ERGONOMICS, 2003, VOL. 46, NO. 12, 1111–1135

Behavioural accident avoidance science: understanding response in collision incipient conditions

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Keywords: Avoidance response; Behavioural evaluation; Driver capability.

Road traffic accidents are the single greatest cause of fatality in the workplace and the primary cause of all accidental death in the US to the age of 78. However, behavioural analysis of response in the final seconds and milliseconds before collision has been a most difficult proposition since the quantitative recording of such events has largely been beyond cost feasibility for road transportation. Here, a new and innovative research strategy is reported that permits just such a form of investigation to be conducted in a safe and effective manner. Specifically, a linked simulation environment has been constructed in which drivers are physically located in two adjacent, full-vehicle simulators acting within a shared single virtual driving world. As reported here for the first time, this innovative technology creates situations that provide avoidance responses paralleling those observed in real-world conditions. Within this shared virtual world 46 participants (25 female, 21 male) were tested who met in two ambiguous traffic situations: an intersection and a hill scenario. At the intersection the two drivers approached each other at an angle of 135° and buildings placed at the intersection blocked the view of both drivers from early detection of the opposing vehicle. The second condition represented a 'wrong' way conflict. Each driver proceeded along a three-lane highway from opposite directions. A hill impeded the oncoming view of each driver who only saw the conflicting vehicle briefly as it crested the brow of the hill. Driver avoidance responses of steering wheel, brake, and accelerator activation were recorded to the nearest millisecond. Qualitative results were obtained through a post-experience questionnaire in which participants were asked about their driving habits, simulator experience and their particular response to the experimental events which they had encountered. The results indicated that: (1) situations have been created which provided avoidance responses as they have been recorded in real-world circumstances, (2) the recorded avoidance responses depended directly upon viewing times, and (3) the very short viewing times in this experiment resulted in a single avoidance action, largely represented by a random choice of swerve to either right or left. The present results lead us to posit that in order to be able to design accident avoidance mechanism that respond appropriately in the diverse situations encountered, there is a need to pay particular attention to mutual viewing times for drivers. The general implications for a behavioural science of collision-avoidance are evaluated in light of the present findings.

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/journals
DOI: 10.1080/0014013031000136386

1. Introduction

The greatest single cause of fatality in the workplace is road traffic accidents. This startling fact is masked by two fundamental but obscuring issues. First, the workplace is traditionally considered to be a static location and so accidents which occur in vehicles in diverse locations are often excluded from the figures concerning workplace injury. Second, transportation accidents are themselves considered a single epidemiological category and so the traffic injuries associated with work are included in the general count of all road traffic crashes. The result of this form of categorization is that vehicle injuries are frequently overlooked or even excluded in the examination of the hazards of working life. Ergonomists work very hard to improve workplace safety and while we especially respect the achievements of allied researchers involved in traffic safety we believe that a fruitful marriage can be made between ergonomic knowledge and the problems posed by traffic accidents. It is this overarching theme that motivates our work.

The present traffic safety community labours against a particularly insidious problem, which is that road traffic accidents are often considered by the public as somehow pre-destined. This popular fatalism is especially evident after high-profile accidents. For example, although the fund established in the name of Princess Diana provides millions of pounds to support efforts in areas as safety critical as land-mine decommissioning, it directs no substantive funds toward road accident reduction, the cause of her death. In his book debunking various conspiracy theories, Gregory (1999) expresses this attitude clearly in noting 'in the shock of Diana's death, many had sought to impose a kind of romantic unity on her senseless end, speculating on a marriage which would lend an air of classical tragedy to what was *a thoroughly ordinary death in an avoidable car crash*.' (p. 125), (italics added). Indeed, such fatalism is reflected also in the fact that the vast majority of safety resources which to date have been directed to the accident question have focused overwhelmingly on crash survival. We are second to none in our admiration of those who have made crucial advances in air bag, crush zone, and restraint technology, they have assuredly saved many thousands of lives. However, it is almost as if collision were a given and the primary safety mandate is the protection of those already involved in such untoward events.

We believe this emphasis needs to be changed and that a formal science of *behavioural accident avoidance* should be established which draws heavily upon the armory of knowledge and tools possessed by those in Ergonomics research. We claim no unique precedent in this establishment and indeed point to the fast growing technical developments of collision-warning and collision-avoidance technologies of Intelligent Transportation Systems (ITS) as evidence of such burgeoning concern. The human-centred approach is clearly one in which Ergonomists provide the lead. Thus, when the vehicle is the workstation, there is a crucial role for those in both physical and cognitive ergonomics in the battle against this silent but most deadly of occupational hazards. Further, we see this marriage as one that benefits both traffic safety and ergonomics since the fundamental issues of human error and response limitation are a strong mutual concern of each (see Hancock 2003). The field of behavioural accident avoidance has only recently become open to empirical investigation through technical innovations in linked simulation and it is this approach we have helped pioneer to produce the results first reported in this work. As a first step, we address the larger picture of accident occurrence as found in major epidemiological accident databases.

1.1. *Accident information*

While the number of motor vehicle collisions relative to the number of vehicles on the road has diminished, the increase in the absolute number of collisions and thus the total number of people killed and injured indicates the persistent and destructive global impact that motor-vehicle accidents have. In 1998, in the USA alone, there were over 6.3 million police reported traffic crashes. Over 37 000 people lost their lives and 4.3 million people were injured. More than four million collisions involved property damage only and it is reasonable to assume that there were many more collisions of lesser severity that went unreported to any database. Our efforts here are initially most relevant to multiple vehicle collisions and in 1998, there were 16 184 such fatalities. Of these 46.3% (7489) occurred with vehicles approaching at an angle, 32.4% (5243) occurred in a head-on configuration, 11.7% (1896) were rear-end collisions and 3.7% (599), were side-on collisions. This national pattern is also reflected in crash statistics for the State of Minnesota. In 1998, Minnesota reported 92 926 traffic crashes in which 650 people lost their lives and 45 115 were injured. In crashes of known configuration, 81.7% (51 820) involved multiple vehicles in which both were in motion.

One level of clarification of these findings can be found by examining reported vehicle tracks prior to collision. These data are derived from diagrams in police reports and are presented in table 1. In examining the adjusted crash figures, we find that the top three categories each involve multiple vehicle configurations. These include; rear-end collisions, left-turns against on-coming traffic and right-angle crashes (and see Hancock *et al*. 1988, 1991, Caird and Hancock 2002). Each of these is particularly relevant to the form of investigation considered in the present experimental procedure. Thus, crash data confirm that inter-vehicle collision is a crucial concern and one that addresses the majority of crashes including fatality and major injury (see also Treat 1980). These collective findings confirm the societal damage, including occupational injury and death, resulting from road traffic

Table 1. Crash involvement illustrated by police diagrams. Data from Minnesota Accident Facts 1998.

Manoeuvre	Reported	Percentage	Adjusted	Percentage
Rear end	20 143	21.7	20 143	21.7
Right angle	17 363	18.7	8682	9.3
Ran off road-right	6703	7.2	6703	7.2
Sideswipe passing	5370	5.8	5370	5.8
Ran off road-left	4918	5.3	4918	5.3
Left turn-oncoming traffic	4537	4.9	13 218	14.2
Head on	2516	2.7	2516	2.7
Sideswipe opposing	1381	1.5	1381	1.5
Right turn-cross traffic	510	0.5	510	0.5
Other/unknown	29 485	31.7	29 485	31.7

In the original reported data, as given in the first column, the 'right angle' category is the second largest. This is reported, however, as a significant error. Traffic engineers have measured the 'true' number of right angle accidents to be half the number the police reports. Crashes that are coded as 'right angle' are often 'left turn into oncoming traffic.' The adjusted numbers take this into account. The large number in the category 'unknown' accounts for the fact that in many cases the diagram is left blank. (See also, Minnesota Department of Public Safety, 1999, Table 1.23).

accidents. Further, such data show the relevance of our particular concern for injury and fatality reduction. In this sense, the epidemiological data serve to focus and direct our efforts.

