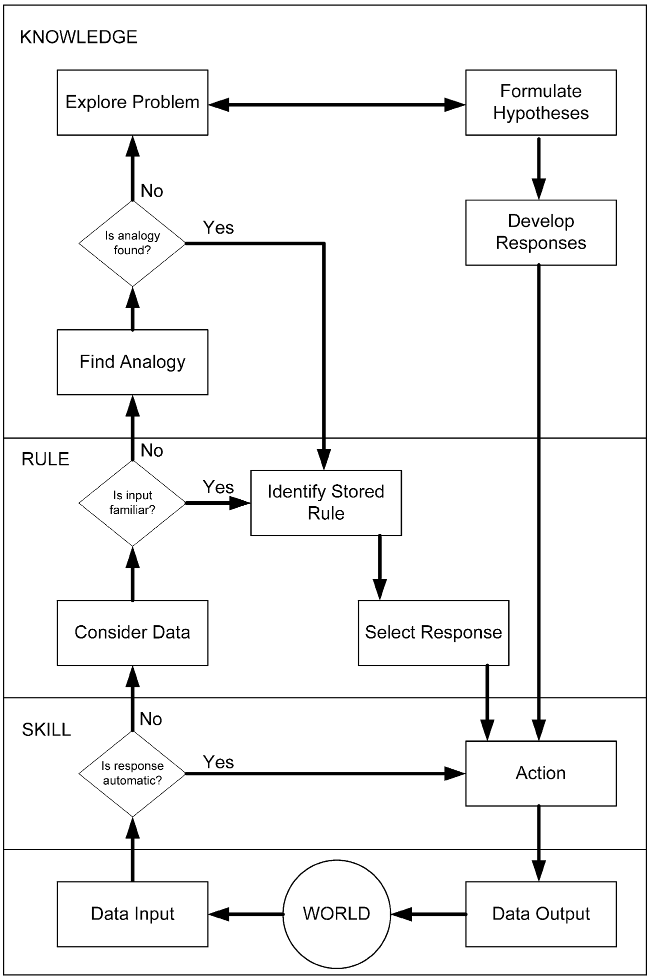

Fig. 1. Levels of cognitive control (adapted from Rasmussen, 1986).

All relate human error to the underlying psychological mechanisms. The information processing perspective is apparent and the degree of skill of the performer will influence the type of error that is committed. The generic nature of the three perspectives discussed allows them to be applied in a driving context (see discussion section).

3. Errors and contributing conditions in driving

Compared to other domains in which human error has been identified as a major problem, the construct has previously received only limited attention. A review of the literature was conducted to determine what is currently known about driver error and to identify driver error data that could be used to inform the development of a taxonomy of driver error.

Further, we also aimed to develop a taxonomy of driver error contributory factors. It is now widely accepted that human error is a systems phenomenon; Reason's (1990) seminal systems perspective approach to human error purports that the entire system, as opposed to merely the operators performing activity in that system, must be considered when discussing error types and their causes. Systems-based approaches contend that the majority of errors made in complex systems are caused by *latent* or *error causing* conditions (e.g. inadequate equipment and training, poor designs, maintenance failures, ill-defined procedures, etc.). This approach is beginning to gain credence within road transport. For example, in the recent World Health Organisation (WHO) report on road traffic injury prevention, it is acknowledged that driver behaviour is governed not only by the individuals knowledge and skills, but also by the environment in which the behaviour takes place (Rumar, cited in WHO, 2004) and that indirect influences, such as road design and layout, vehicle nature and traffic laws and enforcement, affect driver behaviour (WHO, 2004).

Probably the most widely reported driver error study was conducted by Reason et al. (1990) who sought to make a distinction between driver errors and violations. Errors can be defined as occasions where the driver's intended performance was good, but it actually fell short (such as intending to drive within the speed limit, but accidentally pressing the accelerator pedal too far (a slip), forgetting the speed limit (a lapse), or thinking that the speed limit is 70 mph when it is actually 60 mph (a mistake). In contrast, intentional violations may be defined as occasions where the driver's intentions were to perform the action, such as deliberately exceeding the speed limit. Reason et al. (1990) developed the driver behaviour questionnaire (DBQ), a 50-item questionnaire comprising five classes of aberrant driver behaviour: slips; lapses; mistakes; unintended violations; and deliberate violations. The study of errors and violations employed the self-report DBQ, which sampled 520 drivers in nine age bands, from under 20 years to over 56 years. Drivers were asked to report the frequency with which the committed different types of errors and violations whilst driving. The study was undertaken in response to a call for better classification systems for accident investigators. Table 3 presents example driving errors related to Reason's (1990) error and violation taxonomy (adapted from Reason et al., 1990).

