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Driver distraction: implications for individuals with traumatic brain injuries

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DRIVER DISTRACTION: IMPLICATIONS FOR INDIVIDUALS WITH TRAUMATIC BRAIN INJURIES

by

David Michael Neyens

An Abstract

Of a thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy degree
in Industrial Engineering in
the Graduate College of
The University of Iowa

December 2010

Thesis Supervisors: Adjunct Associate Professor Linda Ng Boyle
Associate Professor Geb Thomas

ABSTRACT

Traumatic brain injuries (TBIs) are injuries to the brain associated with the transfer of energy from some external source. There are an estimated 1.4 million TBIs each year, and about half are due to transportation crashes (NINDS, 2007). Driver distraction is defined as a process or condition that draws a driver's attention away from driving activities toward a competing activity (Sheridan, 2004) and has been identified as an under-examined issue for TBI populations (Cyr, et al., 2008). The interaction between the cognitive impairments related to TBIs and the competing demands from driver distraction may be especially problematic. The goal of this dissertation is to investigate the effect of driver distraction on individuals with TBI.

This dissertation uses several approaches and data sources: crash data, a TBI registry, a survey of TBI drivers, and an on-road driving study of TBI and non-TBI drivers. Results demonstrate that a subset of TBI drivers are more willing to engage in distracting tasks and they are more likely to have received speeding tickets. TBI drivers involved in crashes were less likely to wear seatbelts and were more likely to be involved in multiple crashes compared to all other drivers in crashes. Additionally, a subset of TBI drivers exhibits more risk-taking while driving that may result from the TBI or a predisposition to take risks.

A Bayesian approach was used to analyze the effect of distracting tasks on driving performance of TBI drivers in an on-road study. A simulator study of non-TBI drivers was used to develop prior distributions of parameter estimates. The distracting tasks include a CD selecting task, a coin sorting task, and a radio tuning task. All of the tasks contained visual-manual components and the coin sorting task contained an additional cognitive component associated with counting the currency. This suggests that TBI drivers exhibited worse driving performance during a coin sorting task than the non-TBI drivers in terms of the standard deviation of speed and maximum lateral acceleration of the vehicle. This suggests that the cognitive component of the coin sorting task may be causing the decreased performance for the TBI drivers. Across all tasks, TBI drivers spent a larger percent of the task duration looking at the task with a larger number of glances towards the distraction task than the non-TBI drivers.

Driver distractions with cognitive components may be especially problematic for TBI drivers. Future work should investigate if this effect is consistent across more complex cognitive driver distraction tasks (e.g., cell phone usage) for this population. Additionally, future work should validate the high proportion of TBI drivers involved in multiple crashes.

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CERTIFICATE OF APPROVAL

PH.D. THESIS

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To my parents and brother

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CHAPTER 1.
OVERVIEW

Traumatic brain injuries (TBIs) are injuries to the brain associated with the transfer of energy from some external source. There are an estimated 1.4 million individuals in the United States who experience a TBI each year, and about half of these are due to transportation crashes (including automobiles, motorcycles, bicycles and pedestrian crashes) (NINDS, 2007). These injuries are often referred to as the ‘silent epidemic’ because the resulting disabilities associated with these injuries are often invisible to others (e.g. cognitive impairments or personality changes) and because the general public is largely unaware of the prevalence of these injuries (Ruthland-Brown, Langlois, Thomas, & Lily, 2006). TBIs are associated with cognitive decrements, including issues with concentration, memory loss, confusion, as well as aggression, irritability, depression, apathy, anger, impulsivity, and impaired self awareness. There are also physical disabilities that include: decreased reaction time, decreased sensory perception, and general musculoskeletal complications (Walker & Pickett, 2007).

It is important to examine drivers with TBIs because they are a growing population that experiences increased risk while driving. It has been suggested that as many as 18% of soldiers returning from the active combat have experienced a TBI in the line of duty (AAN, 2009; Okie, 2005). The literature suggests that between 38% and 78% of all TBI survivors resume driving after their injury (Fisk, Schneider, & Novack, 1998; Schultheis, Matheis, Nead, & DeLuca, 2002). Additionally, drivers with TBIs have been identified as a ‘quadruple risk’ group because of (1) impaired cognitive functions, (2) overestimation of ability or denial of disability, (3) increases in overall reaction time, and the (4) existing high risk if the individual is young and male (Hopewell, 2002).

Driver distraction is defined as a process or condition that draws a driver's attention away from the safety critical activities toward a competing activity (Sheridan, 2004). It is also identified as an under-examined issue for TBI populations because few studies have examined it (Cyr, et al., 2008). In a psychological reaction time study it was shown that distracting signals increased reaction time in patients with severe concussions (TBIs) more than for controls (Stokx & Gaillard, 1986). The interaction between the cognitive function impairments related to TBIs and the competing demands related to driver distraction may be especially problematic. Distractions have been shown to be problematic for drivers, and the negative safety consequences of distractions may be more severe or have different consequences for individuals with TBI. This dissertation will investigate the effect of driver distraction on individuals with TBI.