1.2. *Accident evaluation*

Accidents are examined by many different disciplines at many different levels. We have illustrated this in figure 1 with a Cartesian coordinate system using the axes of space and time of progressively increasing magnitude. For example, the epidemiological perspective we have initially employed examines accident patterns on a very large scale. Typically, databases are generated at the State and Federal level and are compiled yearly, thus integrating information over large spatial and temporal ranges. As we have shown, such information helps us to frame National policy and show general areas in which to focus more specific research, e.g., the problems experienced by very young and older drivers as shown by classic ‘bath-tub’ curve (Dewar 2002). At the other end of the scale we have mechanical engineers involved with crash severity mitigation technologies such as ‘crush zones’ ‘airbags’ and similar developments. The window on the accident process for these engineers is framed in terms of milliseconds and centimeters since this is the ‘scale’ of their phenomena of interest. In the growth of any one area of research, scientists endeavour to expand

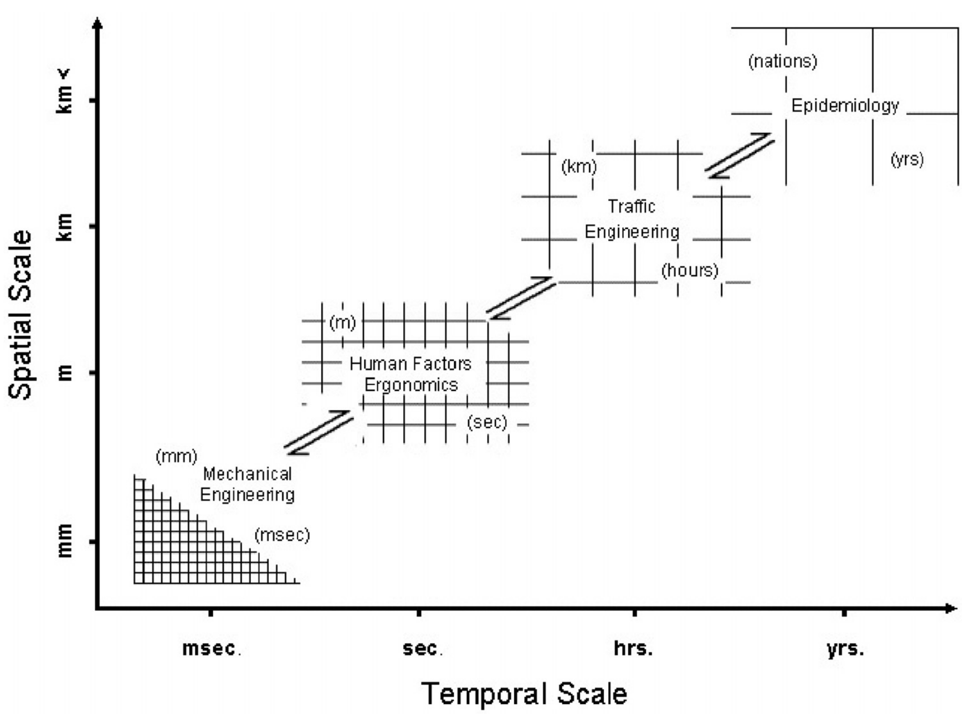

Figure 1. Spatio-temporal representation of the scales of action involved in accident research. At the largest scale, epidemiology identifies trends on a National basis at an annual rate. At the lowest extreme, crash mitigation technologies developed by mechanical engineers deal with millimeters and milliseconds. The present behavioural level analysis permits the investigation of accidents the human scale of seconds and metres.

their range of concern. For example, traffic engineers have traditionally constructed models of traffic flow to better help design and manage roadways. Often, such models focused upon freeway flow with 'node' points for every mile in the model. Today, such researchers are refining their spatial and temporal scales, advocating the addition of arterials and local streets and digitizing at the scale of yards while also significantly increasing the temporal frequency of their sampling. Thus, in the search for causation it is often the case that scientists appeal for explanation to other levels of spatio-temporal levels of analysis than their own.

To truly understand crash causation one has to integrate information from all levels of analysis. However, we suggest that it is most important to feature information from the behavioural level. We have to comprehend events over the ranges of metres and seconds, since these are the scales of immediate human perception (James 1890, Hancock and Chignell 1995). Until recently, quantitative information concerning behavioural response in accident events has been most difficult to collect since we cannot intentionally expose any individual to that level of danger. Subjective accounts of crashes are beset by the severe problems associated with recall memory. While some forms of reconstruction can inform us as to pre-collision physical manoeuvres, almost no technique can elucidate the human perceptual, cognitive, and motor responses that occur in the last fateful seconds before impact. Thus we affirm that the present experimental innovation provides a new 'window' on the accident process that we hope to exploit to provide new information on such crucial events in transportation and indeed other realms beyond.

1.3. *Investigative rationale*

In view of the above observations, there should be relatively few experimental research reports on driver performance in incipient crash circumstances and indeed this is the case. Beyond the vehicle trajectories and subjective report, it is immensely difficult to assemble this portrait of momentary driver response (Hancock and Scallen 1999). Most existing research has concentrated on who gets into dangerous or crash-likely situations (Hakinnen 1979, Summala 1987, 1996, Rothengatter 1997, Trimpop and Kirkcaldy 1997, Berthelon *et al.* 1998). However, evaluating and comprehending quantitative aspects of behavioural response in the vital milliseconds before collision has rarely been reported. Such research that does exist concentrates mainly on obstacle avoidance manoeuvrering where the obstacle put in the field of travel is 'controlled' in some preset fashion, (e.g., Barrett *et al.* 1968, Malaterre *et al.* 1988, Lerner *et al.* 1995). Whenever another vehicle was present it was controlled by the experimenter (Malaterre *et al.* 1988, Lechner and Malaterre 1991). Such approaches render very important data, however, they are limited in that they cannot ascertain and evaluate the reciprocal action between drivers who mutually adapt to the incipient demands.

There are other forms of investigation, which could inform us as to behaviour in collision-likely conditions. These can be divided into three basic categories. The first category focuses on time-to-contact, time-to-passage, and curve negotiation (see for example, Manser and Hancock 1996). The questions here concerns the nature of the information drivers use to determine 'safe' behaviour with respect to the constraints of the roadway and the actions of other drivers (Caird and Hancock 1994, Manser and Hancock 1996, Sidaway *et al.* 1996, Groeger 1999). The relationship to collision is an implicit one with the often unstated but pervasive expectation that poor time-to-contact performance will be correlated and/or causally linked with collision involvement. This is especially the case when drivers in the real-world are required to judge motion-in-depth, such as in the case for on-coming vehicles at left-turns. Evidence for such a correlational relationship is sparse and a causal relation in the real-world has still to be demonstrated. Nevertheless, the obvious fact that time-to-contact estimates and collisions are both intimately involved with navigating around complex, changing environments cannot be denied and it is upon this general basis at least, that such research is hopeful of adding to crash comprehension (see Hancock and Manser 1997). While time-to-contact research is providing an important theoretical foundation it does not represent the whole picture of collision avoidance.

The second relevant field of research that is directed to determining crash causation is epidemiology. As we noted, epidemiology seeks to understand what exogenous factors contribute to crash involvement, such as age, gender, etc. Endogenous factors such as cognitive and or visual impairments, attitudes or risk taking behaviour, reaction time, field dependence and close following behaviour are often inferred from epidemiological information (Babarik 1968, Heyes and Ashworth 1972, Elander *et al*. 1993, Shinar 1993, Summala 1996). While much undertsanding has been gleaned from this form of investigation (see Evans 1991), many causal mechanisms have yet to be clarified. It has been suggested and there is some evidence that variations in attention are related causally to accident involvement (Kahneman *et al*. 1973). However, as might be suspected, providing on-line evaluation of momentary attention as crashes occur imposes exceptionally difficult methodological challenges, although such challenges are being taken up. The third contributory field concerns traditional traffic engineering. This includes elements of the driving environment such as road characteristics, control devices, and traffic flow and how these factors ‘cause’ possible hazardous situations (Rajalin *et al*. 1997, Steyvers and de Waard 1997). The confluence of this collective evidence provides a general framework for behavioural accident avoidance, however, it does not inform us as to the exact behavioural response just prior to the collision or more importantly, inform us as to what characteristics of response permit successful avoidance.

In this work, we are trying to determine what reaction patterns occur when drivers encounter an accident-likely situation and more importantly, successfully avoid collision. The determination of what constitutes a near-accident situation is largely up to the driver and may be construed as the point at which other road users enter their ‘safe field of travel’ (Gibson and Crooks 1938). Drivers generally adapt to changes in the traffic system, whether these changes occur in the vehicle, in the road environment, in the weather and road surface conditions, or in their own skills or state. Such reactions occur in accordance with their motivations (Summala 1987, 1997, Summala and Mikkola 1994). One of the few experimental evaluations of such response is the report of Rizzo *et al*. (1997). These authors developed a graphic tool for analysing driver performance and possible errors that may lead to crashes. Their participants were a group of older, licenced drivers, who were cognitively impaired due to mild or moderate Alzheimer disease. They report the advantage of using a high fidelity simulator in combination with this experimental evaluation tool as a new way of looking at accidents and individual differences in driver behaviour. Another relevant study relating to the issue of individual differences in driver response is that of Babarik (1968) where it is argued that people getting into (multiple) rear-end accidents are not necessarily slower drivers than others, but actually faster. Drivers that are faster to react to somebody else braking in front of them, change the ratio of the cars to inter-vehicle space and make it harder for following drivers to avoid them. Thus slow reaction may be an advantage in this common driving manoeuvre.