They also classified the errors and violations in terms of the degree of risk to others. The classification was based upon the ratings given by six independent judges. An abridged summary of results is presented in Table 4. The table also identifies the rank-order with which different errors are reported, presented in brackets next to the error description. The most frequently reported error was unknowingly speeding. Potentially, speed control devices such as intelligent speed adaptation systems could help reduce the error of unknowingly speeding, at least on roads where the speed limit is fixed rather than variable and the driver is aware of the correct speed limit.

Reason et al.'s results show that, in general, errors (slips and mistakes) and violations decrease with age. A study by Aberg and Rimmo (1998) replicated the study of the Driver Behaviour Questionnaire with 1400 Swedish drivers aged between 18 and 70 years. They largely confirmed the distinction between errors and violations developed by Reason and colleagues. They also extended the analysis to distinguish between errors of inexperience and errors of inattention. Their research shows that errors of inattention increase with age. Reason et al.'s work has since been replicated in a number of different countries, including Australia (Blockey and Hartley, 1995), Greece (Kontogiannis et al., 2002) and China (Xie and Parker, 2002).

A study in the USA identified driver error as the probable cause of crashes in 93% of accidents (Treat et al., 1979). The analysis categorised driver error into *errors of recognition*, *errors of decision* and *errors of performance*. These categories may broadly be aligned to

Table 3
Example error types for reasons errors and violation taxonomy (adapted from Reason, 1990)

Error type	Example errors
Slip	Misread road signs Press accelerator instead of brake
Lapse	Fail to recall road just traveled
Mistake	Underestimate speed of oncoming vehicle
Violation	Exceed the speed limit

Table 4
Classification of driver errors (from Reason et al., 1990)

Driver error (with rank by frequency)	Type	Risk
Unknowingly speeding (1)	Slip	Possible risk to others
Queuing, nearly hit car in front (22)	Slip	Possible risk to others
Manoeuvre without checking mirror (28)	Slip	Definite risk to others
Fail to see pedestrian waiting (23)	Slip	Definite risk to others
Fail to see pedestrians crossing (28)	Slip	Definite risk to others
Fail to see pedestrians stepping out (41)	Slip	Definite risk to others
Only half an eye on the road (6)	Slip	Definite risk to others
Distracted, have to brake hard (7)	Slip	Definite risk to others
Misjudge speed of oncoming vehicle (20)	Slip	Definite risk to others
Miss motorway exit (26)	Lapse	No risk to others
Get into wrong lane at roundabout (4)	Mistake	No risk to others
Overtake queue (14)	Mistake	No risk to others
Fail to give way to bus (3)	Mistake	Possible risk to others
Disregard speed at night (2)	Violation	Definite risk to others
Shoot lights (13)	Violation	Definite risk to others
Risky overtaking (17)	Violation	Definite risk to others
Overtake on the inside (18)	Violation	Definite risk to others
Close follow (21)	Violation	Definite risk to others
Brake too quickly (30)	Violation	Definite risk to others
Race for gap (43)	Violation	Definite risk to others
Disregard traffic lights late on (47)	Violation	Definite risk to others

the stages of information processing shown in Fig. 2, where perception and interpretation can be identified as recognition, plan and intention can be identified as decision, and action execution can be identified as performance. Recognition errors included inattention, distraction and looked-but-failed-to-see errors. These errors accounted for 56% of crashes, as shown in Fig. 2. Decision errors included misjudgment, false assumption, improper manoeuvre, excessive speed, inadequate signaling and driving too close. These errors accounted for 52% of crashes, as shown in Fig. 2. Performance errors included overcompensation, panic, freezing, and inadequate directional control. These errors accounted for 11% of crashes, as shown in Fig. 2. Some crashes involved a combination of recognition, decision and performance errors.

Treat et al. (1979) also investigated the classification of the contributory factors involved in road traffic accidents. Error data were collected from documented incident cases, on-site accident investigations, and accident evaluations (Wierwille et al., 2002). Four primary groups of incident causation factors were identified. These were human conditions and states (physical/physiological, mental/emotional, experience/exposure), human direct causes (recognition errors, decision errors, performance errors), environmental factors (highway related, ambient condition) and vehicular factors. The incident causation factors taxonomy is presented in Table 5.

A more recent study of 687 crash case files by a team of experienced crash investigators supported the findings of Treat et al. (Najm et al., 1995). Najm et al. (1995) used a causal factor taxonomy to determine underlying root causes. This comprised driver errors, driver impairment, vehicle defects, road surface and visibility. The factors related to driver errors are shown in Table 6. Najm et al. report that recognition and decision errors accounted for the largest share of accidents, such as inattention, looked-but-did-not-see, and gap judgment errors.