The overall goal of this research is to develop a greater understanding of how driver distraction influences driving behaviors and subsequent crashes for TBI drivers. Data from an experiment, crash data, and a survey of TBI drivers will provide a means to examine this population from different perspectives to generate a more comprehensive view of the effect of driver distraction for this population.

Specific aims

- *AIM 1: Given that a driver is involved in a crash, determine if the crash characteristics (including driver distraction factors) differ between TBI drivers and non-*

TBI drivers. Crash data from the State of Iowa was linked to Iowa Brain Injury Registry data (using self-identifying information) in a case control design (with one case matched to one control). Additionally, an analysis of the crashes that cause TBIs is conducted to validate the case control and matching methods employed to ensure that conclusion about TBI drivers' crashes are feasible.

- *AIM 2: Evaluate the willingness of TBI drivers to engage in distracting activities.* A survey was distributed to TBI drivers to assess their willingness to engage in a set of distracting activities (e.g., talking on cell phones, text message, change CDs, or daydreaming). The survey provided insights on the association between risky driving situations the likelihood to receive speeding tickets or crash following a traumatic brain injury. The survey responses were clustered on their willingness to engage in these tasks. Given that studies have shown that teen drivers exhibit risk-taking behavior, the results of this survey were compared to another survey on teenage drivers' willingness to engage in the same tasks.

- *AIM 3: Evaluate how driver distraction influences driving performance for TBI drivers compared to non-TBI drivers.* Data from an on-road study and a simulator study was used to achieve this aim TBI and non-TBI drivers engaged in three common distracting tasks (a radio tuning task, a CD sorting task, and coin sorting task) are used to assess the effect of the tasks on driving performance.

These three aims together allow for an examination of how driver distraction influences driving performance and crashes for individuals with TBI. Examining this issue from different data sources allows conclusions that are more general, while accounting for limitations associated with data collected on participants with TBIs. Chapter 2 presents the synergy among these three aims in more detail and also provides a review of the relevant literature related to driver distraction, driving with cognitive decrements as well as TBIs and their influence on driving performance. Chapter 3 presents the results of the crash data analysis to address Aim 1. Chapter 4 presents the results of the survey of TBI drivers and their willingness to engage in distracting activities to support Aim 2. Chapter 5 describes the results of the simulator study used to support the analysis of the on-road data in Chapter 6 and both address Aim 3. Chapter 7 describes the general conclusions of this research and the direction of future research.

CHAPTER 2.
BACKGROUND

The goal of this research is to understand the implications of driver distraction on traumatic brain injured drivers. The first step in achieving this goal is to gain an understanding of the influence that distraction and other cognitive decrements have on driving performance. Defining traumatic brain injuries (TBIs) and describing how this type of injury influences driving are also critical to this research. This chapter summarizes the literature in this area and concludes with a discussion of the research gap that this dissertation addresses.

Driving with cognitive decrements and impairments

Driving following the diagnosis of a neurological or neurologically-related disorder has been a substantial area of research (Marcotte, et al., 1999; Marcotte, et al., 2004; Uc, Rizzo, Anderson, Shi, & Dawson, 2005; Uc, et al., 2006). For all medical-related complications, the responsibility for informing patients about their potential driving impairments has fallen on health care providers and this involves both legal and ethical issues that providers need to consider (Love, Welsh, Knabb, Scott, & Brokaw, 2008). There are several neuro-related conditions that have shown to affect driving performance. For example, HIV positive individuals have shown neuropsychological impairments that translate into decrements in driving abilities (Marcotte, et al., 1999; Marcotte, et al., 2004). Individuals with multiple sclerosis-related cognitive impairment have been shown to perform worse in a neurocognitive driving test (Schultheis, Garay, & DeLuca, 2001). Dementia of the Alzheimer’s type results in an increase in the crash risk per mile driven, regardless of the decrease in driving exposure for this population (Carr, Duchek, & Morris, 2000; Kaszniak, Kyle, & Albert, 1991; Parasuraman & Nestor, 1991). It has been shown that drivers with Alzheimer’s disease perform worse on a landmark and traffic sign identification task compared to a neurologically health drivers (Uc, et al., 2005). Individuals with Alzheimer’s disease have also been shown to almost universally experience spatial disorientation and get lost, in addition to experiencing degradation in directional senses (Monacellli, Cushman, Kavcic, & Duffy, 2003; Rainville, Marchand, & Passini, 2002). Parkinson’s disease is also associated with loss of motor control which also affects driving performance (Dubinsky, et al., 1991) and has been show to result in increased crash risk (Borromei, et al., 1999; Uc, et al., 2006; Zesiewicz, et al., 2002). Individuals who have survived a stroke (cerebrovascular accidents) perform worse in driving simulators, in on-road driving assessments as well as have worse performance on neuropsychological evaluations than control (Lundqvist, Gerdle, & Ronnberg, 2000). It has been demonstrated that individuals with a stroke who scored poorly on two neuropsychological tests were 22 times more likely to fail an on-road evaluation (Mazer, Korner-Bitensky, & Sofer, 1998). In another study, about 54% of stroke patients were considered fit to drive post injury (Ponsford, Viitanen, Lundberg, & Johansson, 2008). Driving simulator based training programs have been shown to improve driving ability for individuals who experienced a stroke (Akinwuntan, et al., 2005).