Our hypothesis of multiple vehicle accidents is a specific one. We view the sequence of events as a form of Markov process in which the avoidance actions of each driver are necessarily linked together and act to negate each other. Thus our hypothesis is amenable to modelling through a closed-loop feedback architecture. A critical feature of the model is that the timing of the respective avoidance actions fall within the respective response times of the two involved drivers. Thus, while each driver seeks specifically to avoid the other, their sequential responses act to nullify their mutual goal of mutual avoidance. The fact that these 'conditions' in which the respective responses become 'locked' together are rare, is reflected in the relatively infrequency of collisions in general as set against the opportunity of their occurrence. Below, we examine our dynamic systems based theory in a specific situation but we are especially aware that our conception can well address other collision configurations and indeed collision etiology in circumstances well beyond transportation alone.

2. Experimental method

In order to answer the question of how drivers perform in an accident-likely situation, a simulated environment was constructed in which two drivers meet each other in the same virtual world in a situation that has a strong potential for a collision. Driver performance is assessed by velocity control, braking, as well as steering response. We chose the respective scenarios in this study based upon accident statistics for the State of Minnesota and the whole USA. (In countries which drive on the left side of the road, clearly, these selections would be different). In the US, the three most common accident situations are the angled, head-on, and rear-end collision. For Minnesota, the situation is somewhat different, since the accident statistics are differently grouped. However, when we sum left-turn oncoming traffic, right-turn cross traffic and right angle collisions together, we end up with a percentage of over 24%, which is comparable to the numbers reported for the whole USA. Simply providing possible crash scenarios does not necessarily mean that the crash will end up in that same category. We cannot predict driver performance to that detail. This means that we need to provide scenarios that will include as many as possible of the prominent categories of accidents: angle (right/left and turning), head-on, and rear end. For this particular study we choose two major crash types, the head-on collision and intersection collisions.

2.1. *Experimental facility*

In order to accomplish the task of investigating collision-likely conditions, we used the dual simulation facility at the Human Factors Research Laboratory at the University of Minnesota that is shown diagrammatically in figure 2.

This configuration is represented in two adjacent, full-vehicle simulators, which share a common, virtual-world. The vehicles 'appear' to one another in a shared virtual world and thus the drivers can interact with each other. In comparable forms of simulation, the alternate vehicles either follow prescribed, pre-set paths and essentially do not interact with the human driver at all, or they follow some form of avoidance algorithm generated in the software, which represents a programmer's

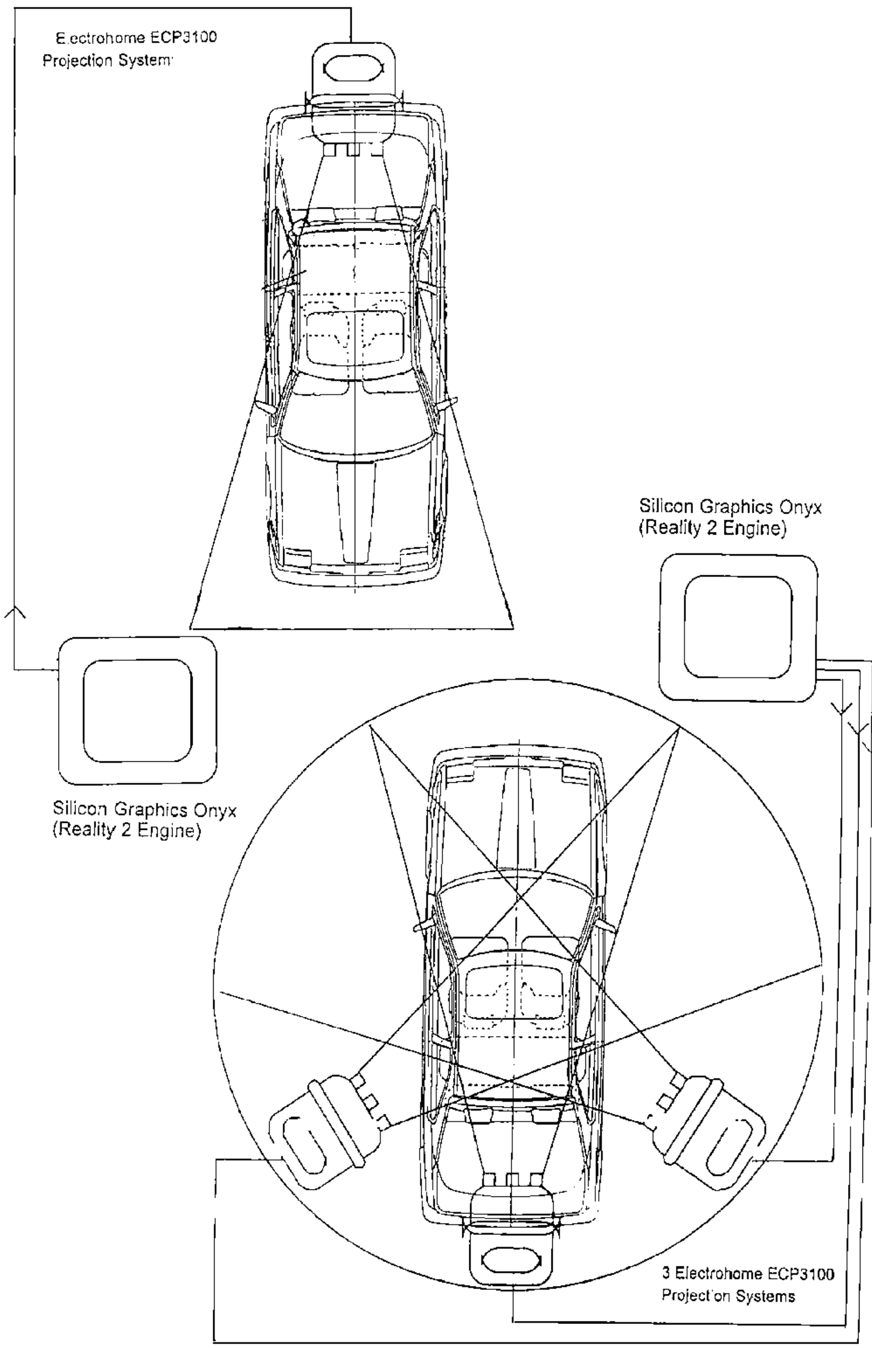

Figure 2. The illustration shows a schematic representation of the two side-by side simulators in Human Factors Research Laboratory of the University of Minnesota. The lower, wrap-around facility provided a panoramic front-field of view, while the single field of view simulator is shown above. The two facilities were linked to, and coordinated by, a single central computer which created the shared virtual world and synchronized actions within the world. Fuller views of the facilities are available on the website at: www.hfrl.umn.edu

view of avoidance behaviour not normal dynamic response. It is only in our shared environment that live drivers mutually interact with one another.

One of the vehicles (a 1990 Honda Accord) was located in front of a flat screen display that was 260 cm from the driver's eye point. An Electrahome three-lens projector projected a 225 by 165 cm field of view composed of a 1024 by 768-pixel display. Sound feedback was provided through a Sony Stereo receiver with home theatre speakers and a base shaker system that gave a representation of road and vehicle noise as calibrated to the momentary speed of the vehicle. A second vehicle (a 1990 Acura Integra) was located in a wrap around simulator, whose dimensions were 549 cm at maximum and 492 cm diameter at the floor. The eye-point of the driver was located 240 cm from the screen. Sound feedback was provided by a satellite-subwoofer speaker system in the vehicle trunk and high-powered subwoofers under the driver's seat.