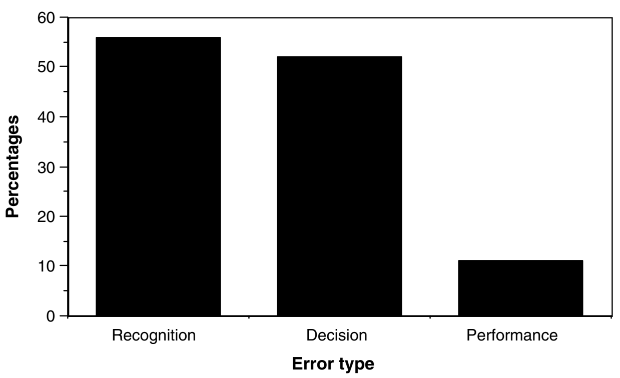

Fig. 2. Percentage of errors implicated in crashes (source: Treat et al., 1979).

Table 5
Driver error and incident causation factors (adapted from Wierwille et al., 2002)

1. Human conditions and states		
A. Physical/Physiological	B. Mental/Emotional	C. Experience/Exposure
• Alcohol impairment	• Emotionally upset	• Driver experience
• Other drug impairment	• Pressure or strain	• Vehicle unfamiliarity
• Reduced vision	• In hurry	• Road over-familiarity
• Critical non-performance		• Road/area unfamiliarity
2. Human direct causes		
A. Recognition errors	B. Decision errors	C. Performance errors
• Failure to observe	• Misjudgement	• Panic or freezing
• Inattention	• False assumption	• Inadequate directional control
• Internal distraction	• Improper maneuver	
• External distraction	• Improper driving technique or Practice	
• Improper lookout	• Inadequately defensive driving technique	
• Delay in recognition for other or unknown reasons	• Excessive speed	
	• Tailgating	
	• Excessive acceleration	
	• Pedestrian ran into traffic	
3. Environmental factors		
A. Highway related	B. Ambient condition	
• Control hindrance	• Slick roads	
• Inadequate signs and signals	• Special/transient hazards	
• View obstruction	• Ambient vision limitations	
• Design problems	• Rapid weather change	
• Maintenance problems		
4. Vehicular factors		
• Tire and wheel problems	• Vision obscured	
• Brake problems	• Vehicle lighting problems	
• Engine system failures	• Total steering failure	

Rumer (1990) identified two primary categories of late detection errors: perceptual errors (e.g. failure to detect another road user in peripheral vision) and cognitive errors (e.g. failure to look in the direction of the road user in question). This categorisation

Table 6
Principal causal-factor taxonomy for accident analysis (adapted from Najm et al. (1995)

Error types	Error descriptions
Recognition errors	Inattention Looked, but did not see Obstructed vision
Decision errors	Tailgating Unsafe passing Misjudged gap or/and velocity Excessive speed Tried to beat signal or other vehicle
Erratic actions	Failure to control vehicle Evasive manoeuvre Violation of signal or sign Deliberate unsafe driving act Miscellaneous

seems very similar to the recognition and decision system shown in Fig. 2.

The 'looked-but-did-not-see error' (LBDNS) is one of the more puzzling error types. It is linked with other error types, such as 'inattention' and 'misjudgments' of 'own approach'. Brown (2001) argues that some of the LBDNS errors may be unreliable, drivers preferring to admit to this error type rather than simply not looking. Of the genuine LBDNS errors, Brown identifies three psychological phenomena that could be implicated. First, the limited information processing capacity of individuals could mean that the information simply is not processed, as there will be competition for attention – particularly in complex scenes. Second, attentional selectivity may result in certain features of the visual scene being given priority over others. Finally, illusory conjunctions between hazardous and non-hazardous aspects of the scene may mean that some hazards are obscured. Brown (1990) reviewed the conditions under which accidents occurred. A rank-ordering of the manoeuvres drivers where performing when a road traffic accident occurred are shown in Table 7.

On analysing the underlying psychological mechanisms leading to the errors, Brown (1990) estimated that approximately 40% were due to attentional problems (e.g., lack of care, distraction, failed to look, and lack of attention), approximately 25% were due to perceptual problems (e.g., looked but failed to see, misjudgment of speed and distance) and approximately 15% were due to judgmental problems (e.g., lack of judgement and wrong decision).

Unfortunately, Table 7 does not provide any detail on the behaviour of the driver at the time of the accident. However, it does provide a relevant classification of the parts of the driving process in which errors occur, which is relevant for a complete driver error classification system.

Sabey and Staughton (1975) conducted detailed investigations into driver errors. Analysis of 2130 accidents taking place in the UK involving 3757 drivers led to the error classifications presented in Table 8. The error analysis was based upon verbal reports of the drivers involved, which may not have been entirely reliable.