This dissertation leverages the quantity of the research related to the effects of cognitive decrements on driving. However, there are distinct differences that warrant their investigation as an independent group. Often, individuals who experience a TBI are much younger than individuals who experience other types of cognitive impairments (e.g., Alzheimer’s disease). Age-related differences have been identified in driving experience, risk taking behaviors, and willingness to engage in non-driving-related activities (Donmez, Boyle, & Lee, 2010; Ferguson, 2003; Massie, Campbell, & Williams, 1995). Therefore, younger TBI drivers may differ from older cognitively impaired drivers. The next section defines TBIs are and describes the incidences and prevalence of these injuries in the US.

Defining a TBI

Figure 2 abstractly shows the location of cognitive processes within the brain. Injuries to specific parts of the brain can cause specific decrements in cognitive functions (e.g. damage to the occipital lobe can relate to decreased visual abilities). TBIs are injuries sustained to the brain due to damaged brain tissue. The damage is caused by bruising, bleeding or penetration related to trauma, rather than disease. These injuries are heterogeneous in nature due to the location of primary injuries and the extent of more widespread damage.

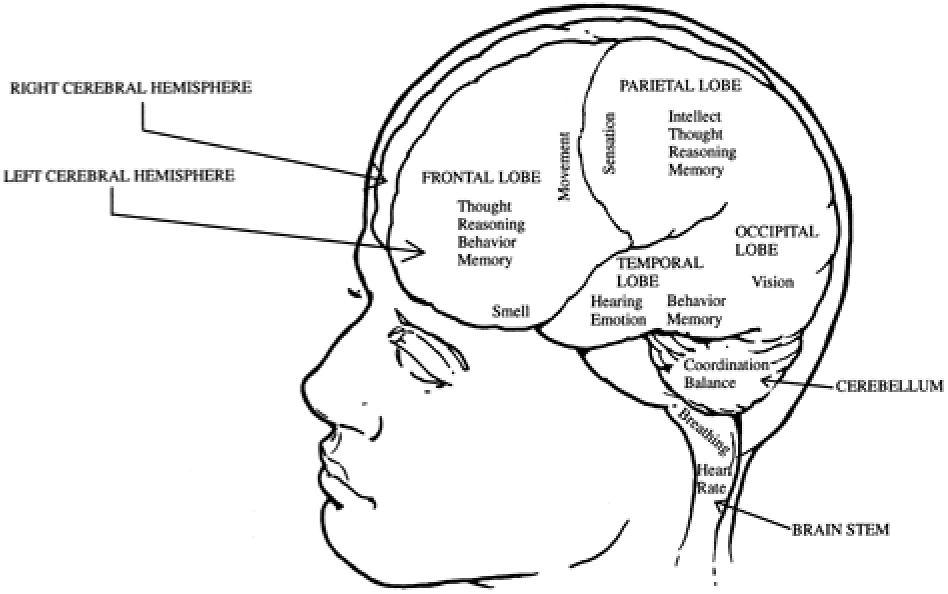


Figure 1. Theoretical locations of brain processes (Wagner & Stenger, 1999)

Given that TBI involve the transfer of substantial energy to the brain, there is often distributed damage within the brain. When an axon (projection of a nerve cell in the brain) is sheared, it releases a toxic level of neurotransmitters that destroy the surrounding neurons (Kochanek, Clark, & Jenkins, 2006). This cascade of toxic levels of neurotransmitters causes the primary injury to disseminate destruction beyond the actual injury site and translates the primary injury into distracting, more widespread, injuries (Kochanek, et al., 2006). This distribution of injury is the root of the widespread types of disabilities associated with TBIs.

Acquired brain injuries can also result in damage to the brain but are not traumatic. These non-traumatic injuries include aneurisms and strokes as well as anoxia (total oxygen depletion to the brain) and hypoxia (partial oxygen depletion to the brain). These non-traumatic injuries are excluded from this dissertation as they do not result from an injury related to a transfer of energy to the brain, but can relate to other causes of brain injuries.

