Discriminating between brain injured and non-disabled persons: a PC-based interactive driving simulator pilot project

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Abstract

This pilot study investigated whether the STISIM Drive^{TM}, a personal computer-based interactive driving simulator could discriminate between 5 cognitively impaired brain-injured persons and 5 non-disabled age/sex matched persons. Dangerous errors like running off-road, crashing, and running stop signs discriminated between the groups as did speed on straight and curved roads and lane position on curved roads. In specific critical events, brain injured subjects used simpler, less adaptive strategies and were more impulsive. Straight road lane position did not discriminate. The results tentatively indicate that a driving simulator can discriminate between brain injured and non-disabled subjects. These indicators should be examined in future studies.

Keywords – Cerebrovascular accident, driving, simulation, critical driving errors

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1. Background

Brain injury, whether from cerebrovascular accident (CVA), traumatic brain injury (TBI), or other cause can permanently impair the cognitive skills needed for safe driving including the ability to process simultaneous information, rapidly shift attention, deal with complex issues, limit distractibility, maintain mental flexibility and control impulses [1-3]. There is no consensus about the best way to identify those who should drive after brain injury [4], although there is an emerging vision of how few of those who need evaluation are actually being assessed [5, 6]. Recent studies found that 38-60% of people post-TBI [4,5,7] and 30-50% of those post-stroke [4, 6, 8] return to driving.

In the United States, driving provides important community mobility and serves as a critical part of one's self-definition as an adult [6, 9, 10]. Except in those few U.S. cities with good public transportation, adults must rely on the private automobile to maintain a social life in the community and to accomplish routine tasks such as commuting to work, shopping, and visiting the doctor [4, 8]. Brain injury can impair the metacognitive skills necessary for individuals to realistically assess their own capacity for safe driving [11]. Persons with brain injury therefore have both organic and motivational supports for adopting unrealistically positive views about their driving abilities. Therefore, the physician and rehabilitation team are often asked to advise, and sometimes decide, whether and when a person with brain injury may drive; to balance the potential risk to the community and driver against the anticipated benefits that a return to driving may hold for the individual.

Driving rehabilitation programs that serve brain injured persons commonly use a combination of measures to evaluate persons for driving after brain injury [1, 5, 6, 12]. Chief among these is the individual's performance while driving a car. There are two types of such driving evaluations: closed course and on-road. Closed course driving assessments are performed on an isolated driving course, typically a large parking lot. They are generally accepted as reasonable measures of vehicle control, but fail to assess the driving decisions and responses that traffic and real life make on public roads [13]. On-road driving evaluations in real traffic, although commonly used as the criterion assessment of driving performance, are hampered by their subjectivity and lack of standardization, unstable reliability, and questionable validity [1, 11, 14-17]. Evaluators, working with patients of unknown ability, and concerned with personal and community safety, typically perform on-road assessments on quiet residential streets thereby reducing the very challenges of traffic, pedestrians, and other stresses of real-world driving that on-road assessments should offer if they are to serve as reasonable criteria for safe driving[14]. Searching for a way to present challenging driving experience with all the opportunities for errors that must be controlled in real on-road experiences, researchers have increasingly recognized the possibilities offered by driving simulation [15, 18, 19]. Though still a developing tool, more researchers are recommending that driving simulation be used as a part of driving assessment [18, 20].

The term 'driving simulator' is used to indicate a variety of tools that place the 'driver' in an artificial environment where technology creates an impression of driving. These devices vary in terms of their cost, verisimilitude of physical environments/control, types of data generated, and degree of interaction [21-26]. Traditionally, less expensive models offered lower verisimilitude. However, with increasing speed, power and graphics capabilities offered by current models of personal computers (PCs), PC-based simulators that provide essential fidelity to the driving experience have become available for less than $30,000, a cost that most clinics can consider.

In non-interactive simulators, the scene viewed by the driver is filmed or videotaped in advance and played back during the simulation. This provides a realistic visual representation of the driving experience, but also creates the major limitation to such simulations, i.e., that the driver's actions on the simulated vehicle's controls have no effect on the simulation [27]. Interactive systems use computer graphics that are less visually realistic than the video or film images used in non-interactive devices, but that have the advantage of being able to alter the driver's car, the traffic and the environmental view according to driver action.