Sabey and Staughton (1975) also developed a taxonomy of accident causal factors based on their analysis. Sabey and Taylor (1980) describe the results of in more detail; they concluded, amongst other things, that in 28% of the accidents, road and environmental factors were identified as contributory factors; in 8.5% of the accidents, vehicle features were identified as contributory factors; and in 65% of the accidents, the road user was identified as the sole contributor. In conclusion, a taxonomy of human errors and causal factors involved in the accidents analysed was developed; this is presented in Table 9.

A study reported by Verwey et al. (1993) mapped the driver errors onto accident scenarios. Errors reported by drivers in 1786 accident and near-accident scenarios are presented in Table 10. The most frequently associated error reported by drivers was failing to look in the appropriate direction at the time immediately prior to the accident. This type of error was identified in all of the accident scenarios shown in Table 10.

As Table 10 shows, the other frequently reported errors included incorrect interpretation of the situation and wrong estimation of the speed of other traffic. Collision warnings and collision avoidance technologies (Walker et al., 2001) have the potential to reduce the frequency and severity of rear-end collisions, partic-

Table 7
Contribution of vehicle manoeuvres to road accidents in the UK (adapted from Brown, 1990)

Type of manoeuvre	Number of vehicles
Going straight ahead	162,854
Turning, or waiting to turn, right	48,339
Going ahead on a bend	32,747
Overtaking a moving or stationary vehicle	20,310
Held up, waiting to go ahead	19,273
Parked	19,206
Turning, or waiting to turn, left	12,061
Stopping	10,497
Starting	4823
Changing lane	4019
Reversing	3556
U-turning	2593
All known manoeuvres	340,278

Table 8
Driver's errors as contributing to accidents (adapted from Sabey and Staughton, 1975)

Description of error types	Number of errors
Lack of care	905
Too fast	450
Looked, but failed to see	367
Distraction	337
Inexperience	215
Failed to look	183
Wrong path	175
Lack of attention	152
Improper overtaking	146
Incorrect interpretation	125
Lack of judgement	116
Misjudge speed and distance	109
Following too close	75
Difficult manoeuvre	70
Irresponsible or reckless	61
Wrong decision or action	50
Lack of education or road craft	48
Faulty signaling	47
Lack of skill	33
Frustration	15
Bad habit	12
Wrong position for manoeuvre	7
Aggression	6
Total number of errors	3704

Table 9
Human error and causal factors taxonomy (source: Sabey and Taylor, 1980)

Human Errors	Road environment contributory factors
Perceptual errors	Adverse road design
– Looked but failed to see	– Unsuitable layout, junction design
– Distraction or lack of attention	– Poor visibility due to layout
– Misjudgement of speed or distance	
Lack of skill	Adverse environment
– Inexperience	– Slippery road, flooded surface
– Lack of judgement	– Lack of maintenance
– Wrong action or decision	– Weather conditions, dazzle
Manner of execution	Inadequate furniture or markings
– Deficiency of actions: too fast, improper overtaking, failed to look, following too close, wrong path	– Road signs, markings
	– Street lighting
– Deficiency in behaviour: irresponsible or reckless, frustrated, aggressive.	
Impairment	Obstructions
– Alcohol	– Road works
– Fatigue	– Parked vehicle, other objects
– Drugs	
– Illness	
– Emotional distress	

Table 10
Errors associated with accident scenarios (adapted from Verwey et al., 1993)

Accident scenario	Most frequently reported errors
Rear-end collisions	Did not look in appropriate direction Wrong estimation of speed of other traffic Speed too high
Crossing junction	Did not look in appropriate direction wrong estimation of speed of other traffic
Sudden obstacle	Did not look in appropriate direction
Curve in the road	Did not look in appropriate direction speed to high
Changing lane	Did not look in appropriate direction Incorrect interpretation of situation Did not check blind spot in mirror
Overtaking	Did not look in appropriate direction Incorrect interpretation of situation Wrong estimation of speed of other traffic Did not check blind spot in mirror
Roundabout	Did not look in appropriate direction

ularly when the braking of the lead vehicle is within the range of the host system. Most of these errors seem, on the face of it, to be associated with the situational awareness of the driver; situation awareness refers to the level of awareness that an individual has of a situation, their dynamic understanding of 'what is going on' (Endsley, 1995). Loss of situation awareness has been found to be a significant causal factor in accidents and incidents in other transportation domains. For example, in conclusion to a review of major airline accidents, Endsley (1995) reported that 88% of those incidents involving human error could be attributed to problems with situation awareness rather than problems with decision-making or flight skills. Ostensibly situation awareness also appears to be closely connected to driver error; thus given the necessity to optimise the situational awareness of the driver, it is important to consider the implications of situational awareness when making changes to the driving task and designing new in-car technology.