The residual impairments associated with TBIs can result in dementia with many individuals maintaining the ability to perform many daily activities to a level similar to pre-injury levels. Additionally, there are several residual neuropsychological impairments associated with these injuries, including: irritability, impulsiveness, aggressiveness, poor concentration, increased fatigueability, poor memory, and personality changes (van Zomeren, Brouwer, & Minderhoud, 1987). Individuals with TBIs are at in increased risk of developing depression and can require personalized treatment plans due, in part, to their reactions to their difficulties and failing to regain their pre-injury roles (Ownsworth & Oei, 1998). Aggressive behaviors are experienced by about 25% of all individuals with TBIs and aggression has been shown to be significantly related to post injury depression and also being younger when the injury occurred (Baguley, Cooper, & Felmingham, 2006). Agitation has also been shown to occur in post injury in individuals with TBI (commonly in conjunctions with confusion) which impacts rehabilitation efforts (Lequerica, et al., 2007). Individuals with TBI can also experience both verbal and motor impulsivity, which are complex and difficult to assess clinically (Votruba, et al., 2008). Additionally, these injuries are also associated with difficulties with short term memory, sequencing events, formulating goals, planning and problem solving, carrying out a plan, and effective performance (Hopewell, 2002; IDPH, 1998). All of these characteristics (e.g., aggressiveness, impulsivity, planning and problem solving) are especially important for safe driving (Lajunen & Parker, 2001).

The symptoms of TBIs affect every aspect of a survivor's life. Survivors have reported experiencing disabilities in administrative tasks (including financial management), calculating, driving, planning, and using public transportation as most related to social autonomy (Mazaux, et al., 1997). Additionally, depression, psychomotor slowness, loneliness and reduced family and social functioning were found (both ten and twenty years after injury) to be associated with more severe injuries than moderate injuries (Hoofien, Gilboa, Vakil, & Donovick, 2001).

TBIs are also associated with many neuro-musculoskeletal disabilities. Much of the discussion of musculoskeletal problems are related to prolonged bed-rest as part of TBI recovery (Bell, 2007) and damage to the motor control area of the brain and the corticospinal tract (Mayer, Esquenazi, & Keenan, 2007). TBIs can result in muscle tightening, spasms, co-contraction of muscles, and spasticity (Mayer, et al., 2007). With rehabilitation, these physical disabilities have been shown to improve in some patients, however, tandem gait impairment (walking on a straight line with the heal of the front foot touching the toes of the back foot) is persistent and common (Walker & Pickett, 2007).

The severity of a TBI is an important aspect in terms of the residual impairments and the rehabilitative outcomes including resuming driving and safe operation of a vehicle (Schanke & Sundet, 2000). Typically the severity of TBIs is categorized into mild, moderate and severe injuries based on the Glasgow Coma Scale (GCS) score (Rowley & Fielding, 1991; Teasdale & Kannett, 1974) or the duration of the posttraumatic amnesia (van Zomeren, et al., 1987). As expected, the severity of injury is a moderating variable in terms of driving outcomes and driving performance for TBI drivers with those who are more severely injured less likely to resume driving or pass driving evaluations (Brenner, Homaifar, & Schultheis, 2008; Handler & Patterson, 1995; Priddy, Johnson, & Lam, 1990; van Zomeren, et al., 1987).

Incidence and causes of TBIs

As mentioned earlier, each year approximately 1.4 million individuals in the United States experience a TBI and about 50,000 are fatal (NINDS, 2007; Thurman & Guerrero, 1999). In 2003, there were 1,565,000 TBIs in the US, which resulted in 1,224,000 emergency room visits, 229,000 hospitalizations, and 51,000 fatalities (Langlois, Rutland-Brown, & Wald, 2006; Ruthland-Brown, et al., 2006). Between 1980 and 1995, there has been a decrease in the hospitalization of TBI-related injuries, with the most notable decrease occurring for mild injuries and for patients between 5 and 14-years-old (Thurman & Guerrero, 1999). The decrease has been associated with better injury prevention efforts, changes in hospital admittance procedures, and better diagnostic and classification of these injuries (Thurman & Guerrero, 1999). However, the shift towards treating these patients as outpatients raises additional concerns regarding their ability to drive to and from the medical and rehabilitative services (Thurman & Guerrero, 1999). Additionally, implementation of trauma systems in rural areas have been shown to lead to more appropriate injury triage and emergency transportation, thus reduced mortality (Tiesman, et al., 2007). TBIs have the highest incidence rates in the elderly (greater than 85 years-old) and the young (15-24 year-olds) with males more likely to experience TBIs in each age category (IDPH, 1998).

There are several common causes of TBIs. For example, in Iowa the two leading causes of TBIs are motor vehicle crashes and falls, accounting for about 70% all TBIs (IDPH, 1998). Nationally, the majority of TBIs are related to falls (32%), followed by motor vehicle crashes (19%), being struck by or against (18%), assault (10%), and other or unknown (21%) (Ruthland-Brown, et al., 2006).