2.2. *Scenario description*

In order to explore driver behaviour enacted in collision-likely conditions, the first requirement is to generate such conditions. This presents a number of conceptual and methodological challenges. In order that the findings from such simulation research be valuable in understanding real-world collisions, the development of the scenarios have to be as realistic as possible. That is, the drivers cannot be in the position of 'expecting' either a collision, or a near-collision event. Further, in order to understand the unconstrained behaviour of drivers, it is not possible to then constrain their behaviour in terms of free-control of the vehicle. Therefore, one of the first problems to be faced is how to coordinate the actions of the two drivers without their being aware of the on-coming event. We achieve this objective through use of traditional traffic control devices by having the drivers stopped at a traditional stop-light. When both drivers are in position, we let them proceed into one of the two scenarios, see figure 3. As a result, we developed two scenarios that sought to answer these concerns and these are illustrated in figures 4 and 5.

The first scenario involved an unregulated, off-angle intersection. Both drivers approached the intersection and their mutual sight distance and therefore time prior to conflict could be controlled through the imposition of obstructive buildings positioned on the two corners of the intersection. This is a realistic circumstance for collision, although in many countries, sight distances at intersections are regulated to avoid this form of crash. In the second scenario, two drivers were placed on a uni-directional, three-lane highway and told to proceed in a safe manner obeying the traffic central laws. The drivers proceeded toward each other while their mutual progress was obscured by a hill whose dimensions and characteristics were manipulated in software, in order to influence sight distance and thus time for avoidance. This general condition is the equivalent in the real world to a 'wrong-way' incursion along a one-way thoroughfare. Thus the circumstance was unusual but not unrealistic.

2.3. *Experimental participants*

Forty-six participants (25 female, 21 male) were recruited from staff and students of the University of Minnesota. All participants included in the analysis currently held a Minnesota driver's licence; they had normal, or corrected to normal vision, and were between the ages of 18 and 80 years. Specifically, the mean age was 22.14 years of age (std. 4.07 year). All drivers completed a driving questionnaire concerning their

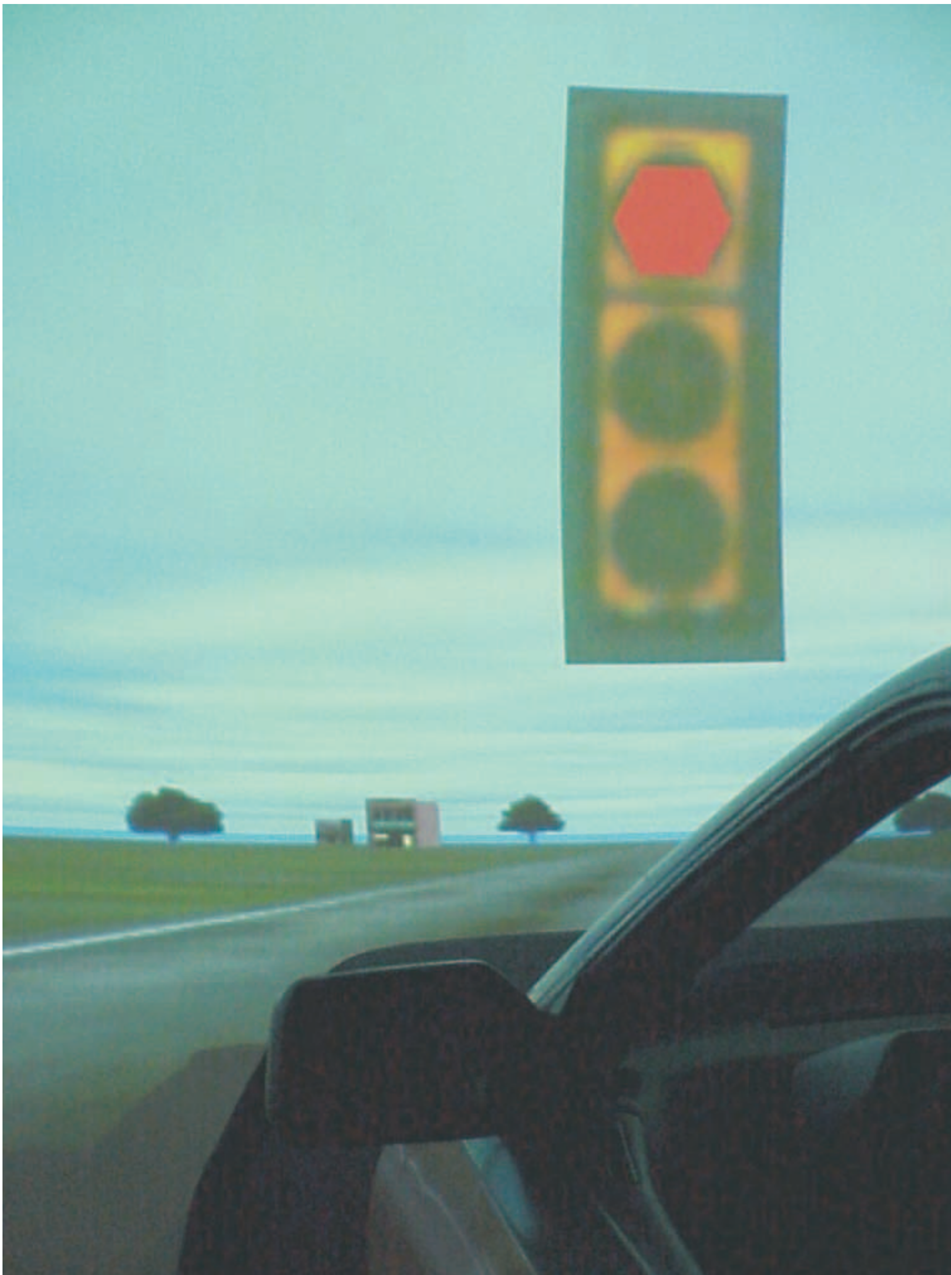

Figure 3. In order to bring drivers into an accident likely circumstance without interfering with their natural driving, we used traffic control devices. Here, a driver is waiting at a red light in the wrap-around simulation facility and when each driver is in position, we change the light to green which then triggers the collision-likely situations as described in the text.

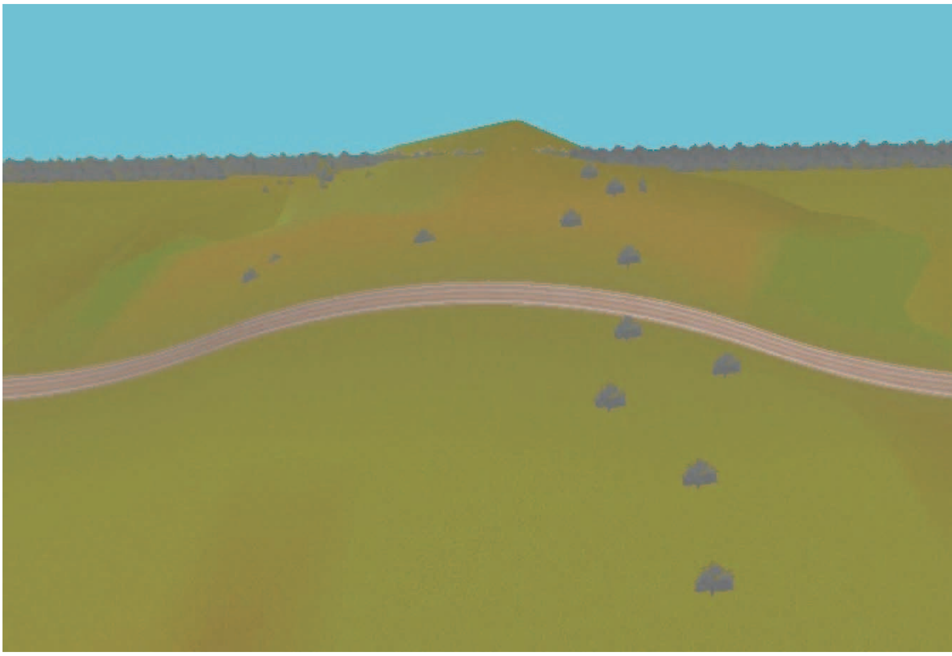

Figure 4. The illustration shows the 'hill' scenario from a high-up, side-on perspective. The respective drivers approach each other from the two ends of the roadway. By instruction set as to desired speed and change in the curvature (apparent steepness) of the hill, the experimenter can manipulate crucial independent variables such as mutual sight distance and therefore, time-to-contact. This is accomplished without prejudicing the situation by warning the driver of a potential impending collision. We suggest here that any such prior warning negates the value of data collected when the driver is 'on-guard.' Our method provides a way of circumventing this problem.

driving experience and driving habits and were debriefed as to the nature of the experimental procedure and their reactions to the procedure following completion. The rules and regulations of the permission of the Human Subjects Committee were adhered to at all times.