Wierwille et al. (2002) describe a comprehensive study that was conducted at the Virginia Tech Transportation Institute in order to, amongst other things, investigate the nature and causes of driver errors and their role in crash causation. On the basis of an observational study of road user error at over 30 problematic road transport sites, Wierwille et al. (2002) developed a crash contributing factors taxonomy of latent conditions and driver errors, presented in Fig. 3. According to the taxonomy, there are four different groups of factors that contribute to driver performance problems that occur during crashes: inadequate knowledge, training and skill; impairment; wilful behaviour; and infrastructure and environment.

Wagenaar and Reason (1990) identified two distinct classes of causes in road traffic accident scenarios, *token* causes and *type* causes. Token causes refer to the direct causes of the accident that occur immediately prior to the accident, while type causes refer to those causes that might have been present in the system for a long time. Wagenaar and Reason (1990) suggest that to be effective, accident countermeasures should focus on the identification of *types* rather than *tokens*, and that accident analysis should extend beyond the identification of those events that immediately precede accidents. Wagenaar and Reason (1990) also identified the following general failure types that precede accidents:

- hardware defects (e.g. poorly designed intersections, unsafe car designs);
- incompatible goals (speed limits increase safety but incur a loss of time);
- poor operating procedures (poor or illogical traffic regulations, e.g. on roundabouts);
- poor maintenance (roads in poor condition, street lights broken, too many defective cars);

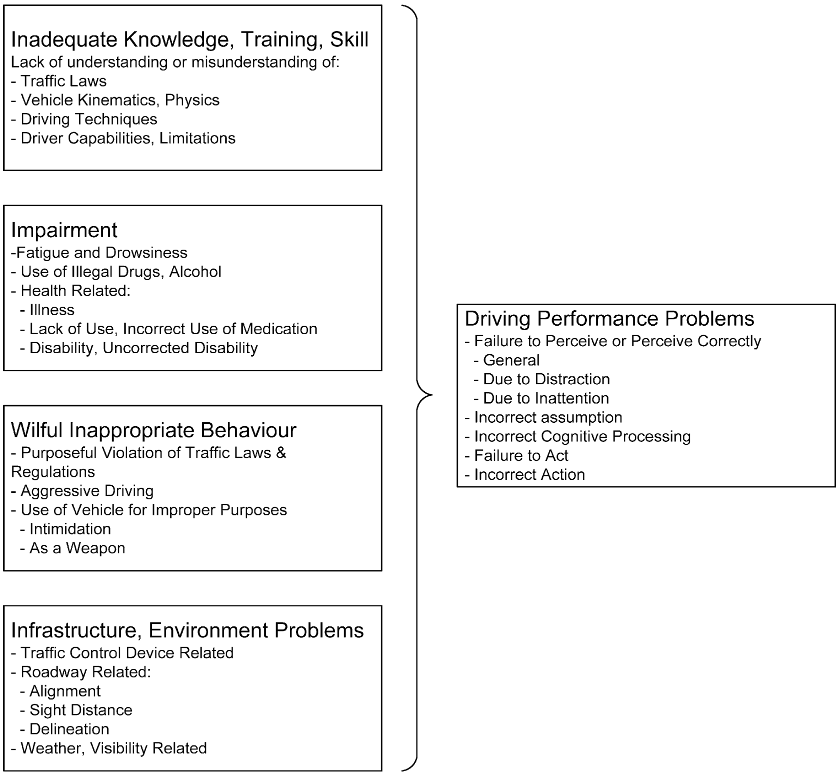

Fig. 3. Contributing factors taxonomy (source: Wierwille et al., 2002).

- inadequate training (many drivers too young, inadequate driver qualification testing);
- conditions promoting violations (unnecessary traffic lights, lack of police control, road repairs causing long delays, insufficient parking space); and
- lack of organisation (no systematic traffic policy, no systematic collection of accident statistics, no organised reaction to public complaints).

4. Discussion and proposed error taxonomy

It is highly likely that the types of driver errors described in this paper will continue to be observed in road traffic accidents and incidents. Some of these errors might impact upon new vehicle technologies at least for the driver of the host vehicle. To inform the design of future in-vehicle systems (such as intelligent transport systems) and investigation and analysis of human error within the road transport domain, taxonomies of driver errors and their causal factors are required. A driver error taxonomy could potentially be used to identify, a priori, driver errors and also to classify the errors involved in road transport accidents and incidents. A causal factors taxonomy could be used to inform the development of error management strategies and error countermeasures, and also to classify the causal factors involved in driver error-related incidents.