Research on driving simulation's use with persons with brain injury is only beginning to appear in the literature [11, 27-29]. Galski et al [27], compared on-road scores and a non-interactive simulator (Doron L225 Driving System/Analyzer), and found that signaling errors and attempts to steer away from hazards were strong predictors of on-road pass/fail scores earned by brain injured adults. In a later study using the same simulator, Galski's group [15] concluded that three factors strongly affected the results of the simulated experience. They described these as: anticipatory braking (i.e., braking to avoid danger), defensive steering (i.e., steering to avoid danger) and behaviors of complex attention (i.e., the ability to remain focused on task and resist distraction). Liu et al [29] compared the simulator driving performance of 17 individuals with head injury and a non-disabled age and sex matched group using the interactive DriVR virtual reality simulator system. They found that the simulation was able to discriminate between the groups based on lane positioning relative to centerline, avoiding collisions, running onto the road shoulder, and compliance with STOP signs. This paper furthers that research, reporting the results of a Phase I study that compared the behaviors of brain injured and non-disabled drivers during a simulated driving experience.

2. Method

2.1. Instrumentation

The study used a STISIM Drive PC-based driving simulator developed by Systems Technology, Inc, that has been proven in other varied applications [30-32]. The simulator comprised 3 identical 400 MHz Pentium-based personal computers, 3 VGA monitors, and a driver's console. The computer systems were networked creating a synchronized 135° roadway field of view across the 3 monitors. An additional monitor connected to the core computer system acted as a clinician's display. The driver's console (Model WT-2000 Interactive Driving Simulator Console from Advanced Therapy Products) consisted of a full size steering wheel, adjustable tilt steering column, turn signal, throttle and brake pedals and an adjustable seat. The console provided proprioceptive feedback via a torque motor connected to the steering shaft.

The STISIM Drive software package used a multi-processor approach and high-speed graphics accelerators to minimize system delays. This decreased the lag time between driver input and update of simulation graphics, reducing the likelihood of "simulator sickness" [33-35], a traditional problem of driving simulators. The study used an orientation drive to introduce subjects to the simulation before data collection. This drive included all basic aspects of car control including starting and stopping, negotiating curves and hills and turning. In addition to orienting the driver to the simulator experience, the orientation exposure helps reduce simulator sickness[36] and can help eliminate from further study those individuals who may be highly susceptible. Each subject drove the orientation until comfortable driving the simulator. No data was collected during the orientation drive. The simulated driving scenario was approximately 19 miles long and took about 40 minutes to complete when driven at the posted speed limits. The route was designed to simulate rural, residential, and commercial/business areas and included curves and hills. The majority of the simulation was spent driving 2 lane (rural and residential areas) and 4 lane (business) roadways. The drive also included over 2 miles of 6 lane limited access highway. Subjects were told to maintain the posted speed limit and remain in the right lane except when passing, turning, or avoiding an obstacle. Commands for turns were given by the researcher, timed to specific simulator events (e.g. appearance of landmark). Routine cognitive challenges throughout the drives included merging with traffic, negotiating intersections containing pedestrians, changing lanes, and passing other vehicles. The drive was divided into 2 parts, a simple part comprising the first half of the simulation, and a more complex section comprising the second half. The simple portion required basic vehicle operation such as maintaining speed and lane position, starting and stopping, and avoiding other traffic. The complex portion contained critical events such as vehicles cutting off the driver or ignoring traffic control devices, potential head-on collisions, and traffic lanes merging to increase the driver's workload. Drivers were offered a break of 1-3 minutes between the 2 sections. Data were collected throughout the simulation drive and stored in ASCII text files for post-simulation processing. Collected data included time in simulation, distance travelled, lateral lane position, vehicle speed, steering wheel angle, longitudinal (forward and backward) acceleration, and use of turn signals. We also collected data on driver errors that could result in a serious accident: running off the road, crashing into a moving or fixed object, and failing to stop at a STOP sign or red traffic signal.