2.4. *Experimental procedure*

Participants came into the Human Factors Research Laboratory in pairs. Unbeknownst to each other, these two participants drove in the same simulated environment together. If, however, one of the two participants did not show up, one of the experimenter's would drive the flat-screen simulator and act as an unresponsive driver, meaning, the experimenter drove at a constant speed of 45 mph (72.4 kph) and was totally inactive when an accident likely situation occurred. These cases are referred to as a 'single-case' and were subject to separate analyses. Participants were randomly assigned to either the wrap-around simulator, or the flat screen simulator. In the single-case trial, however, the participant always drove in the wraparound simulator.

All participants were given practice that lasted 5 min, or until they felt comfortable driving the vehicle in our simulated environment. At the end of practice all participants were asked via a standardized checklist if they felt

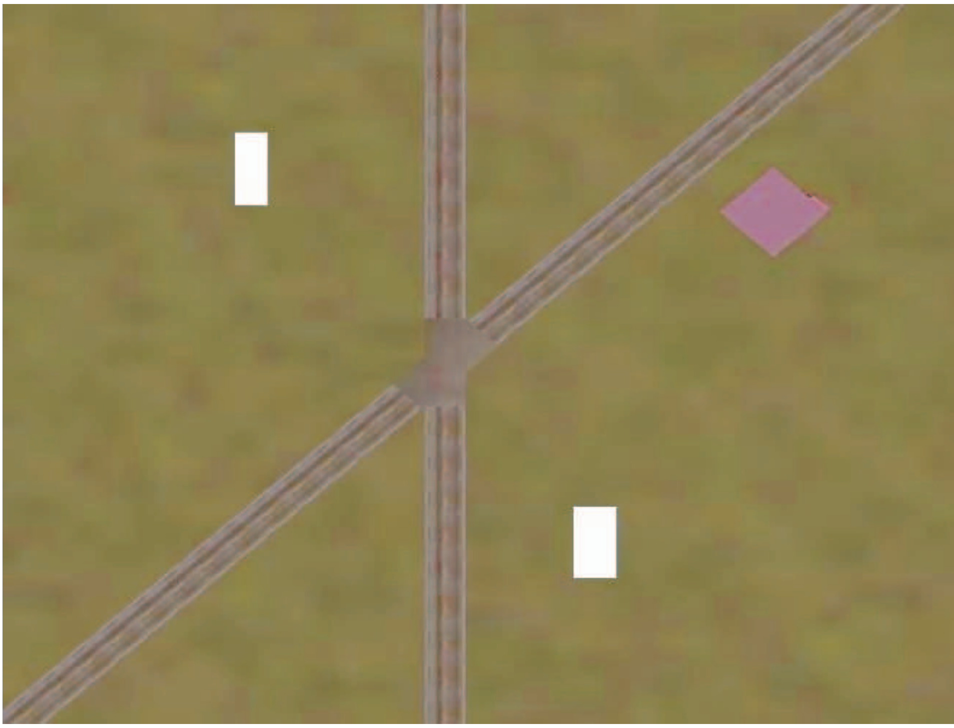

Figure 5. God's-eye view of the intersection collision scenario. As the curvature of the hill provides the control of certain independent variables in that scenario, so the positioning of the buildings accomplishes the same function in the intersection. Two caveats are important. First, in the real-world, many roadway design and driver regulation manuals would prevent the minimal sight distance we have used in this experiment. Second, we experienced much greater difficulties in generating conflicts in this situation where the cars approached at an angle, compared to the head-on situation of the hill scenario.

comfortable enough to proceed with the next stage of the experiment. The experimenter then stepped out of sight and both participants were presented with four subsequent scenarios. Participants were asked to accelerate up to 45 mph (72.4 kph), in the lane that they were positioned in, at the start of the trial. During the trial they were informed that it is their task to drive at a safe and comfortable speed and obey any traffic laws that may apply. In this way driving behaviour is structured as it occurs in the real world, but not constrained unrealistically. All scenarios started with a red traffic light displayed on the screen. Participants were instructed to start driving when it turned green. The first and third scenarios consisted of a straight two-way road with buildings on either side. Other vehicles occurred both in the driver's own lane and the on-coming lane, but no accident likely situations occurred. In these two scenarios that each lasted about 2 min, the two cars were not coupled.

The two cars were coupled into the same simulated environment in the second and the fourth scenario. After confrontation in the second scenario, both participants drove for another minute and were then uncoupled to drive the third trial. This trial again lasted 2 min where other traffic again was present but no accident likely situations occurred. Participants were then coupled again and the fourth scenario was displayed. Following confrontation, participants would drive for another minute until the experimenter reappeared and told them the experiment had ended. Immediately after the experiment, participants were asked to fill in a questionnaire that consisted of questions about themselves and their driving habits, a survey on accidents the participants were involved in the past, and their remembrance of perceptions and actions before and during any accident they had been involved in. Questions about the feeling of control of the simulator and car and questions to gain information on the remembrance of perceptions and actions of the participants during the trials and possible accidents were also asked. After completing the questionnaire participants were debriefed as to the purpose of the study. The experimenter finally ensured that all participants left the experiment feeling relaxed and comfortable.

2.5. *Experimental design*

In only one trial scenario (the intersection) the participants have a different viewpoint of the simulated world approaching from different directions to the 'target location'. The 'target location' is where the two cars are in an accident-likely situation and where avoidance strategies were measured. The intersection scenario is a case in which the two participants are both positioned in front of a stoplight and start driving at the same time when the traffic light turned green. In this way we can ensure, as far as possible, that the participants are coupled in a timely manner and thus give the greatest probability of conflict. After 200 metres both cars approached the intersection where the view from the other car is blocked by a building standing at the corner of the intersection. The two drivers cannot see each other and because there are no stop signs positioned at the intersection this is an accident-likely situation. The second coupled trial scenario involves the hill. Both cars started driving through a rural environment and were positioned on the middle lane of a three lane one-way road. They each start at a stoplight at the base of the hill. Both participants presumably 'assume' that no traffic will face them, but they are driving in the same lane on the same road approaching each other head on. They are not able to see however, because of the intervening hill. At the crest, or a little beyond (the 'target location') the two cars meet and it is here that avoidance strategies are measured. To examine avoidance strategies, we examined three responses: swerving, acceleration, and braking. We look upon braking and acceleration as active responses whereas releasing the accelerator is a more passive, waiting response. We recorded the 20 s before, during and after the point of closest approach. Even if drivers did not collide, they often swerve off the road seconds after the avoidance manoeuvre, as they do not appear to be able to stabilize due to, for example, distraction or shock.

3. Experimental results

For the purposes of analysis, the results from the two scenarios were examined individually. In the intersection scenario, we evaluated the reactions of 13 pairs of drivers compared to the hill scenario in which we examined responses from 16 driver pairs. Decisions to exclude data for specific pairs from analysis were based on a number of factors. The first factor, consisting of four cases, involved the intersection scenario and was represented by a significant discrepancy in velocity between the two participants ($>$ 30 kilometres per hour (18.6 mph) at point of first sight). This led to situations where only one of the two participants briefly saw another vehicle passing the intersection far away in the distance and in these cases, neither of the two drivers engaged in any avoidance behaviour. These velocity discrepancies are evidence of just how difficult it is to create collision-likely conditions when no direct control can be exert over driver response. The second exclusion of three cases involved the hill scenario and was justified by the fact that one of the two participants decided to drive in a lane other than the middle one by changing lanes prior to encountering the conflict situation. Again this represents an individual driving decision which our protocol permitted but which essentially negated the sought after avoidance response. In one hill trial, the speed difference between the two vehicles meant that the cars encountered each other near the base of one side of the hill. This led to a situation with greatly extended viewing times and therefore was incompatible with all other recorded trials. However, from this trial, information was individually very useful and we employed this particular result as illustrative of a multiple response avoidance event that is the basis of a following investigation. We discuss this particular trial later in greater detail.

For the analysed trials, point of first sight and point of closest approach were calculated using the following procedure. First, we determined the distance between the two vehicles throughout the whole trial by using the following coordinate equation:

$$d = \sqrt{\begin{array}{l}((x\ coordinate\ of\ car\ \#1) - (x\ coordinate\ of\ car\ \#2)2)+\\((y\ coordinate\ of\ car\ \#1) - (y\ coordinate\ of\ car\ \#2)2).\end{array}}$$

Once the distance between the cars for every data point was determined the respective points at which the two drivers are able to see each other for the first time are specified. These were calculated as 56 metres (61.2 yds.) for the hill scenario and 209 metres (228.6 yds.) for the intersection scenario. The point of closest approach is specified as the location where the minimal value of d is recorded. The following results are discussed in terms of first, the intersection trials and then the hill trials.

