

To err (on the road) is human? An on-road study of driver errors

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Abstract

Human error, its causes and consequences, and the ways in which it can be prevented, remain of great interest to road safety practitioners. This paper presents the findings derived from an on-road study of driver errors in which 25 participants drove a pre-determined route using MUARC's On-Road Test Vehicle (ORTeV). In-vehicle observers recorded the different errors made, and a range of other data was collected, including driver verbal protocols, forward, cockpit and driver video, and vehicle data (speed, braking, steering wheel angle, lane tracking etc). Participants also completed a post trial cognitive task analysis interview. The drivers tested made a range of different errors, with speeding violations, both intentional and unintentional, being the most common. Further more detailed analysis of a sub-set of specific error types indicates that driver errors have various causes, including failures in the wider road 'system' such as poor roadway design, infrastructure failures and unclear road rules. In closing, a range of potential error prevention strategies, including intelligent speed adaptation and road infrastructure design, are discussed.

Keywords

Human error, road safety, on-road study, cognitive task analysis, verbal protocol analysis.

Introduction

Estimates on the contribution of human error to road traffic accidents vary, but typically suggest that anywhere from 75% (Hankey et al, 1999; cited in [1]) to 90% [2] of all road traffic crashes involve some form of human error. Research into the concept has led to significant safety gains in a range of safety critical domains; however, despite receiving significant attention in road transport, similar safety gains have not yet been achieved through error-related applications [3].

Human error has been investigated in a range of contexts within road transport; for example, the nature and frequency of driver errors [e.g. 4], the errors and contributing factors involved in road traffic accidents [e.g. 2], the errors made by different driver groups [e.g. the elderly, 5], and driver error probabilities at intersections [e.g. 6] have all been explored. The majority of research has focussed on ascertaining the nature and frequency of driver errors through the application of the Driver Behaviour Questionnaire (DBQ) [4], which asks drivers to report the frequency with which they have previously made different errors while driving. Whilst this approach has its benefits, it leaves many questions unanswered in terms of the frequency of different error types being made, the system-wide causal factors involved in their occurrence, and also the consequences and error recovery strategies associated with them. The data is also subjective and so is affected by a range of issues associated with the collection of post task subjective data. Most of the other research described in the literature has focussed on identifying the different error types and system-wide contributory factors involved in road traffic accidents through retrospective crash data analysis, observational study and interviews [e.g. 2]. This has led to the development of various driver error and contributory condition taxonomies; however, universally accepted taxonomies of driver error and error causing conditions are yet to emerge, and most are beset by a lack of validation evidence.

Limitations in the methods used (e.g. questionnaire, retrospective accident analysis) to date to investigate human error in road transport have limited our understanding of the concept. An in-depth understanding of error, including its nature, the role of different error types in road traffic accidents, the role of wider systems failures in error causation, and the ways in which drivers mitigate the consequences of errors, is yet to be achieved. Further investigation in a road transport context is therefore required. Encouragingly,

in recent times the introduction of instrumented vehicles has pushed the boundaries in terms of the error-related data that can feasibly be collected. Instrumented vehicles now allow more accurate and unobtrusive collection of objective, real time data regarding driver errors, which allows their nature, causes and outcomes to be interrogated in more detail than through conventional approaches. This paper describes the findings derived from an on-road study of driver errors, which was conducted to investigate the different errors that drivers make during everyday driving, with a view to identifying and classifying the range of errors that drivers make.

Methodology

The methodology employed during the on-road study utilised a range of different approaches for collecting detailed data on driver performance and error. An overview of the methodology used is presented in Figure 1. A brief overview of the component methods used is given below. Since the Driver Behaviour Questionnaire [4] data are not reported in this paper, an overview of this method is not provided.