2.2. Subjects

Persons with brain injury were solicited by postings and direct contact from physicians and therapists. Brain injured subjects had to be between 25 and 65 years old with mild to moderate cognitive impairment from an adult onset brain injury such as CVA, TBI, or tumor. Cognitive deficit was verified using the Neurobehavioral Cognitive Status Examination (NCSE, Cognistat) [37-40]. Subjects had to be at least 3 months post injury, have physician approval for a driving evaluation and to have expressed a desire to return to driving. Subjects had to have been an active driver at time of their brain injury and still hold a valid driving license. Individuals who needed adaptive driving equipment or those with any secondary diagnosis that could influence cognition or movement were excluded.

A convenience sample of 5 adults with brain injury (3 women, 2 men) volunteered and met the criteria. Two subjects had tumors (mengiomas), two had experienced a CVA (1 left parietal; 1 right basal ganglia), and 1 had experienced anoxia secondary to a cardiac event. All subjects ambulated without devices, lived in the community, and were independent in self-care. All had upper extremity strength and motor control within functional limits, and all could drive without adaptation. Subjects ranged from 29-54 years old (M=40.4 years (s.d =11.04) (Table 1). Average time post-injury was 1.9 years (s.d. =1.34). A non-disabled group of subjects, matched for sex and +/-5 years for age, was recruited by posting and word of mouth. Control subjects had valid licenses and driving histories with less than 3 reportable accidents and no license suspensions/revocations. Non-disabled subjects' average age was 39.4 (sd= 12.44).

3. Results

3.1. Discrete Data

We examined three types of discrete data that, in the real world, could result in a serious accident: running off the road, crashing into a moving or fixed object, and failing to stop at a STOP sign or red traffic signal. We also considered failure to execute a turn where directed and failure to use turn signals when executing a turn. As illustrated in Figure 1, none of the non-disabled subjects committed any potentially dangerous driving errors, whereas every one of the subjects with brain injury committed at least one serious error: 1 failed to stop at a STOP sign on two separate occasions, 3 ran off the road (1 in the presence of pedestrians), and 2 were involved in a crash with another vehicle when they failed to observe that vehicle running a red light. Two of the brain injured subjects failed to turn at one or more of the required locations:1 missing a single turn; the other missing 3 turns. None of the non-disabled subjects failed to execute a required turn. Brain injured and non-disabled subjects failed to signal turns in almost equal numbers.

3.2. Continuous Data

We studied three measures of steady state driving performance for straight and curved segments: mean lane position, percentage that speed was above or below the posted limit, and speed deviation (as a measure of driving consistency). We collected data for 2 straight segments and 4 curved segments. The first straight segment and the first two curved segments were located in the simple portion of the simulation. The remaining segments were part of the complex portion of the drive. One subject (#103) failed to complete the drive. Thus the results represent data for all ten subjects for the first straight roadway and for the first two curved segments, and for 9 subjects thereafter.

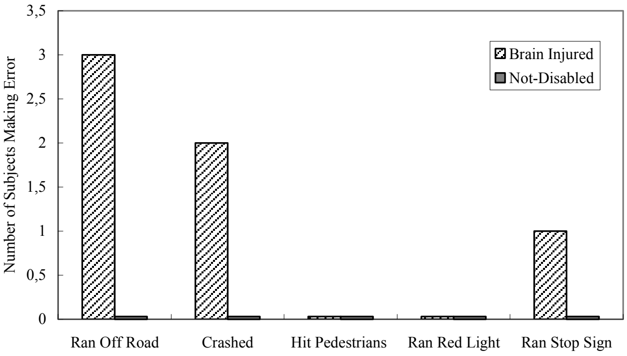

Fig. 1 – Numbers of brain injured and non-disabled subjects who committed dangerous errors during the simulated drive

3.2.1. Straight Roadway Segments

Two 1000 feet straight roadway segments were examined.