In order to develop a driver error taxonomy, the prominent human error taxonomies from the literature (described previously in sections two and three) were reviewed and those errors deemed applicable to driving were extracted. This process allowed us to generate a taxonomy of driver errors based on the current theoretical perspectives and research on human error. The driver error taxonomy is presented in Table 11. This includes each error type along with examples and their associated psychological mechanism. In addition, each errors origin in terms of the error taxonomy that they were extracted from (from Sections 2 and 3) is also presented (i.e. Tables 1–10).

As Table 11 shows, 24 driver errors were identified from the human error literature.

The same process was used in order to develop a taxonomy of driver error causal factors. Each causal factor taxonomy (described in section four) was reviewed and a synthesis of these causal factors was used to construct a driver error causal factors taxonomy. The taxonomy is presented in Table 12.

According to the taxonomy, inadequate conditions from each of the five categories of causal factors can potentially impact road user behaviour in a way that can potentially lead to road user errors being made. Each of the causal factors can be further decomposed to identify specific causal factors. For example, the causal factor 'Mechanical' can be decomposed into engine failure, brake failure, steering failure, signal failure or other vehicle failure. A summary of each causal factor group is presented below.

1. Road infrastructure – inadequate conditions residing within the road transport system infrastructure, including road layout (e.g. confusing layout), road furniture (e.g. misleading signage), road maintenance e.g. (poor road surface condition) and road traffic rules, policy and regulation related conditions (e.g. misleading or inappropriate rules and regulations).

Table 11
Generic driver error taxonomy with underlying psychological mechanisms

Underlying psychological mechanism	External error mode	Taxonomy source	Example
Action errors			
Action execution	Fail to act	Tables 1, 4, 2, 8, 10	Fail to check rear view mirror
Action execution	Wrong action	Tables 2, 4–6, 8, 9	Press accelerator instead of brake
Action execution	Action mistimed	Tables 1 and 2	Brake too early or too late
Action execution	Action too much	Tables 5 and 6	Press the accelerator too much
Action execution	Action too little	Table 5	Fail to press the accelerator enough
Action execution	Action incomplete	Table 1	Fail to turn the steering wheel enough
Action execution	Right action on wrong object	Tables 1 and 2	Press accelerator instead of brake
Action execution, planning, and intention	Inappropriate action	Tables 1, 2, 4–6, 8, 9	Following too close, race for gap, risky overtaking, etc.
Cognitive and decision-making errors			
Perception	Perceptual failure	Table 2	Fail to see pedestrian crossing
Perception	Wrong assumption	Table 2	Wrongly assume a vehicle will not enter path
Attention	Inattention	Tables 5, 6, 8, 9	Nearly hit car in front when queuing
Attention	Distraction	Tables 4, 5, 8, 9	Distracted by secondary task e.g. mobile phone conversation
Situation assessment	Misjudgment	Tables 1, 4–6, 8–10	e.g. misjudged speed of oncoming vehicle, misjudge speed and distance, misjudge gap
Perception	Looked but failed to see	Tables 6 and 9	Looked at road ahead but failed to see pedestrian
Observation errors			
Memory and recall	Failed to observe	Tables 1, 2, 4, 5, 8, 9	Failed to observe area in front of vehicle
Memory	Observation incomplete	Tables 4, 6, 10	Failed to observe offside mirror when changing lanes
Situation assessment	Right Observation on Wrong Object	Tables 4 and 10	Failed to observe appropriate area
Memory and recall	Observation Mistimed	Tables 1 and 2	Looked in drivers side mirror too late when changing lane
Information retrieval errors			
Situation assessment	Misread information	Table 10	Misread road sign, traffic control device or road markings
Situation assessment	Misunderstood information	Tables 1 and 10	Perceive information correctly but misunderstand it
Situation assessment	Information retrieval incomplete	Table 10	Only retrieved part of information required
Situation assessment	Wrong information retrieved	Table 10	Read wrong information from road sign
Violations			
Action execution, planning, and intention	Intentional violation	Tables 4, 6, 8, 10	Overtake on the inside, knowingly speed
Action execution	Unintentional violation	Tables 4, 6, 8, 10	Unknowingly speed

Table 12
Driver error causal factors

Causal factor group	Causal Factor	Source
Road infrastructure	Road layout	Tables 5, 9, Fig. 3
	Road furniture	Tables 5 and 9
	Road maintenance	Tables 5 and 9
	Road traffic rules, policy and Regulation	Fig. 3
Vehicle	Human machine interface	Table 5
	Mechanical	Table 5
	Capability	Table 5
	Inappropriate Technology Usage	Table 5
Driver	Physiological state	Tables 5 and 9, Fig. 3
	Mental state	Table 5
	Training and experience	Tables 5 and 9
	Knowledge, skills and attitudes	Fig. 3
	Context	Table 5
	Non-compliance	Fig. 3
Other road user	Other driver behaviour	Table 9
	Passenger influence	Table 5
	Pedestrian behaviour	Table 5
	Law enforcement	Table 5
	Other road user behaviour	Table 9
	Weather conditions	Tables 5 and 9, Fig. 3
Environmental conditions	Lighting Conditions	Table 5
	Time of day	Table 5
	Road surface conditions	Tables 5 and 9