As mentioned earlier, vehicular crashes are a major source of severe injuries that include TBIs (NINDS, 2007; Peden, et al., 2004). Viano et al. (1997) showed that between 1981 and 1992, there were 695 individuals hospitalized in a Swedish hospital due to head injuries and of which 38% were sustained in vehicular crashes. Tagliaferri et al. (2006) reviewed several European studies and found similar results, with vehicular crashes associated with between 11% and 60% of all individuals who sustained a TBI.

The literature documents several factors that can influence the likelihood of sustaining a TBI in a crash. These factors can relate to the individual, the vehicle involved, or the crash type. Viano et al., (1997) examined individuals admitted to the hospital for traffic-related injuries and reported that pedestrians who collided with a motor vehicle had the most severe head injuries when compared to other groups (e.g., drivers, passengers, motorcyclists).

Javouhey et al. (2006) examined data from a road trauma registry from the Rhône region of France. They established incidence and mortality rates based on population estimates and found that un-helmeted motorcyclists, pedestrians, un-helmeted bicyclists and unrestrained car occupants have between 2.8 and 18.1 times higher risk of sustaining severe TBIs compared to restrained car occupants when in a crash (Javouhey, et al., 2006). In the same study, collisions with fixed objects and other vehicles were associated with an increase in risk of severe TBIs compared to collisions with non-motorized road users (Javouhey, et al., 2006). Additionally, alcohol has also been related to anywhere from 24% to 51% of crashes that cause TBIs (Tagliaferri, et al., 2006). Airbags have been shown to significantly reduce fatalities and have protective effect at higher changes in velocity during a crash (higher delta-V), they may exhibit an harmful effect at lower change in velocities during crash (lower delta-V) especially for female drivers (Segui-Gomez, 2000).

Driving with a TBI

TBIs vary dramatically in terms of severity and recovery time. Driving following a TBI has been related to the level of community integration that TBI survivors experience (Rapport, Hanks, & Bryer, 2006) and has been shown to be a moderating factor in terms of steady employment after a TBI with drivers being more likely to be steadily employed (Kreutzer, et al., 2003). Pietrapiana et al. (2005) found that there were several factors that influence driving safety following a TBI including the number of years post injury, premorbid crashes and violations, premorbid highly risky personality, and premorbid driving style. This suggests that premorbid factors including a history of traffic violations and crashes should be included in the evaluation of whether an individual with a TBI should resume driving. However, these factors did not explain all of the variability in driving performance following a TBI. There are several substantive reviews of the literature synthesizing the research in this field (Fox, Bowden, & Smith, 1998; Handler & Patterson, 1995; van Zomeren, et al., 1987).

In Michon’s hierarchical model of driving there are three levels of driving skill and control, including strategic (planning and trip level decisions including willingness to engage in distracting tasks), tactical (maneuvering decisions) and operational (vehicle control) levels (Michon, 1985, 1989) (see Figure 1). For example, drivers make decisions at the strategic level of driving control by making decisions to avoid certain driving situations including adverse weather, high traffic density, complex intersections, or engaging in distracting tasks. At the operational level drivers may select larger following distances, or avoid driving in the left lane during highway driving. At the tactical level of driving, drivers can adapt the actual control the vehicle including anticipatory braking, speed maintenance and maintaining a desired lane position.

The time scales of Michon’s model of driving performance are important to identify the hierarchical nature of the model. Operational control is the millisecond-by-millisecond lateral and longitudinal control of the vehicle. Tactical control related to decision earlier than the actual control of the vehicle including turn signal use, anticipatory braking, and lane selection (on a multi-lane road). Strategic control can relate to decisions related to planning trip routes, time scheduling, and decisions to engage in distracting tasks in general and the willingness to engage in distracting tasks when they present themselves to the driver (e.g., cell phone rings). These decisions at the strategic level of driving reduce the time pressure at the operational level, which then reduces tactical demand. de Raedt & Ponjaert-Kristoffersen (2000) suggest that drivers can exhibit behaviors at each hierarchical level of driving as a goal to reduce a drivers’ cognitive load and with a potential byproduct of increased safety, rather than safety as the main goal of the behaviors at each level of driving.