3.2.1.1. Lane Position

Of the nine subjects who had data for both segments, all but 1 improved in mean lane position (i.e., approached zero deviation) from the first to the second data collection segment. By the second segment, all 5 of the non-disabled subjects had moved to a more centered position, as did 3 of the 4 brain injured subjects. The range of lane position was similar for both groups during the first segment (1.1 ft). In the second segment the ranges increased slightly for both groups (1.1 ft for brain injured; 1.6 ft for non-disabled subjects). One non-disabled subject consistently maintained the same off-center position throughout the drive. The other 4 non-disabled subjects substantially improved lane positions.

3.2.1.2. Speed

All non-disabled subjects closely adhered to the posted speed limit across the two segments, as illustrated in Figure 2. Four of the 5 showed better speed control during the second segment. During the first segment, non-disabled subjects' speed ranged from 1.8-6.4% above the posted limit. By the second segment, their range had narrowed to .44% below-6.2% above the posted limit. In contrast, the speeds of the brain injured group had wider range from posted speed limits during the first segment (16.1% below to 7.1% above), and this increased as they continued the drive. By the second segment, brain injured subjects' speed ranged from 9.0% below to 25.4% above the speed limit. Only 1 subject, a person with brain injury, drove both segments below the speed limit.

3.2.1.3. Speed Deviation

Speed deviation is a measure of a driver's ability to maintain a consistent speed. Little deviation indicates smooth, steady speed maintenance, whereas large deviation indicates that the driver is sometimes driving faster and sometimes slower even though the posted speed limit remains constant. As shown in Figure 3 all non-disabled subjects decreased their speed deviation from the early to the later road segment, while all brain-injured subjects increased their speed deviation between these same segments. The range of deviation decreased for the non-disabled subjects across the simulated drive (from .09mph at the first segment, to .03mph at the second), whereas the range increased for brain injured subjects (from .08 mph at the first segment, to .13 mph at the second). In the later segment of road, the brain injured group had a deviation range more than four times that of the non-disabled group.

3.2.2. Curved Roadway Segments

Four curved road segments were examined: 1) 45 mph posted left curve, 200 ft. length, tight radius; 2) 45 mph posted right curve, 200 ft. length, medium radius; 3) 35 mph posted left curve, 500 ft. length, medium radius; 4) 35 mph posted right curve, 1000 ft. length, wide (gentle) radius.

3.2.2.1. Lane Position

In the curved segments, Figure 4 shows that non-disabled subjects' lane positions were tightly clustered, and alternated from overall negative to positive values in response to the directions of the four curves (left-right-left-right) as subjects positioned their vehicles close to the inside of each curve.

Conversely, subjects with brain injury kept their vehicles positioned toward the left side of the lane regardless of the direction of the curve. In addition, in three of the four curves, brain injured drivers showed wider variability in lane position than did non-disabled drivers.

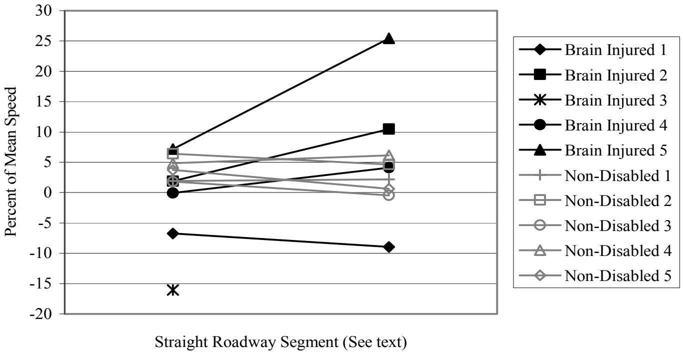

Fig. 2 – Percentage that subjects' mean speed was above/below posted speed limit on straight road segments