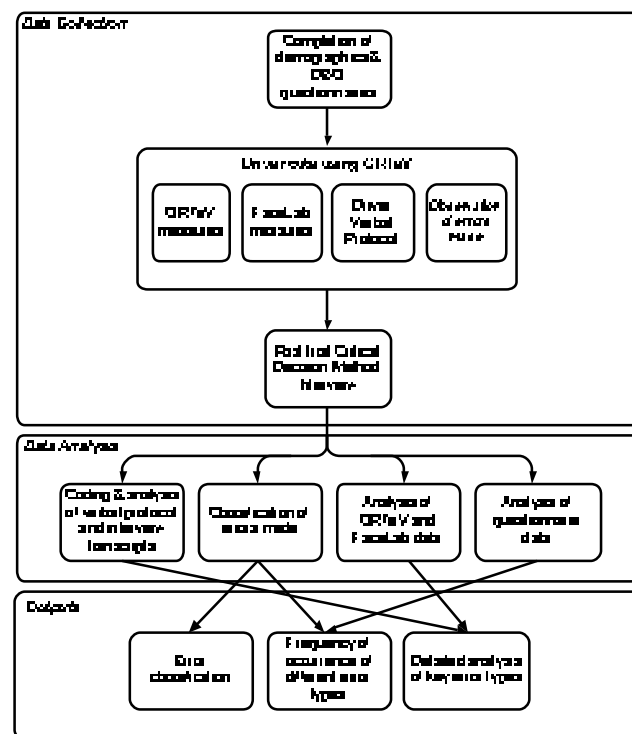


Figure 1. On-road study methodology.

On-Road Test Vehicle (ORTeV)

The MUARC ORTeV is a state-of-the-art instrumented vehicle for use in studies on driver behaviour. ORTeV has been equipped to collect data for both controlled and naturalistic studies and three main types of information can be continuously logged: vehicle-related data, driver-related physiological data, and eye tracking data. The vehicle data is acquired from the vehicle network and includes: vehicle speed, GPS location, accelerator and brake position (as well as vehicle lateral and longitudinal velocity and acceleration), steering wheel angle, lane tracking and headway logging, primary controls (windscreen wipers, turn indicators, headlights, etc.), and secondary controls (sat-nav system, entertainment system, HVAC, etc.). Driver eye movements can be tracked and overlaid on a driver's-eye camera view using the FaceLab eye tracking system. ORTeV is also equipped with seven unobtrusive cameras recording forward and peripheral views spanning 90° each respectively as well as three interior cameras and a rearward-looking camera. For the purposes of this study, vehicle-related data and eye tracking data were collected whilst drivers drove ORTeV around the pre-determined route.

Driver Verbal Protocols

Verbal Protocol Analysis (VPA), also commonly referred to as ‘think aloud’ protocol analysis, was used to elicit data regarding the cognitive and physical processes undertaken by drivers whilst driving the route. VPA is commonly used to investigate the cognitive processes associated with complex task performance and has been used to date to explore a range of concepts (e.g. situation awareness, decision making) in various domains, including road transport [7]. In the present study participants provided verbal protocols as they drove the instrumented vehicle around the route.

Critical Decision Method Interviews

Cognitive task analysis interviews were held post-drive with each participant using the Critical Decision Method (CDM) [8], which is a semi-structured interview approach that has previously been used to investigate cognition and decision-making in a range of domains, including road transport [9]. Each interview focussed specifically on one of the errors made by the participant during their drive and involved using a series of cognitive probes to interrogate the cognitive processes underlying participant decision-making and task performance surrounding the error. For this purpose a set of appropriate cognitive probes was adapted from the literature on previous CDM applications [e.g. 10-12]. The CDM probes used are presented in Table 1.

Table 1. CDM probes used during on-road study.

Goal Specification	What were you aiming to achieve during this activity?
Decisions	What decisions/actions did you make during the event?
Cue Identification	What information/features did you look for/use when you made your decisions?
Influencing Factors	What was the most important factor that influenced your decision making at this point?
Options	What other courses of action were available to you? Why was the chosen option selected?
Situation Awareness	What sources did you use to gather this information? What prior experience or training was helpful in making the decisions?
Situation Assessment	Did you use all of the information available to you when making decisions? Was there any other information that you could have used/would have been useful when making the decisions?
Information integration	What was the most important piece of information that you used to make your decisions?
Influence of uncertainty	At any stage, were you uncertain about the accuracy or relevance of the information that you were using?
Mental models	Did you run through in your head, the possible consequences of this decision/action?
Decision blocking - stress	At any stage during the decision making process did you find it difficult to understand and use the information? How much time pressure was involved in making the decisions/performing the task? How long did it take to make the decision? Did you, at any point, find it difficult to process and integrate the information?
Conceptual	Are there any situations in which your decisions/actions would have turned out differently?
Basis of choice	Do you think that you could develop a rule, based on your experience, which could assist another person to make the same decision/performing the same task successfully? Were you confident at the time that you were making the right decision/performing the appropriate actions?
Analogy/generalisation	If you could go back, would you do anything differently? If yes, what?
Interventions	Is there anything that you think could be done to prevent similar errors being made during similar situations?

Error classification

The errors observed during the on-road study were classified using the driver error taxonomy presented by Stanton and Salmon [3], which contains 22 error types grouped into the following categories of error: action errors, cognitive and decision making errors, observation errors, information retrieval errors, and violations). Two researchers independently classified the errors observed into error types using the taxonomy.