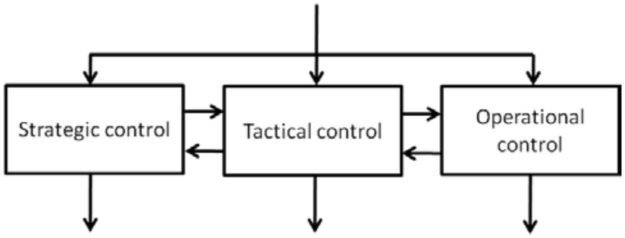


Figure 2. Abstract view of Michon's model of driving performance

In terms of TBI drivers, van Zomeren et al. (1988) suggests that they can make decisions at the strategic and tactical level of driving to reduce the time pressure at the operational level of driving such that they are able to perform similar to non-TBI drivers. Additionally, anticipatory attention is critical for TBI drivers to be aware of changes in the complexity of the driving task. When the driving task does become more complex, then drivers can either devote more attentional resources to the driving task or they can reduce their driving speed (Lundqvist, 2001). An interest in driving and motivation for safe driving and driving experience have also been shown to be associated with adaptive aspects of safe driving for this population (Lundqvist & Rönnberg, 2001). TBI survivors report that they drive at lower average speeds than prior to their injury, they leave earlier to allow more time, and avoid adverse weather, nighttime and freeway driving (Hopewell, 2002). TBI drivers report that they limit their driving (e.g. driving at night, rush hour) more than non-TBI drivers limit their driving (Schultheis, et al., 2002). Typically studies investigate behaviors of TBI drivers at the strategic and operational level of driving. Examining the driving performance at different levels of driving can offer insights into how TBI drivers differ from non-TBI drivers.

Differences have also been shown between those individuals with TBIs that resume driving and those that have not (Leon-Carrion, Dominguez-Morales, Barroso, & Martin, 2005). In one study, 32% of patients with severe TBIs (29 out of 90) resumed driving. Of these 29 drivers, 38% were involved in a traffic crash following injury with a relative risk of 2.3 (Formisano, Bivona, Brunelli, Giustini, & Taggi, 2001; Formisano, et al., 2005). However, a separate study showed that individuals with TBI or cerebrovascular accidents (strokes) were not at a greater risk for crashes or citations than non-injured individuals (Haselkorn, Mueller, & Rivara, 1998). It has also been shown that the number of citations and crashes may not change significantly before and after an individual experienced a TBI, for those who resumed driving (Dimarco & Cantagallo, 2001). The lack of significant increases in risks for TBI drivers may relate to license suspension or self-regulation in driving. Some individuals with TBIs voluntarily restrict themselves from driving. In fact, brain injured patients surveyed a minimum of six months after TBI showed only 38% (n=19) were actively driving and 42% (n=21) chose to keep their drivers' license (Priddy, et al., 1990). However, once a TBI patient passes a driving evaluation, Schultheis, et al., (2002) found no significant differences in the self reported or police documented crashes between individuals with TBI and age, gender, education and driving experience matched non-TBI drivers.

Using neuropsychological tests as a construct to relate cognitive ability to driving safely could be a cost effective means of determining those individuals who have the highest risk of crashes. However, many neurological tests (and combinations of neurological tests) have been associated with inconclusive driving results (Allegri, Tanzi, & Cattelani, 2001; Martelli & Mazzucchi, 2001; Strypstein, Arno, Eeckhout, & Baten, 2001). Combining neuropsychological test with driving evaluations has also produced inconsistent results (Brooke, Questad, Patterson, & Valois, 1992; Strypstein, et al., 2001; van Zomeren, et al., 1988). In fact, a perceptual speed test and time estimation test, in addition to coma duration, and driving experience were used to explain the variability experienced with an on-road driving test for brain injured subjects (Korteling & Kaptein, 1996). While significant, these variables did not explain enough of the variability in the on-road test (only 34.3% of the variability) and the results were deemed insufficient to replace a traditional on-road driving evaluation (Korteling & Kaptein, 1996).

A very important aspect of TBI and driving research is discriminating between those who maintain the ability to drive following a TBI and those who do not. It has been suggested that more than 75% of individuals with brain injuries do not receive on-road driving evaluations (Fisk, et al., 1998). TBI patients who receive appropriate driving rehabilitation and evaluation appear able to compensate for cognitive impairments and were able to pass a driving evaluation at the same rate as a matched control group (Katz, et al., 1990). Additionally, the means by which individuals compensate for their decrements while driving may also impact their ability to drive (Strypstein, et al., 2001). Additionally, a positive relationship was found between neuropsychological impairment and failure in driving evaluations, yet the ecological validity of standard neuropsychological tests remains somewhat uncertain (Schanke & Sundet, 2000). While neuropsychological tests are useful in identifying substantial impairment in this population and thus those that should not resume driving, they may not appropriately provide a measure of the driving ability of those with mild-moderate impairments.

Driver distraction review

Driver distraction is defined as the process or condition that draws a driver's attention away from the safety critical activities toward a competing (non-safety critical) activity and can result from factors inside and outside of the vehicle (Sheridan, 2004; Stutts, Reinfurt, & Rodgman, 2001). Distractions have been estimated to relate to 23% of crashes in the U.S. (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006), and the increasing number of devices that can be used in a vehicle suggests that this trend will only increase (Olsen, Lerner, Perel, & Simons-Morton, 2005; Sarkar & Andreas, 2004).. The effects of driver distractions on driving performance and the mechanisms used to mitigate these effects have been a substantial area of research (Consiglio, Driscoll, Witte, & Berg, 2003; Donmez, Boyle, & Lee, 2003; Donmez, Boyle, & Lee, 2006; Hancock, Lesch, & Simmons, 2003).