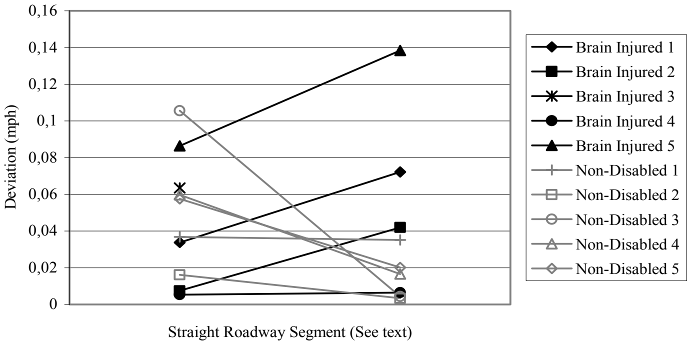

Fig. 3 – Speed deviation during straight segments of road

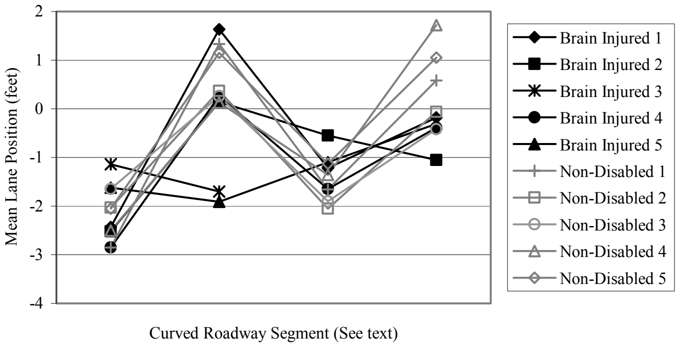

Fig. 4 – Mean lane position during curved segments of road

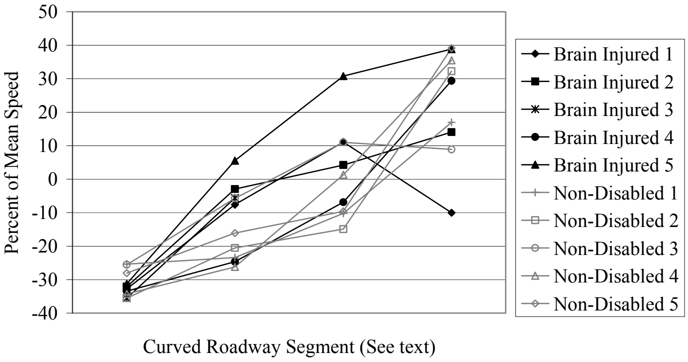

Fig. 5 – Speed deviation during curved segments of road

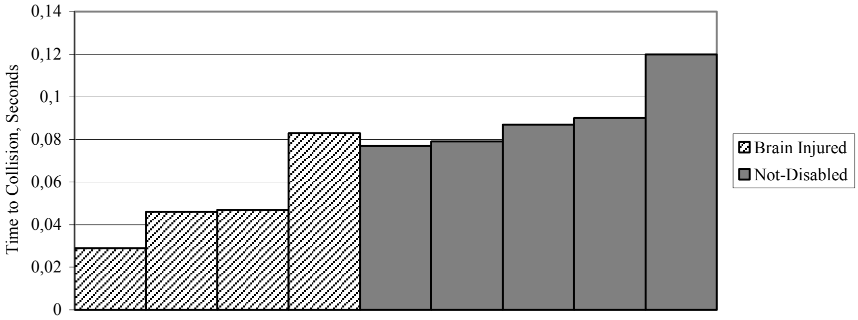

Fig. 6 – Time to collision for head on collision critical event

3.2.2.2. Speed

During the first curve, all 10 subjects drove 25-36% below the posted speed limit as shown in Figure 5. By the fourth curve, 8 of the 9 subjects were driving 9-39% faster than the posted limit. Though nearly all subjects increased their speeds for each successive curved segment, the brain injured subjects sped more than the non-disabled. The one exception, a person with brain injury, increased speed across the first three segments, but slowed on the fourth.

3.2.2.3. Speed Deviation

Individually, the brain-injured drivers demonstrated a less consistent drive than the non-disabled drivers. In addition, the range of speed deviations was wider for the brain injured group than for the non-disabled group across all of the curved segments.

3.3.Critical events

There were several cognitively demanding scenarios in the complex portion of the drive.