Participants

Twenty-five drivers (15 males, 10 females) aged 19-59 years (mean = 28.9, SD = 11.9) took part in the study. Nine participants held a valid Full license while the remaining sixteen held a valid Victorian Probationary (P2) license. Participants were recruited through the weekly on-line Monash University

newsletter and were compensated \$50 for their time. Prior to commencing the study ethics approval was formally granted by the Monash Human Ethics Committee.

Materials

Demographic and DBQ questionnaires were completed using pen and paper prior to the on-road study. A 21km urban route incorporating 26 intersections around the suburbs surrounding the Monash University Clayton Campus was used for the on-road study. For VPA practice and vehicle familiarisation purposes, the route used also incorporated a short practice route, which included 4 intersections. Participants drove the route using ORTeV (Holden Commodore), which utilised a range of data collection equipment including the FaceLab eye tracker system and the SceneCam video recording system (see ORTeV description above). A Dictaphone was used to record participant verbal transcripts during the drive, and the post drive CDM interviews. In-vehicle observers used pen and an error pro-forma to record the errors made during the drive. A series of cognitive probes (see Table 1) were used by the interviewer during the CDM interview, and participant responses were recorded on a CDM interview pro-forma.

Procedure

Upon completion of an informed consent form and demographic and DBQ questionnaires, participants were briefed on the research and its aims, and informed what was required of them during data collection. After a short training session on the VPA method, participants were taken to the ORTeV and told to set themselves in a comfortable driving position. Once comfortable, the FaceLab eye tracking system was calibrated with the participant and the ORTeV data collection systems were initiated. Two observers were present in the vehicle. Upon commencing the drive, participants completed a practice route and familiarised themselves with ORTeV and the VPA method. When the end of the practice route was reached, participants were informed that the test had begun and that data collection had now commenced. On-route, the observer located in the front passenger seat provided directions, and a Dictaphone was used to record the driver verbal protocols. Both observers recorded all errors that they observed throughout the drive, including the error, where on the route the error occurred, the time of occurrence, the context in which it occurred, and what the outcomes were. Upon completion of the drive, the two observers and checked for agreement on the errors recorded and for any errors missed. They then selected an appropriate error for further analysis through CDM interview. The participant was then interviewed using the CDM probes. The CDM interview was recorded using a Dictaphone, and the interviewer also took written notes using a CDM interview pro-forma. The errors recorded during the on-road study component were classified independently by two researchers using a taxonomy of error types [3]. For the errors subject to CDM interview, data of interest (e.g. FaceLab, speed, braking, lateral vehicle position, video data) was extracted from ORTeV to enable more detailed analysis.

Results

Classification of errors

A total of 298 errors were made by participants during the on-road study, with participants on average making 11.92 errors per drive. The 298 errors were categorised into 39 specific error types. A breakdown of these is presented in Table 2, including the frequency with which each error was made during the study.

Various errors were observed on multiple occasions. The most common error observed was speeding violations, with 95 instances of participants exceeding the speed limit observed. The next most common was entering the wrong lane after turning at an intersection, which was observed 49 times. There were 25 instances of participants failing to activate the indicators before a turn, and participants also activated the indicators too early on 15 occasions. Travelling too fast for a particular turn was observed 14 times, followed by braking hard and late, which was observed 13 times. Instances of participants accelerating too quickly away from an intersection were observed on 12 occasions, as were instances of poor lane keeping. Giving way unnecessarily, running a red light, and activating the wind screen wipers instead of the indicator occurred 4 times, and attempting to make an incorrect turn occurred 3 times.