There has been a substantial amount of research conducted on the effect of driver distraction on driving performance including a special section of the Human Factors journal in 2004 (Poysti, Rajalin, & Summala, 2005; Reed & Green, 1999; Salvucci, 2001; Strayer & Drews, 2004; Stutts, et al., 2001; Summala, Nieminen, & Punto, 1996; Tsimhoni, Smith, & Green, 2004). Cooper et al. (2003) suggest that a distracted driver may also make more risky decisions. They found that distracted drivers make left hand turns with smaller gap acceptance (the distance between vehicles in oncoming traffic) than drivers who were not distracted. Additionally, cell phones have received substantial attention in both research and in the popular press. Cell phone tasks have been shown to result in greater variability in lane control (standard deviation of steering wheel angle) and speed control (standard deviation of speed) (Reed & Green, 1999). In-vehicle tasks have been associated with poorer performance and mitigating the effects of these tasks have been a substantial area of research (Donmez, Boyle, & Lee, 2003; Donmez, Boyle, & Lee, 2006).

The location, duration, and frequency of glances while engaged in a distracting task are also very important to understand since they give insights on what information drivers are acquiring from the environment and how they are engaged in the task [e.g., Lee (2009)]. Drivers tend to not glance away from the roadway for longer than 1.5 seconds, and when glances exceed more than two seconds their crash risk is twice that of normal driving (Klauer, et al., 2006; Wierwille, 1993). Several studies have investigated the eye movements and gaze durations while drivers are engaged in distracting tasks (Hoffman, Lee, McGehee, Macias, & Gellatly, 2005; Sodhi, Reimer, & Llamzares, 2002). In fact, Hoffman et al., (2005) found that characteristics of in-vehicle text messaging system affected the number of glances to the display more than the duration of the glances to the display. However, Sodhi, Reimer, and Llamazares (2002) found that a radio tuning task resulted in longer glances to the radio than other in-vehicle systems and devices (e.g., rear-view mirror, or odometer).

Some drivers are more willing to engage in secondary tasks than others. For example, Young & Lenné (2010) showed that younger drivers are more willing to engage in distracting tasks than either middle-aged or older drivers. Teenage drivers can also comprise different groups with some being very willing to engage in distracting activities when compared to other young drivers (Westlake, 2009). Crash involvement is correlated with increases in willingness to engage in distracting tasks, with those most willing to engage in distracting tasks having the highest number of crashes (Westlake, 2009).

Gaps in the literature

While there is a plethora of literature examining the effects of driver distraction on driving performance and the ability of individuals with TBI to drive following the injury, these areas are not well connected. In fact, driver distraction has been identified as an under-examined issue for individuals with TBI (Cyr, et al., 2008). It has been shown that distracting signals increase reaction time in individuals with TBIs more than for non-TBIs (Stokx & Gaillard, 1986). Deficits in cognition including attention, information processing speeds, and divided attention, are well established in the literature for individuals with TBIs (Mathias & Wheaton, 2007; Park, Moscovitch, & Robertson, 1999). The interaction associated with cognitive impairments from TBI and the demands for cognitive resources from distracting tasks can be problematic for these drivers. In one of the only studies linking TBIs and driver distraction, Cyr et al. (2008) found that drivers with TBIs crashed more during incursion events while completing a distracting task in a driving simulator than non-TBI drivers.

Specific aims

The interaction associated with cognitive impairments from TBI and the demands for cognitive resources from distracting tasks will be addressed with three specific aims: examining the crash characteristics of crashes of TBI drivers, examining TBI drivers' willingness to engage in distracting activities, and examining the influence of driver distraction on the driving performance of TBI drivers. Figure 3 shows the relationship between the three specific aims. The strategic, operational and tactical control for all three levels of driving are affected by driver characteristics (e.g., age experience, TBI status), driving task demands (e.g., traffic conditions, road design, vehicle speed) and distracting task demands (e.g., task complexity, duration and resource complexity with driving task) (Young, Regan, & Lee, 2008). Michon's hierarchical model of driving is operationalized according to three specific tasks that cascade into crash characteristics. The first specific aim of this dissertation assesses the crash factors associated with TBI drivers (Chapter 3). The second specific aim of this dissertation assesses TBI drivers' willingness to engage in distracting tasks (strategic control) (Chapter 4). Tactical control relates to the eye gaze variables related to engagement in the distracting task and tactical control is associated with the driving performance measurements during the engagement of the distracting tasks. Specific Aim 3 assesses the operational control and tactical control (Chapter 6).

The results of these analyses will quantitatively build on the existing knowledge base. Bayesian statistical methods will be used (when appropriate) so that the results of these analyses can support future work and to obtain higher confidence in the effect estimates.