2. Vehicle – inadequate conditions residing within the vehicles that are used within the road transport system, including human–machine interface (e.g. poor interface design), mechanical (e.g. brake failure), maintenance (e.g. lack of maintenance), and inappropriate technology-related conditions (e.g. mobile phone usage).
3. Road user – the condition of the road user involved, including road user physiological state (e.g. fatigued, incapacitated), mental state (e.g. overloaded, distracted), training (e.g. inadequate training), experience, knowledge, skills and abilities (e.g. inadequate skill), context-related (e.g. driver in a hurry) and non-compliance related conditions (e.g. unqualified driving).
4. Other road users – the contributing conditions caused by other road users, including other driver behaviour, passenger effects, pedestrian behaviour, law enforcement and other road user behaviour related conditions.
5. Environmental – the environmental conditions that might affect road user behaviour, including weather conditions, lighting conditions, time of day and road surface-related conditions.

It is intended that the taxonomies presented in Tables 11 and 12 are used to inform driver error data collection efforts. Further, it is recommended that the taxonomies be validated and refined through further study.

5. Technological solutions

There is great potential for driving technologies to be used to eradicate driver errors or to mitigate their consequences. For example, intelligent transport systems (ITS) such as route navigation systems, adaptive cruise control systems, and intelligent speed adaptation systems could all potentially be used to either reduce error occurrence by preventing a driver from performing an erroneous action, or mitigate the consequences associated with errors

Table 13
Potential technological solutions for driver errors

External error mode	Example	Intelligent transport system solution
Fail to act	Fail to check mirrors	Collision sensing and warning systems, pedestrian detection and warning systems
Wrong action	Press accelerator instead of brake	Intelligent speed adaptation systems, adaptive cruise control
Action mistimed	Brake too early or too late	Adaptive cruise control
Action too much	Press the accelerator too much	Intelligent speed adaptation systems, speed control systems
Action too little	Fail to press the accelerator enough	Adaptive cruise control
Action incomplete	Fail to turn the steering wheel enough	No solution
Right action on wrong object	Press accelerator instead of brake	Adaptive cruise control, collision sensing and warning systems, intelligent speed adaptation systems, speed control systems
Inappropriate action	Following too close, risky overtaking, etc.	Adaptive cruise control, auto-take systems
Perceptual failure	Fail to see pedestrian crossing	Collision sensing and warning systems, pedestrian detection and warning systems
Wrong assumption	Wrongly assume a vehicle will not enter path	Adaptive cruise control, collision sensing and warning systems
Inattention	Nearly hit car in front when queuing	Vigilance monitoring systems
Distraction	Distracted by secondary task e.g. mobile phone conversation	Collision warning systems, pedestrian detection and warning systems, intelligent speed adaptation
Misjudgment	e.g. misjudge speed and distance, misjudge gap	Adaptive cruise control, intelligent speed adaptation systems, speed control systems
Looked but failed to see	Looked at road ahead but failed to see pedestrian	Collision warning systems, pedestrian detection and warning systems
Failed to observe	Failed to observe area in front of vehicle	Collision sensing and warning systems, pedestrian detection and warning systems
Observation incomplete	Failed to observe offside mirror when changing lanes	Collision sensing and warning systems, pedestrian detection and warning systems
Right observation on wrong object	Failed to observe appropriate area	Collision sensing and warning systems, pedestrian detection and warning systems
Observation mistimed	Looked in drivers side mirror too late when changing lane	Collision sensing and warning systems, pedestrian detection and warning systems
Misread information	Misread road sign, traffic control device or road markings	In-car road sign presentation systems, route navigation systems
Misunderstood information	Perceive information correctly but misunderstand it	HUD/HDD depicting correct information and indicating potential hazards
Information retrieval incomplete	Only retrieved part of information required	In-car road sign presentation systems, route navigation systems
Wrong information retrieved	Read wrong information from road sign	In-car road sign presentation systems, route navigation systems
Intentional violation	Overtake on the inside, knowingly speed	Auto-take system
Unintentional violation	Unknowingly speeding	Intelligent speed adaptation systems, speed control systems

by increasing the tolerance of the vehicle to driver errors. For each of the errors presented in Table 11, a potential technological solution has been assigned in Table 13.

Further details of these technologies may be found in Stanton and Marsden (1996), Stanton et al. (1997), Stanton et al. (2001), Walker et al. (2001) and Salmon et al. (2007). A brief description of each technology referred to in Table 13 is offered below.