Table 2. Different error types made by drivers during on-road study

Error	No. of errors	%	Error	No. of errors	%
Speeding	95	31.88	Mounted kerb	2	0.67
Entering the wrong lane after turn	49	16.44	Selected unsafe gap when turning right at intersection	2	0.67
Failing to indicate	25	8.39	Stopped in a keep clear zone	2	0.67
Activating indicator too early	15	5.03	Approaching intersection too fast	1	0.34
Traveling too fast for turn	14	4.70	Blocked pedestrian crossing	1	0.34
Braking late and hard	13	4.36	Failed to give-way to pedestrian on crossing	1	0.34
Accelerating too fast	12	4.03	Failed to see lead car braking	1	0.34
Lane excursion/poor lane keeping	12	4.03	Failed to select safe gap when turning	1	0.34
Activating indicator too late	8	2.68	Got into turn lane late	1	0.34
Gave way unnecessarily	4	1.34	Indicated right instead of left and vice versa	1	0.34
Ran red light	4	1.34	Indicated twice to change lanes	1	0.34
Activated wipers instead of indicator	4	1.34	Delayed movement away from traffic lights	1	0.34
Attempted to make an incorrect turn	3	1.01	Missed/misinterpreted direction instructions	1	0.34
Didn't see vehicle in adjacent lane (but checked)	3	1.01	Mistakenly thought cars were parked on road	1	0.34
Failed to make turn	3	1.01	Overshot stop line	1	0.34
Tailgating	3	1.01	Hit object on road (e.g. bird)	1	0.34
Delayed recognition of green traffic light	3	1.01	Tried to merge when no clear gap	1	0.34
Blocking intersection due to there not being enough room to complete turn	2	0.67	Uneven speed	1	0.34
Changed lane within intersection	2	0.67	Waited until last minute to get into correct lane for turning	1	0.34
Failed to notice indicator had turned off	2	0.67			
			TOTAL	298	100
			Average no. of errors per driver	11.92	

External error mode classification

The errors made during the on-road study were independently classified into external error modes by two researchers using the error taxonomy presented by Stanton and Salmon [3]. This involved taking the error descriptions recorded during the on-road study and classifying them into an error type from the taxonomy using expert judgement. Based on a comparison of both analysts' classifications, there was agreement on 90% (267 out of 298) of the error classifications. The outstanding error classifications were resolved through further discussion and reclassification if necessary. Figure 3 presents a breakdown of the different error types identified.

Violations (e.g., breaking road rules such as speeding, etc) were the most common error type, with a total of 95 identified. Following this, there were 77 'fail to act' errors (e.g., fail to indicate, changing lanes without indicating after turn), 44 misjudgements (e.g., misjudging braking requirements or a gap in the traffic), 23 instances where the driver mistimed an action (e.g., activated the indicator too early), and 20 instances where the driver performed an action 'too much' (e.g., too much acceleration). There were 9 perceptual failures (e.g., failure to see pedestrian), 6 instances where the driver made an action that was inappropriate (e.g., tailgating) and 7 instances where the driver failed to observe something in the roadway (e.g., fail to observe vehicle). Other errors identified included 2 'right action on wrong object' errors (e.g., activating windscreen wipers instead of indicators), 3 instances of inattention (e.g., failing to see traffic lights change to green) and 3 'wrong assumption' errors (e.g., wrongly assuming the speed limit is 50km/h when it is in fact 60km/h).

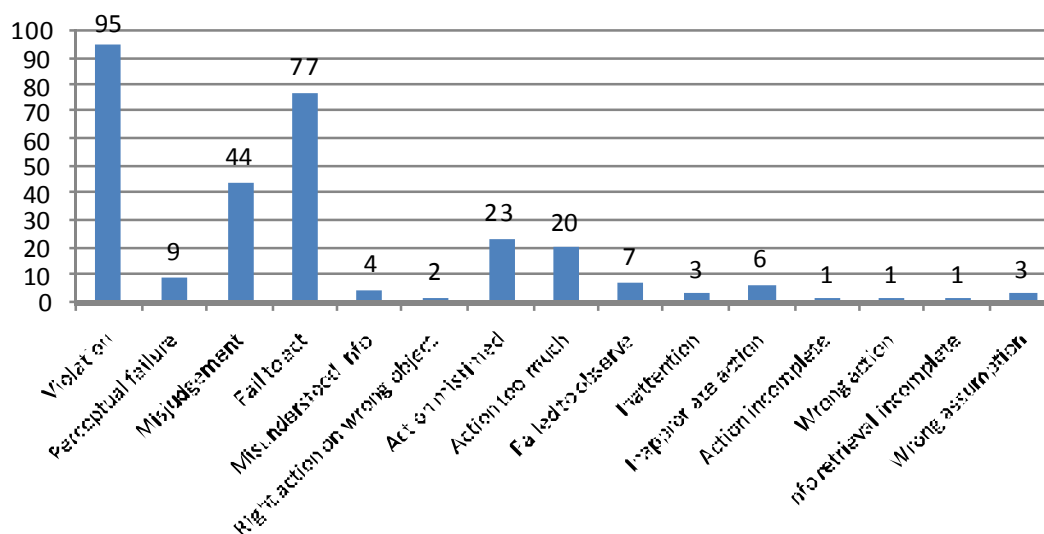


Figure 3. Frequency of different error types made during on-road study.