3.3.1. Head-on collision

As the participant driver rounds a left curve, an oncoming sedan pulls into the driver's lane to pass a bus that had been obscuring it. When the sedan and the driver's vehicle are within 2 seconds of colliding with each other (based on relative velocities), the sedan pulls back into its lane in front of the bus. The participant driver has a small window of time (3 seconds) to release the throttle, apply the brake, and steer away or the vehicles will collide. We measured the point where the driver recognized a threat, as indicated by removal of his or her foot from the throttle or the initiation of steering to avoid the obstacle. Time to collision shown in Figure 6 represents the amount of time remaining prior to collision when the participant driver first initiated evasive action of braking or steering. All subjects applied their brakes during the event, though brain injured subjects did so later than non-disabled.

All of the non-disabled subjects used steering in addition to brakes. Only 1 person with brain-injury deviated lane position to any significant degree, and one other brain-injured participant actually steered into the path of the oncoming vehicle.

3.3.2. Decision to pass

In this event, the participant driver is behind a slow-moving vehicle on a two-lane road where pavement markings do not permit passing. The slow pace of the lead vehicle assures that the subject cannot maintain the posted speed limit as instructed. We measured the distance that elapsed before the participant executed a passing maneuver once the roadway pavement markings permitted passing. All 4 of the brain injured subjects performed this passing maneuver sooner than any of the 5 non-disabled individuals despite the presence of oncoming traffic (Figure 7).

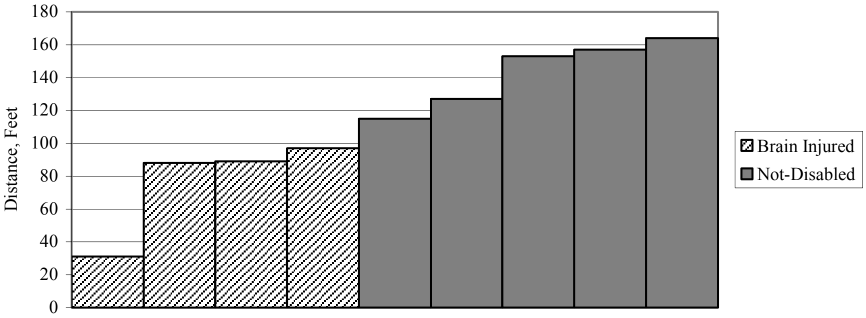

Fig. 7 – Critical Event: Distance before passing

Initiation of the passing maneuver once permitted ranged from 31-97 ft for the brain injured and from 115-164 ft for the non-disabled participants. The mean elapsed distance before passing was nearly twice as great for the non-disabled (143.2 ft) as it was for the brain injured (76.25 ft).

4. Discussion

Tally of discrete driving errors is the easiest data to access from the STISIM Drive software. It was, therefore, interesting to find that this data discriminated well between non-disabled subjects and those with brain injury, with strongest impact being derived from monitoring the number of times drivers ran off road (i.e., beyond shoulder), collided with other vehicles or objects, or failed to stop at STOP signs. Wald, et al., [41] reported failed stops as a common error among brain injured adults during simulated driving and Liu et al [29] demonstrated that a similar constellation of discrete events was able to discriminate between groups of brain injured and non-disabled individuals. The current study also partially supports a previous finding [29] that lane position may discriminate between brain injured and non-disabled groups in simulated driving. Though lane position on straight roadway segments did not appear to differentiate between brain injured and non-disabled subjects, positioning on curved roadways did appear to be differently handled by the two types of drivers. Non-disabled drivers “tracked” the curves, keeping their vehicles close to the inside of the curve affording themselves the best view of the road ahead. Subjects with brain injury showed a wider range of lane positions, and none demonstrated the flexible strategy of adaptive tracking based on curve direction. Instead, those with brain injury kept their vehicle position relatively fixed with regard to the road centerline. Liu, et al [29] do not note whether their lane position data is based on straight, curved, or a combination of roadways.