Vision enhancement: Examples of vision enhancement include the provision of an infrared camera with either head-up display or head-down display (HUD/HDD) to capture and present the road scene with greater contrast in scenarios with reduced visibility.

Pedestrian detection and warning systems: Detection of small slow moving soft objects with critical path projection and warns driver, helping the driver identify pedestrians that might be in their planned path.

Collision sensing and warning: Detection of other vehicles that are likely to cross the projected path of the host vehicle, with an associated warning.

HUD/HDD indicating potential hazards: A head-up display or head-down display that picks out potential hazards for the driver, such as pedestrians and/or other vehicles.

Adaptive cruise control: A system comprising microwave radar, sensor, distance control device for longitudinal vehicle control. Set speed of the vehicle is maintained until the leading vehicle is slower than the host, at which point the host vehicle maintains a safe gap by reducing speed.

Speed control devices: Either speed limiters or set speed control, such as conventional cruise control or adaptive cruise control.

Intelligent speed adaptation systems: Warns the driver when driving in excess of the current speed limit. Also informs the driver of current speed limit. Limiting systems are also available which prevent the speed limit from being exceeded.

In-Car road sign presentation systems: Presents proximal road signs within the vehicle based on GPS route navigation system information.

Auto-take system: An automated overtaking system that uses sensors to detect a gap in the traffic and executes the overtaking manoeuvre without intervention from the driver. Various levels of automation may be envisaged, at the lowest level the system could advise the driver that there is sufficient space for a manual overtake, at a mid-level the system could propose an overtake which the driver could authorise, and at the highest level the system could overtake without reference to the driver.

Navigation system: A systems that can plan routes and navigate in real time so that the driver may be advised of when to join or leave roads in sufficient time to take the action safely.

Stop-and-start system: A further development of adaptive cruise control that enables the vehicle to stop and start automatically in queuing traffic.

Rear parking sensors: Warns driver when reversing of objects in close proximity to the vehicle. Camera-based systems allow the driver to see what is behind the vehicle.

Vigilance monitoring system: Monitors driver eyes off road time and warns the driver if his/her eyes are off the road for too long a duration.

The appropriateness of driver behaviour with advanced technologies will, in part, depend upon the design of the interface between the driver and the behaviour of the system. The driver is required to anticipate and predict the behaviour of the system. This will depend upon him or her developing an accurate mental representation and being aware of what the system is doing at any point in time. Woods et al. (1994) argue that avoidance of mode error and optimisation of situational awareness go hand-in-hand. They propose that design of automated systems should:

- eliminate unnecessary modes;
- provide clear indications of mode status;
- provide feedback about mode changes; and
- be tolerant of mode error if possible.

The design of an unambiguous interface that communicates the status of the system in a direct manner addresses the middle two points. As with pilot error, the challenge for the designers will be to introduce technologies that actually reduce driver error, without creating the possibility for new types of error.

6. Further research

It is clear that there is much further investigation is required surrounding the area of driver error within the road transport domain. The majority of complex safety critical systems (e.g. aviation, process control, etc.) use validated error and causal factor taxonomies to drive the investigation and analysis of human error, which in turn leads to the development of effective countermeasures. This article has made the first steps towards the development of a driver error taxonomy that can be used to investigate the construct within road transport systems.

In particular, study on the different kinds of errors made by drivers and other road users (e.g. pedestrians, bicyclists) and on their causal factors is required. Further, investigation into the implications that these driver errors have on both the design and integration of intelligent transport systems into future vehicles is required. It is our opinion that this research should initially take place in three main areas. Firstly, HEI techniques should be used to identify the likely errors that might arise when driving. Secondly, driving simulators should be used to further explore driver errors and for prototyping and analysis of emergency scenarios. Thirdly and finally, naturalistic on-road studies should be undertaken for confirmatory analysis. In addition, the natural collection of human error data within road transport systems through avenues such as accident reporting and investigation, close circuit television cameras and incident reporting schemes is encouraged. Once sufficient research has been conducted, it is recommended that a generic model of driver error be developed, detailing the different types of errors that drivers make, and the causal mechanisms (driver-based and systemic) involved in their occurrence.

The lack of appropriate error-data collection approaches within the road transport domain has previously been highlighted e.g. Salmon et al., 2006a. Salmon et al. (2006b) also describe the numerous problems associated with the accurate classification of driver error data which impact the validity of driver error study results. It is therefore recommended that investigation be made into the development and implementation of appropriate data collection procedures be investigated within road transport systems. Potential error data collection procedures include observational study, site-surveillance, in-car recording systems (e.g. DriveCam), Police accident reporting and investigation, driver incident reporting and analysis of insurance data.

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