In-depth analysis of errors

For each participant, one of the errors made during the on-road study was selected for further analysis post drive through CDM interview. The purpose of this was to exhaustively analyse the error using a range of additional data sources (e.g. CDM interview, on-road test vehicle, eye tracker, verbal transcripts, error classification). This process led to detailed data being collected for 25 specific errors (1 from each participant). These errors were then analysed in-depth, using the range of data sources available. To demonstrate, a detailed analysis of two of the speeding violations identified is presented below.

Speeding unintentionally versus speeding intentionally

Two of the errors subjected to more detailed analysis (hereafter referred to as errors 1 and 2) both represented instances where the driver was speeding along a 50km/h road and were thus classified as ‘violation’ type errors. Further analysis of each error using all of the data sources available, however, suggests that both violations were very different, with the first (error 1) representing an ‘unintentional violation’ whereby the driver was unintentionally exceeding the speed limit, and the second (error 2) representing an ‘intentional violation’, whereby the driver was intentionally exceeding the speed limit.

Error 1 occurred when the driver drove at 60km/h in a 50km/h zone. The error was classified as a ‘violation’ type error. The following verbal transcript surrounding the error was extracted from the VPA data: “I didn’t see a speed sign so I’ll just go 60.” A graph showing the speed, brake, throttle and steering profiles for the duration of the road on which the speeding event occurred is presented in Figure 4. As represented in Figure 4, the driver reaches speeds of up to 60km/h whilst travelling along the 50km/h limit road.

The ORTeV speed profile confirms that the driver was speeding, showing that the vehicle was travelling up to 60km/h along the 50km/h limit road. The VPA and CDM data indicates that the driver missed the speed limit sign and then made a judgement that the speed limit was 60km/h based on the characteristics of the road. The speeding violation can therefore be classified further as an ‘unintentional violation’, since the driver believed that the speed limit was 60km/h rather than 50km/h. The ORTeV video and Facelab data gives insight into why the driver missed the 50km/h speed limit sign. Figure 5 clearly shows on the gaze Y profile a glance to the left made by the driver to check for the rear view mirror for traffic merging. The data therefore indicate that the driver was unintentionally speeding having missed the speed limit sign due to checking for merging traffic after negotiating a turn into the roadway.

Error 2 occurred when the driver also drove at 60km/h in a 50km/h zone (on the same road as error 1). The error was classified as a ‘violation’ type error; however further analysis allows it to be further classified as an ‘intentional violation’ type error. A graph showing the speed, brake, throttle and steering profiles for the duration of the road on which the speeding event occurred is presented in Figure 7. As

represented in Figure 7, the driver reaches speeds of above 55km/h whilst travelling along the 50km/h limit road.

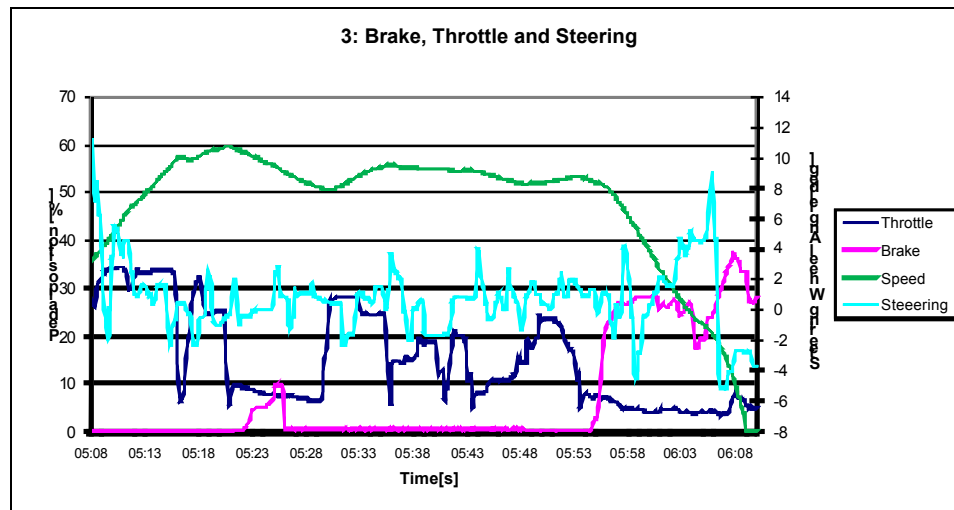


Figure 4. Graph showing speed, brake, throttle and steering profiles during speeding event. Note: the figure depicts the entire length of the road in question, which has a 50 km/h speed limit.

Figure 5 shows the driver's head rotation, gaze and the lateral position of the vehicle during the speeding violation event.