3.1. *Intersection scenario results*

The mean age of the eight males and eighteen female drivers in this scenario was 21.4 years. All had valid drivers licences that had been in their possession for an average of 5 years and they drove an average of 600 miles (965 kilometers) per month. Each participant was asked to answer a debriefing questionnaire designed to elicit responses concerning their driving habits, their perception of the simulator and the simulator controls, their perception of the trial conditions, and their perception of their own behaviour and performance. The questionnaire was composed of a combination of Likert-type, forced choice, and open-ended questions. Of their own on-road driving, they reported using city streets and highways more often than rural roads and almost never following a car too closely but almost always knowingly driving faster than the posted speed limit. They only periodically drove faster than the weather, traffic or road conditions allowed. Eight participants had been involved in a self-reported accident. In general participants reported normal driving behaviours and felt comfortable in the simulated environment. They felt in control of the steering, accelerator and brake and drove at a speed that felt safe and comfortable. Twenty-five out of the forty-six participants felt their vision of traffic was obscured during part of the experience with most comments related to the intersection situation. This was reasonable given that our intended manipulation of sight distance in the intersection was specifically through the use of buildings to obstruct such sight distance. Characteristics of the participants based on the results of the questionnaires specific for these trials can be found in table 2.

In respect of the quantitative results for the intersection trials, the first outcome was that the intersection scenario evoked considerably fewer active avoidance manoeuvres compared with the hill scenario. Only nine participants felt it likely at some point in the trial they were getting into an accident and only two drivers reported having experienced an accident. Speed differences between drivers had an overwhelming influence here since any significant difference meant that no conflict occurred. The closest point of approach had a wide range (5.47 – 44.33 metres), resulting a mean of 19.4 metres (21.2 yds.) and a standard deviation of 14.22 metres (15.5 yds.). Given the longitudinal difference for an accident (i.e., instant co-location of the two virtual vehicles) was only 4.5 metres (4.92 yds.) and the comparable lateral distance was 2.0 metres (2.19 yds.), it is evident that few actual collisions occurred. Although accident-likely situations in this particular scenario were thus infrequent, it is interesting that only three participants chose to register no response reaction at all as they approached the intersection. An overview of the response behaviours that participants manifested can be found in table 3. As is evident, the strongest response pattern is one of conservatism in the uncertain situation as represented by the reduction of speed. However, this is a relatively passive and cautious response consisting of an 'Off Acceleration' reaction. Positive brake activation was itself relatively rare. Few drivers exhibited any form of aggressive response, although there was one participant who sped up in order to 'beat' the other driver to the intersection. In keeping with our hypothesis, drivers who respond with different strategies, e.g., cautious vs. aggressive, do not meet in this present scenario since they start at a common distance from the intersection. However, those with common response strategies do tend to encounter each other. Although this might, in general, be considered a limitation of the present intersection scenario, examining collision-likely conditions between drivers of difference response type can be accomplished in this configuration by staggering start distance. However, since the hill scenario answers this particular concern and produced significantly more conflicts it is to these results we now turn.

3.2. *Hill scenario results*

Thirty-two drivers, with a mean age of 22 years, participated in the 16 trials. They drove 600 miles per month on average and they had possessed a valid Minnesota Driver licence for approximately 6 years. They classed their own driving as 'normal' and reported driving on city streets and highways 'almost always' as to 'almost never' on rural roads, which is a reasonable pattern given our local Metropolitan sample. The drivers reported almost never following a car too closely, almost always driving faster than the posted speed limit, but never faster than the road or weather conditions would allow. Fifteen participants reported having been involved in an accident and filled in our special questionnaire on these accidents. In relation to simulator control, participants felt in control of the steering, the gas, the brake and the car in general drove at a speed that was safe and comfortable.

Twenty-three participants reported that they felt their vision was obscured at some point in the trial. When asked more specifically about the obstruction, all of these individuals referred to problem of not being able to see over the hill. While this

Table 2. Characteristics of the participants in the intersection trial based on the questionnaire.

Question	Min	Max	Mean	SD
Age	18	31	21.4	4.04
Year first acquired driver's licence	1984	1998	1994.4	3.26
Number of kilometres per month	0	3218	978.9	943.4
Number of accidents involved in	0	3	0.52	0.87
Question in Likert-type scale, (1 = always, 3 = sometimes, 5 = never)			**Mean**	**SD**
How often do you drive?			1.9	0.93
How much of your driving occurs on city streets?			2.4	0.96
How much of your driving occurs on rural/ country roads?			3.5	0.81
How much of your driving occurs on highways?			2.4	0.81
How often do you knowingly follow a car in front of you too closely?			3.7	0.84
How often do you knowingly drive faster than the posted speed limit?			2.1	1.01
How often do you knowingly drive faster than weather, traffic or road conditions allow?			3.6	1.02
Question in Likert-type scale, (1 = always, 3 = mostly, 5 = none)			**Mean**	**SD**
I felt nauseous			4.2	1.20
I felt in control of the steering			2.8	1.10
I felt in control of the accelerator			2.3	1.04
I felt in control of the brake			2.5	1.24
I felt in control of the car			2.3	0.72
I drove at a speed that was comfortable			1.8	0.88
I drove at a speed that was safe			2.3	1.02

Table 3. Avoidance manoeuvres for the intersection trial.

Avoidance Manoeuvre	Number occurred	Percentage
Brake	6	23.07
No brake	20	76.9
On accelerator	4	15.39
Off accelerator	22	84.61
Brake plus off accelerator	5	19.23
No brake plus on accelerator	3	11.53
Sped up	1	3.85

accords with our experimental design to control mutual sight distance, it suggests that participants were aware of the problem of the configuration of this road. Five participants reported having lost their attention at some point in the trial. When asked directly they again referred to the road configuration as the reason for this. Twenty-nine participants reported *in retrospect* that they felt they were getting into an accident. They referred to a fear of another car at the other side of the hill but this was after the event had occurred. Characteristics of the drivers based on the questionnaire results are presented in table 4.

All driver pairs experienced an accident-likely event in this scenario. The closest distance between the two cars ranged from 2.91 metres (3.18 yds.) to 0.374 metres (0.4 yds.). This means that all drivers needed to perform a control manoeuvre to avoid colliding with the car that entered their forward 'safe field of travel' (Gibson and Crooks 1938). Twelve participants reported a crash in this situation. The distance between the cars is measured from the midpoint of each car model. When the cars are positioned head on towards each other the minimum distance without being in collision is 4.5 metres (4.92 yds.). A smaller distance is required when the cars are passing each other, at which point the minimum distance is only 2 metres (2.2 yds.). If, at the point of closest approach, the distance between two cars does not exceed 2 metres (2.2 yds.) they have collided. In eight of the 16 pairs this was the case and a collision did occur. Two participants reported a collision that in fact, according to the quantitative data for point of closest approach represented a very near miss. Ten participants correctly identified collision, and four reported not to have collided while in fact they did. All participants performed at least one avoidance manoeuver and these are detailed in table 5. A representation of one of these individual avoidance manoeuvres is illustrated graphically in figure 6.

As was evident in the intersection situation, the predominant response on the hill is also a passive, off the gas response. In most cases, this is *not* accompanied by a braking response, rather this seems to be a 'wait and see' strategy as to how the situation will develop. As for the actual avoidance manoeuvre itself, it is overwhelmingly a change in direction, that is lateral control of the vehicle, rather than braking which represents longitudinal control. We are very aware that our scenario promotes this form of response and indeed a valuable future contribution will be to distinguish how and in what manner the configuration of the roadway and the approaching vehicle trajectory dictates the predominant form of response. In the present circumstance, the lateral avoidance manoeuvre is certainly consistent with Gibson and Crooks (1938) 'field of safe travel' conception, however, it is important to note that given that

Table 4. Characteristics of the participants in the hill trial based on the questionnaire.