Liu et al [29] noted that normal subjects across a wide age range consistently drove below posted speed limits during simulations. In the current study, all of the non-disabled subjects drove straight segments at or slightly above the posted speed limits, and both brain injured and non-disabled subjects reduced their speed in early curves, gradually increasing so that nearly all subjects were speeding in later curves, some dangerously above speed limit

We could find no study that examined speed deviation (consistency of speed) for its discriminative possibilities. Our results indicate that brain injured subjects became less consistent in speed during later straight road segments, whereas non-disabled drivers’ speed maintenance became more consistent. Both brain injured and non-disabled subjects showed more similar trends across curved segments, where all subjects demonstrated increasingly inconsistent speed maintenance as the simulation progressed. It is difficult to know whether the brain injured subjects’ diminished ability to maintain smooth speed control was influenced by fatigue or by the stress associated with the complex traffic conditions that occurred closer to those portions of the simulation. In driving, braking is the most basic response to a potential collision [15]. It is learned before steering and is more in keeping with a person seeking a single act to meet a demand. Indeed, defensive steering though ‘regarded by experts as the quintessential ability for safe driving’ (15, p357), takes years to refine, and is considered a more complex action because it demands that the driver continue to dynamically control the vehicle. Indeed, anticipatory braking, defensive steering, and maintenance of focus on task during simulated driving have all been cited as strong factors in safe driving [15]. In the current study’s “head-on collision scenario” all subjects used anticipatory braking to slow their forward motion when they saw the on-coming vehicle. While this is the first impulse, the safest procedure is a combination of steering and braking. That combined strategy was seen in 3 of the non-disabled subjects. Thus, the majority of those without brain injury recognized, took quicker action, and took more complex action to avert the threat of head-on collision. This observation is strengthened when one notes the difference between the brain injured and non-disabled subjects' times to collision. Time to collision has been shown to be a sensitive measure of impairment [42]. It is unknown whether simple reaction time may also have contributed to the oversimplified strategy used by subjects with brain injury. A future study may wish to examine this element further.

Clear and consistent differences were also seen between the brain injured and non-disabled subjects' passing decisions and avoidance of collision. In all cases brain injured subjects initiated their passing maneuver sooner than did any of the non-disabled participants. This may indicate both a greater degree of impulsivity on the part of the impaired persons and their general failure to attend to the potential for oncoming traffic prior to taking this action.

A third specific challenge required participants to approach a cross road with a green traffic signal in their favor. To avoid a collision they had to attend to a vehicle approaching the intersection from the left along the cross road, and failing to stop for the red light. That 2 of the 4 impaired participants were involved in a crash with this vehicle indicates a failure of "proper lookout" and a lack of situation awareness. None of the non-impaired participants crashed.

5. Limitations

The current study is preliminary. Its results are based on an extremely small sample and therefore data cannot be examined statistically, nor can we securely generalize to the population. In addition, data was coded by subject group when evaluated, thus the results cannot be viewed as blinded and could reflect a bias of interpretation. In addition to its small sample, the results may be confounded by differences between the two groups, separate from brain injury or cognitive deficit. The brain injured subjects had not driven for an average of nearly 2 years, while the non-disabled group drove on a regular basis. It is also recognized that brain injured individuals have problems with fatigue [43]. Differences in performance on segments or critical events during the complex portion of the simulation could reflect differing fatigue levels and subtly differing motor abilities rather than differing cognitive abilities.

6. Conclusions

The purpose of this pilot study was to determine whether the STISIM driving simulator could be used to discriminate between the driving performance of cognitively impaired, brain-injured drivers and non-disabled drivers. The results demonstrated that in general, discrete events such as running off the road, crashing, running a stop sign or red light, and failure to execute turns are good discrimination indicators. Continuous indicators such as speed deviation on straight and curved roads and lane position during a curve also discriminate between the two populations. Other continuous indicators such as lane position on straight roads and average speed do not appear too useful as discriminators. The sample size in our study was too small to form conclusions based on statistical significance, but did point the way towards which indicators will be examined in future studies with larger numbers of subjects.

Acknowledgements

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