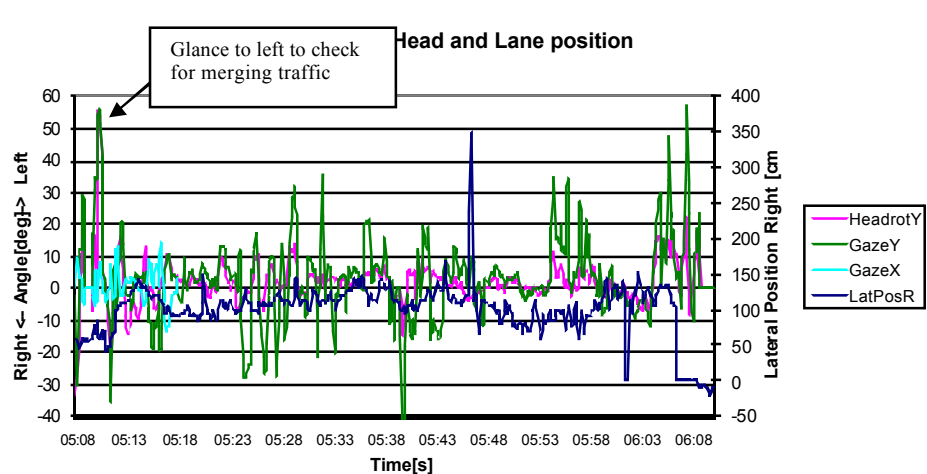


Figure 5. Graph showing participant's head rotation, gaze and the lateral position of the vehicle during speeding violation event.



Figure 6. Participant passing 50 km/h speed limit sign (yellow circle).

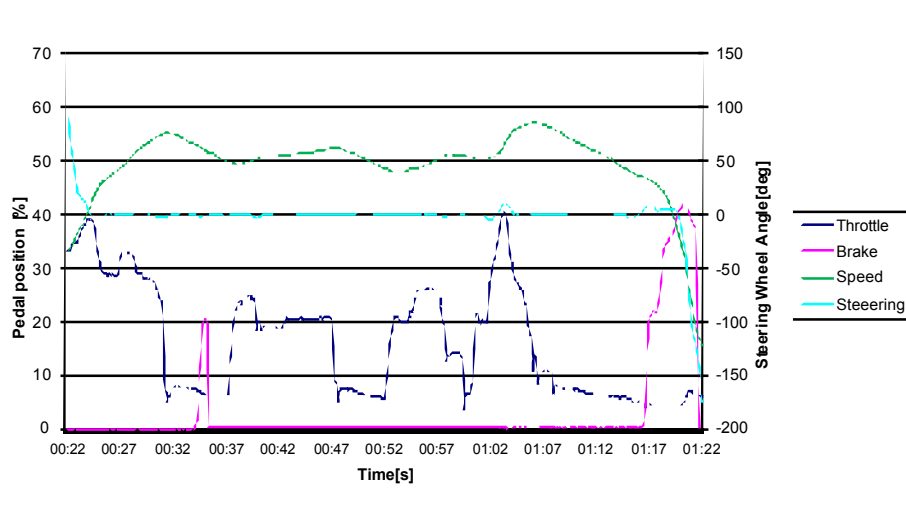


Figure 7. Speed, braking, steering and throttle profiles during Participant 4's error event. Note: the figure depicts the entire length of Gardiner Rd, which has a 50 km/h speed limit.



Figure 8. Participant passing 50 km/h speed limit sign (yellow circle).

The still images from the ORTeV cameras are presented in Figure 8. These clearly show that the driver did not glance at the 50 km/h speed limit sign. The ORTeV data shows that the vehicle was travelling in excess of the speed limit. The CDM data indicates that the driver knew that the speed limit was 50km/h, but that he felt that he knew the road well enough to travel in excess of the speed limit without there being any hazard. The following extracts from the CDM transcript reflect this:

"I noticed that speed limit was 50, and I know its 50 because I drive down that road everyday. So there were two points where I know I was speeding, so I had to slow down a bit. Mostly no more the 10km/h over, so about 60, but the cars ahead were going a bit more which may have contributed, because it is always a desire to keep up with the cars in front. I'm quite familiar with road and there was no one turning onto road."

"Turned onto road, knew it was 50, saw sign, felt comfortable travelling at 60, I know the road and that time of day it's not much of a hazard. So I think it was more me paying attention to what speed the other cars were doing, rather than what speed my speedo was doing."

The driver also reported that if he thought he would get caught speeding, he would stick to the speed limit, but in this case he knew based on his experience of driving on the road in question that there would not be speed cameras.