Question	Min	Max	Mean	SD
Age	18	34	22.8	4.9
Year first acquired driver's licence	1981	1997	1992.5	4.4
Number of kilometres per month	0	3218	973.7	805.8
Number of accidents involved in	0	5	0.87	1.18
Question in Likert-type scale, (1 = always, 3 = sometimes, 5 = never)			Mean	SD
How often do you drive?			2.03	0.97
How much of your driving occurs on city streets?			2.38	0.94
How much of your driving occurs on rural/country roads?			3.50	0.80
How much of your driving occurs on highways?			2.20	0.79
How often do you knowingly follow a car in front of you too closely?			3.60	1.00
How often do you knowingly drive faster than the posted speed limit?			2.20	0.95
How often do you knowingly drive faster than weather, traffic, or road conditions allow?			3.50	1.10
Question in Likert-type scale, (1 = always, 3 = mostly, 5 = never)			Mean	SD
I felt nauseous			4.34	1.12
I felt in control of the steering			2.60	1.02
I felt in control of the accelerator			2.03	0.78
I felt in control of the brake			2.25	1.04
I felt in control of the car			2.25	0.72
I drove at a speed that was comfortable			1.70	0.88
I drove at a speed that was safe			2.25	1.05

Table 5. Avoidance maoneuvres for the hill condition.

Avoidance Manoeuvre	Number of occurrences	Percentage
Swerve left	17	53.1
Swerve right	14	43.8
No swerve	1	3.1
Brake	9	28.1
No brake	23	71.9
Off accelerator	29	90.6
Not off accelerator	3	9.4
Swerve plus brake	8	25.0
Swerve plus no brake	23	71.9
No swerve plus brake	1	3.1
No swerve/no brake	0	0

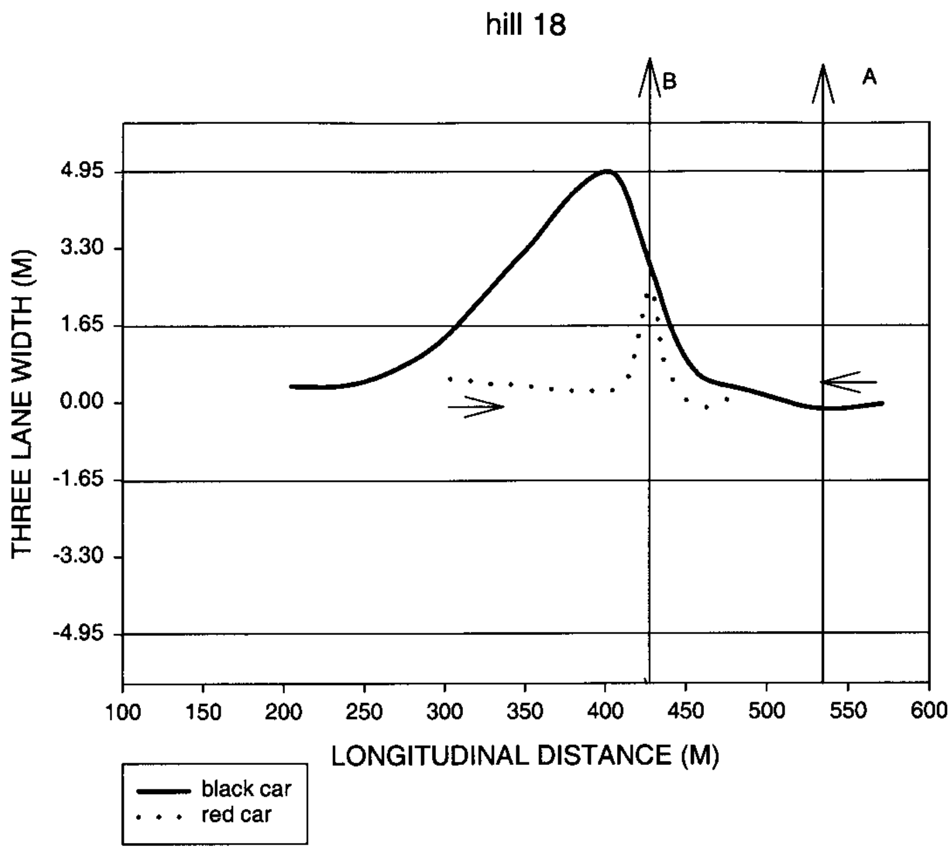

Figure 6. This graph shows a 'window' of the original data stream. Once the point of closest approach is measured between the cars, 10 s before and 10 s after this point are plotted in order to examine driver performance in the few essential seconds before and after an accident likely situation. In this particular trial (Hill 18) participants meet each other after the actual crest of the hill due to different velocities which lengthens viewing times and also results in the difference between the length of the plotted lines. (A = Crest of the hill, B = Point of closest approach).

each vehicle travels in the centre lane, the option to go either right or left is not specified by the 'field of safe travel' proposal. As we discuss below, the response of the individuals in this experiment is informative as to our own specific hypothesis.

Of the 21 participants who reported what direction they swerved in, only two accurately identified their own response. Given that this was a relatively benign simulation with no legal ramifications, the misidentification rate strongly illustrates the problem of memorial recall of these forms of emergency event. An important observation is that participants did not react in any systematic fashion. Right and left swerves occurred almost equally and these did not seem to be directly contingent upon any pre-emptive action on behalf of the other conflicting driver. Why this is the case is at present not clear. In point of fact, some drivers report having been taught to swerve to the right in such a condition, a most useful strategy. Therefore we performed a *post-hoc* calculation ascertaining that the mean mutual viewing time for each pair was small (approximately a 1.2 s mean). Given so limited a viewing time, it is evident that response patterns are essentially single reactions rather than avoidance strategies *per se* and thus the swerve right strategy would serve driver well in such conditions. More evidence for the restriction to a single response lies in correlations between the time of first possible sight and the onset of the first avoidance action for each driver are very high (0.998 and 0.996 respectively) as well as the fact that braking occurred only infrequently (71.8% did not use the brake pedal at all). In essence, this was a 'see and avoid' situation which did not permit enough time for multiple, linked avoidance responses to occur. Interestingly however, the correlation between the reaction times of both drivers even in this brief interval is high (0.95). This supports the contention that the behaviour of the two drivers is still 'interlocked' in some fashion even for these brief mutual, viewing times. The results presented in figure 7 as well as table 6 confirm these observations. Of course we recognize the general problem of time restriction here, i.e., the drivers only have a certain 'window' of time in which to respond anyway. As a consequence of these findings, we are proceeding with subsequent experiments that open up the window of possible response by permitting longer viewing times.

Evidence that more extended viewing times may result in more interactive patterns of response come from the data for one pair of drivers (where the trial was designated 'Hill 18,' see figure 6). Due to the large speed difference between the two vehicles (one had crested the hill as the other began the ascent) these drivers had a much longer mutual viewing time, in the order of several seconds. This gave the opportunity to examine interaction for a greater period of time. In this case a mutual interaction did occur and although we have the evidence in the kinematic traces for the trial as illustrated in figure 6, it is perhaps best expressed by the subjective report of one of the drivers:

> *'When a car emerged over the top of the hill, in the lane I was in, I steered to the right, then left when the car facing me followed my direction. The car appeared to follow me when I tried to avoid it by steering right.'*

There is perhaps no better evidence as yet to date for the linked avoidance response hypothesis, in which the intended avoidance actions of each individual cancel each other out to result in unwanted collision.