Discussion

The main aim of this study was to investigate the nature and frequency of the errors made by drivers during everyday driving. The 25 participants tested made a total of 298 errors during the on-road study and on average made almost 12 errors per drive. Within these errors, 39 different errors were identified. The most common error made was speeding violations in which participants either intentionally or unintentionally exceeded the speed limit. These represented almost a third of all of the errors made by participants. The next most common error was entering the wrong lane after turn (16.44% of all errors made), followed by failing to indicate when changing lane or indicating (8.39%), activating the indicator too early (5.03%) and travelling too fast for a turn (4.70%). The errors made were also compared across the participants who held a full driving licence and those who held a Victorian probationary (P2) licence. For the 5 most common errors, it was found that full driving licence holders made more of the speeding violations (59 compared to 36), turn into wrong lane errors (28 compared to 21), travelling too fast for a turn errors (10 compared to 4), failure to indicate (13 compared to 12) and indicating too early (9 compared to 6) errors than probationary licence holders did during the study.

Stanton and Salmon's [3] driver error taxonomy was used to further classify the errors made during the on-road study. From this it is concluded that the majority of the errors made by participants were violations (95), followed by fail to act errors (77), misjudgements (44), mistimed action errors (23) and action too much errors (20). Further, 9 perceptual failures were identified, followed by 6 inappropriate actions, and 7 fail to observe errors. Other errors identified included 2 'right action on wrong object' errors (e.g. activating windscreen wipers instead of indicators), 3 instances of inattention (e.g. failing to see traffic lights change to green) and 3 'wrong assumption' errors (e.g. wrongly assuming the speed limit is 50km/h when it is in fact 60km/h).

25 errors were analysed further using the additional data collected (e.g. CDM interview, on-road test vehicle, eye tracker, verbal transcripts). This analysis allowed the 25 errors to be interrogated in much more detail, and was used to demonstrate the utility of using instrumented vehicles, VPA and cognitive task analysis in the study of driver errors. Although this paper only presented 2 of the errors analysed further, evidence from the overall analysis suggests that the use of additional data collection methods (e.g. VPA, CDM) and the ORTeV allow driver errors to be analysed more exhaustively than merely classifying them into error types. For example, speeding errors, initially classified as 'violation' type errors, can be further classified as either unintentional or intentional violations based on interrogation of the CDM, VPA and ORTeV data. Without this additional data, there is no way of knowing whether the speeding was undertaken intentionally or unintentionally. Of further relevance is the ability, when present, to identify road transport system failures that played a role in the error being made. Using the speeding violations presented in this paper as an example, the additional data indicates that, for error 1, the participant was unaware of the current speed limit having missed the speed limit sign due to checking

for vehicles merging and mistakenly assumed that the speed limit was 60km/h rather than 50km/h based on the road characteristics. The placement of the speed limit sign adjacent to the area of the road where two lanes merge into one, which places an already high visual load on the driver, is therefore questionable. Further, other instances where failures in the wider road transport system, such as unclear rules and regulations or inappropriate or poor road and infrastructure design contributed to the errors being made were identified through the additional analysis. The important role of the overall road transport 'system' in error prevention is therefore highlighted by this study.

From a theoretical viewpoint, the findings from this study lead these authors to question the use of the term 'driver error'. Although based on a small sample of drivers, evidence was found for the role of road system failures in the errors made by participants. Although further research is required focussing on how different failures across the road transport system influence driver behaviour in a way that errors are made, it is these authors' opinion that this research negates use of the term 'driver error'; although ultimately the errors are made through the physical and mental activities of the driver, other factors outside of the individual may often have a role in causing them. The role of system failures in human error causation is also well known and accepted across most safety critical domains. It is these authors' opinion therefore that, for future research and road safety efforts, the term driver error be replaced with a more appropriate term, such as 'driving error' or 'road system error'.

Error prevention strategies have had significant success in a range of safety critical domains [e.g. 13]. Although caution is urged since this study used such a small sample of drivers, based on the prevalent error types identified in the present study, it is possible to discuss potential strategies for eradicating them. First and foremost, however, it is worth noting that a systems approach to error prevention is supported by this research. As pointed out by Reason (1997), error prevention strategies focussed on individual operators often ignore problems across the wider organisational system. Any future driving error prevention strategies should therefore be developed using a systems approach. For example, for speeding violations, error prevention strategies should focus on both the driver (e.g. intelligent speed adaptation systems) and problems across the wider road system (e.g. appropriate placement of speed signage, clear rules regarding speed limits on different road types, improved enforcement of speed limits). Based on the prevalent error types identified in the present study, it is possible to discuss potential strategies for eradicating them, including the use of in-vehicle technologies and improved road system design. Given the high incidence of speeding violations, speed countermeasures will form a major component of any driver error prevention strategy. One promising approach for reducing excessive and inappropriate speeds is the use of Advanced Driver Assistance Systems (ADAS), namely Intelligent Speed Adaptation, which is a generic term for a class of ADAS in which the driver is warned and/or vehicle speed is automatically limited when the driver is, intentionally or inadvertently, travelling over the posted speed limit. The key role of road system design in error prevention was also highlighted through this study. Within the wider human error literature, it is widely acknowledged that system failures, including inappropriate design and rules and regulations, play a significant role in error occurrence [e.g. 4, 14]. Further analysis of a sub-set of errors in the present study found instances where inappropriate design of the road transport system or unclear road rules and regulations influenced driver behaviour in a way that facilitated errors being made. It is therefore critical that road system design is included as part of any driver error prevention strategy. Considering error potential during the design of road transport systems and artefacts can be achieved in many ways, including through the use of human error identification methods to predict design-induced errors during the road system design process. This has been proven to be a valid approach for identifying design induced errors in a range of domains [e.g. aviation; 15]; however it has only received limited attention to date in a road transport context. Identifying driver errors, their causal factors and their consequences, a priori, will allow countermeasures to be implemented in a pro-active manner. Such approaches can be applied through the design lifecycle of road infrastructure, furniture and road user technologies (e.g. Intelligent transport systems) to identify errors and refine designs before they become operational. Further, the use of error-based audit tools to identify the error causing conditions present within existing road systems (e.g. intersections) could be used to remove them. Reason [16], for example describes various audit tools used in other safety critical domains (e.g. rail, oil exploration) that are used to identify error-causing conditions within systems.

Finally, the importance of enhanced error data collection in error prevention efforts is once more highlighted through this study. One of the main problems associated with developing an understanding of error and its causes and developing appropriate strategies to tackle it within road transport is the paucity

of error data available. For example, research has highlighted the lack of data available for supporting valid identification of the role of, and interaction between, driver error and road transport system error causing conditions in road traffic accidents [e.g. 17]. For informed error prevention strategies, improved data collection and analysis systems are required to enhance knowledge on the role of errors and error causing conditions in the long term. For example, structured, theoretically underpinned systems-based accident analysis and investigation is a proven safety enhancing method in most safety critical domains; however, there are no such approaches used in road transport [17]. Whilst studies such as the present one are useful in providing a snapshot of the errors made by a particular sub-set of drivers, development and implementation of more exhaustive crash data collection and analysis systems is required to enable enhanced knowledge on error and its causes and the development of appropriate error prevention strategies.

Conclusion

Using a novel approach to the study of driver behaviour and error this research has shown that drivers most commonly made errors related to speeding (violation), changing lanes without indicating immediately after turning (fail to act), failing to indicate (fail to act) or indicating too early (action mistimed) and travelling too fast for a turn (misjudgement). While this research has provided unique insight into the error types observed in real-world driving conditions, more importantly, it provides great insight into the wider systemic factors involved in shaping driver behaviour and contributing to driver error. For example, a number of instances where road design was deemed to contribute to the errors made were revealed. These included speed signs being placed at merge locations leading drivers to miss the speed sign and consequently exceed the speed limit, pedestrian crossings being placed at high workload segments of the roadway such as slip lanes, and high traffic intersections not being fully signalised leading to conflicts with other vehicles and pedestrians when turning. It was also found that a number of the errors made, particularly those associated with failing to indicate, were caused by driver confusion over the road rules and whether they were required to indicate in certain circumstances, such as when changing lanes immediately after turning. The data also provide insight into the cognitive processes contributing to errors, such as drivers being distracted or inattentive and misjudging stopping distances or failing to make a turn at an intersection, and drivers making incorrect assumptions about other road users' behaviour leading to potential conflicts.

Having demonstrated the richness that this multi-method framework approach provides, it is now possible to explore more specific issues in more detail. For example, the influence of type of lane markings, signage, road designs, lane merges, traffic signal control, and so on, would all be well suited to this form of examination. Other behavioural and perceptual issues including intentional and unintended speeding, distraction arising from in-vehicle and external sources (i.e., visual clutter) would benefit greatly from this form of analysis. While traffic engineering approaches can often be used to manage the consequences of driver error, such as wire-rope barriers to prevent run-off-road crashes, these engineering solutions are not always possible. Understanding the role of road design and operation in shaping driver behaviour and errors could lead to improvements in those areas that reduce the incidence of the errors occurring in the first instance.

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