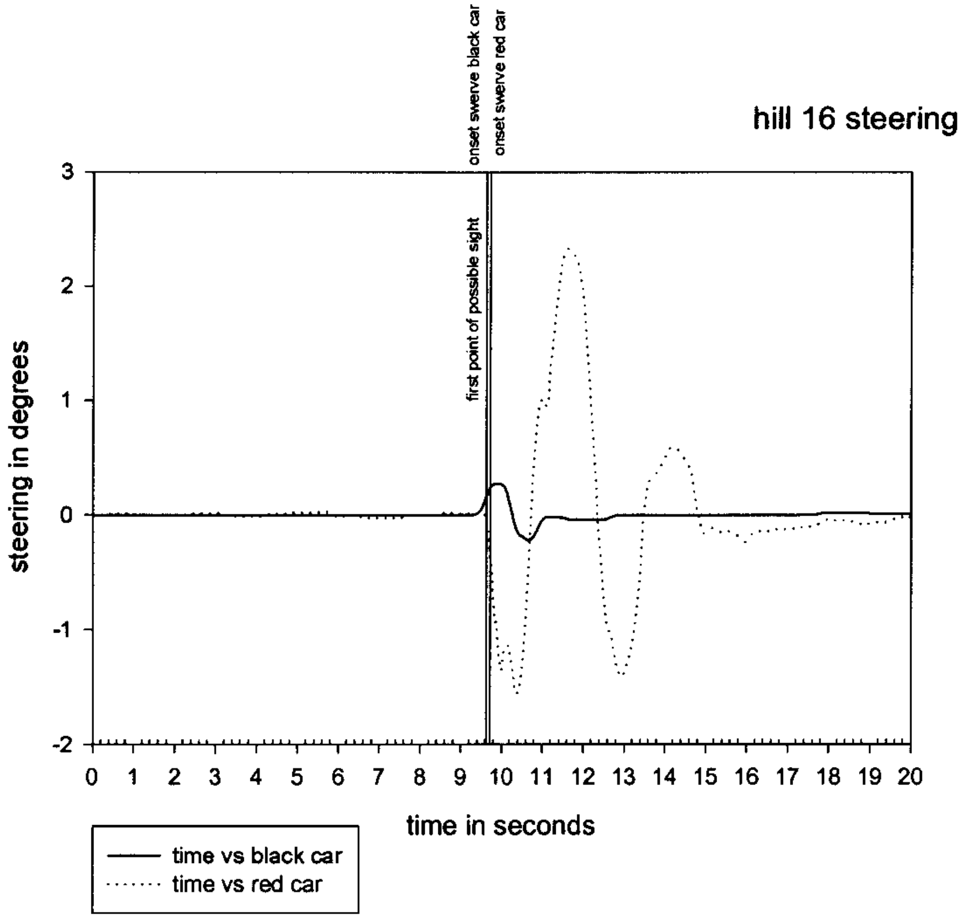

Figure 7. Illustration of the a-typical joint kinematic traces of the opposing vehicles. This measure shows vehicle lateral control through change in steering direction.

Table 6. Driving and avoidance profile of both cars in the hill trials.

Measurement	Car 1	SD	Car 2	SD
Mean speed in kilometres per hour	56.7	12.2	59.3	8.3
Mean onset of swerve in sec.	8.78	0.63	9.13	0.61
Mean speed at onset of swerve	50.5	17.4	55.9	11.9
Mean total reaction time	1.82	2.36	1.48	1.61

4. Discussion

It is our hope that, using the tools and methods of Ergonomics, we have opened a new window on the accident process by examining avoidance response at a behavioural level. In terms of the present results, we have found that when there is a relatively ambiguous driving situation in which drivers identify cues that suggest possible problems, the primary response is one of caution, expressed as an 'off the accelerator' action. In effect this action, by reducing velocity, serves to increase the global time-to-contact and thus time to reach the general problem area. As evident in the formulation of Gibson and others (see Gibson 1966, 1979, Hancock *et al*. 1995), this action response may itself allow time for the situation to disambiguate itself and for the appropriate response to become evident. Given the relative infrequency of accidents compared to the number of *opportunities* for their occurrence, it is evident that this response is overwhelmingly effective and it is only in very rare or unusual circumstances that such ambiguity persists. In both of the scenarios we have investigated, the preferred acute avoidance response is one of lateral control (i.e., swerving the vehicle), as compared to our original expectation of much greater use of braking. In part, this is of course, a response to the configuration we have exposed our participants to. However, it remains a surprising finding given the supposed greater efficacy of both brake and steering response in mitigating high momentum impact.

In the present experimental research we have shown that realistic avoidance behaviours can be created and replicated in the interactive simulation environment. As such the first, and in essence, the major contribution of this work is that a new technique is now available for the investigation and amelioration of all vehicle collisions. This conclusion is buttressed by both the objectively recorded driver responses and their concomitant subjective report of the validity of the experiences they encountered during the different scenarios. In addition, we have also addressed and provided one innovative solution to the highly intractable problem of behaviour shaping. In many experiments in the behavioural research laboratory, the experimenter 'frames' the participant's response through instruction sets and testing protocols. In the present work, we sought specifically to overcome this form of self-fulfillment and to do so, we created purpose-specific conditions in which through the simplest of instructions 'drive safely and follow the rules of the road' we have managed to bring drivers into a surprise conflict situation which only they can resolve. Together, with these successes of methodology we have also created an interactive simulation environment in which the time-lag problem across two facilities has been sufficiently controlled to permit essentially co-incident driving. Thus the present work has exhibited technical as well as investigative success.

Having indicated these successes, it is equally important to indicate current shortfalls that provide areas in which substantive improvement is possible. In the case of the intersection scenario, the result of permitting each driver complete freedom is that the velocity differential between vehicles often negated the occurrence of conflict. This itself is evidence that providing participants freedom of action will often 'compromise' an experimental procedure to the point where the experimenter's purpose is obviated. To remedy the intersection situation, we are in the process of developing dynamic software manipulations, which, without the knowledge of either driver, or any change in the perceptual environment can momentarily change the relative positions of the respective vehicles to increase the probability of a conflict, although driver's avoidance responses will not be affected in any way.

With respect to the hill scenario, a major problem in the present experiment was mutual viewing time. With the hill curvature we have chosen, in combination with the speed selected by the drivers, the viewing time on average was sufficiently small that only a single avoidance action could be taken. In our continuing experiments we are providing longer viewing times by changing hill curvature and through the use of simulated levels of fog. However, our basic thesis concerning interaction between drivers received most encouraging support from the hill trial in which viewing time was extended by the great speed differential. In addition to these useful advances, we have had to develop some new approaches to examining the contingent dual kinematic traces, an illustration of which is shown in figure 7.

With respect to the specific findings of the present experiment in the two different scenarios, the hill trial showed unequivocally that the reaction times of the drivers permitted only a single avoidance manoeuver. Overwhelmingly these manoeuvres consisted of a swerve in a single direction. In respect of the limitation of viewing time this is not surprising. Further, the swerving tactic may well have been encouraged by the presence of an open lane on either side of the on-coming vehicle. We expect that specific avoidance patterns (i.e., swerving, braking, or swerving and braking) will be contingent on the characteristics of the roadway in a manner consistent with Gibson and Crooks' (1938) notion of the 'field of safe travel'. Our present methodology that we have developed permits the first true test of this proposition over 60 years since its postulation.

5. Summary and practical recommendations

Our first simple and practical recommendation relates to head-on collisions. Our information confirms that in the process of driver education, young drivers should be taught to 'swerve to the kerb-side' in the case of incipient, head-on collision. It is clear that in any multi-vehicle collision the opportunity for avoidance and propensity for damage and injury is contingent on the actions of both drivers. Thus while one driver might make a significant avoidance response, collision may still not be avoided if the other driver makes no response, or worse makes a response which cancels out that of the other. Through the recommendation of the kerb-side swerve strategy, we will maximize the chance of collision avoidance even if both drivers can make only a minor manoeuvre. Parenthetically, this will require different directional response contingent upon whether one is in a country that drives on the left or the right side of the roadway. Thus, in head-on conflicts – swerve to the kerb.

In the conception, fabrication and installation of computer-assisted collision-warning and collision-avoidance systems, currently envisaged under many ITS programmes, the optimal design configuration is one that reinforces and supports the natural driver avoidance response. While it is clear that the specific situation will prove a primary influence on what tactic it is best to adopt, it is clear from the present results that a system which complements the anticipatory process and assists in vehicle slowing when approaching ambiguous situations does serve the process of support for human-centred, rather than technology-centred avoidance activities. Thus, in potentially ambiguous situations, assistive devices should focus on prediction and prevention rather than instanteous amelioration as current technologies are envisaged.

Our final recommendation is one that occurs in the vast majority of experimental papers and that is a call for further research. However, here we wish to articulate such a need in a little more detail. In the present, we have sought to help open a new window on the accident process. However, this is only a start. What is clearly required as a next step in the process is a programmatic and sustained effort on behalf of many researchers in order to take advantage of the opportunity which dynamic, interactive simulation presents. In the very first statements of the present work we established the clear societal importance of this effort for both occupational concerns and general injury. However, also evident was that the sheer number of researchers in behavioural accident avoidance research is too small for the task.

Therefore, by the present work, we appeal to fellow Ergonomists to take up this challenge. Interactive simulation can certainly address traffic collisions, however, judiciously developed such a technology can also inform many other areas of human – human – machine interaction. If this capability can help in the battle to save life and reduce injury, we shall have earned our salt.

Acknowledgements

We are very grateful for the help of Neil Ganey and Derek Diaz in the final preparation of this manuscript. The experimental situation would not have been possible without the technical skills of Jim Klinge and Peter Easterlund and we gratefully acknowledge their assistance. An earlier version of the present work was awarded the Liberty Mutual Prize for Ergonomics and Occupational Safety, given by the International Ergonomics Association (IEA). We are most grateful for the comments of the respective award reviewers and adjudicators on an earlier version of this paper. Finally, we would like to thank the editor and the unknown reviewers for their comments which helped to finalise the work.

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