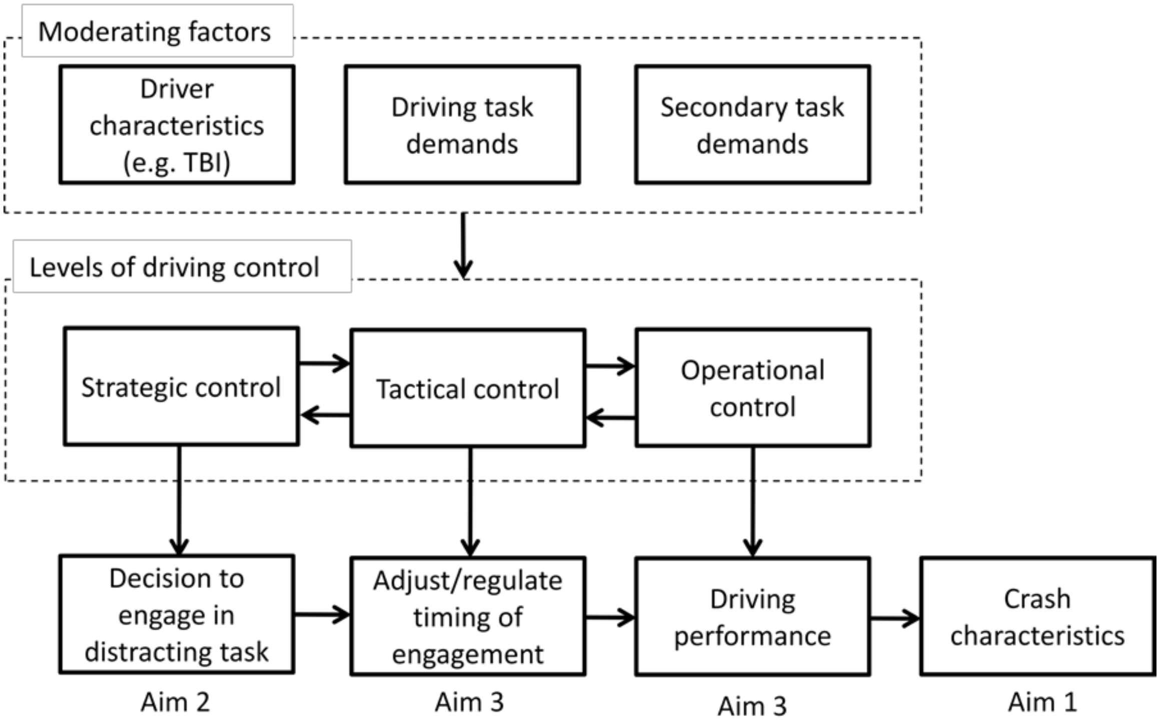


Figure 3. Factors that influence the engagement and effects of driver distraction on driving performance and crash characteristics based on Young, Regan, & Lee (2008) and Michon (1985, 1989)

CHAPTER 3.
TRAFFIC CRASHES AND TRAUMATIC BRAIN INJURIES

The work presented in this chapter addresses Specific Aim 1 of this dissertation through two objectives, to examine: (1) the characteristics of crashes that are associated with an individual sustaining a TBI, and (2) the crash factors associated with drivers who are TBI survivors. The first objective will demonstrate that the crash factors observed in Iowa are consistent with the existing TBI literature. This will then support the use of the Iowa data for examining crashes that involve TBI drivers and support the generalization to TBI survivors in other areas.

Incidence of TBI in Iowa

The analysis presented in this chapter used data from the State of Iowa as a case study to examine factors related to crashes and TBIs. While it is estimated that Iowan's experience a relatively small number of TBIs compared to individuals in other states in the US (Kegler, Coronado, Annest, & Thurman, 2003) the incidence rate is comparable to the rates reported in several European studies (i.e., Tagliaferri, et al., 2006). In Iowa, there were on average 2,610 hospitalizations per year for TBIs between 2003 and 2005 (IDPH, 2007b). In an analysis matching crash-related hospital data (Iowa CODES [Crash Outcome Data Evaluation System]) and hospital inpatient discharge data (between 2001 and 2003), an average of 577 cases of TBIs caused by motor vehicle crashes were observed each year (IDPH, 2007a). This study revealed differences in the likelihood of sustaining a TBI in traffic crashes when compared to other possible injuries. They found that motorcycle riders (regardless of helmet use) were 1.5 times more likely to sustain a

TBI when compared to car occupants (regardless of restrain use) (IDPH, 2007a). When involved in a crash, un-helmeted motorcycle riders were 2.7 times more likely than helmeted motorcycle riders to sustain a TBI (than other injuries). Likewise, unrestrained SUV occupants were 2.0 times more likely to sustain a TBI compared to restrained occupants in SUVs, and unrestrained passenger car occupants were 1.5 times more likely to sustain a TBI when compared to restrained occupants in passenger cars (IDPH, 2007a). Additionally, when involved in a crash, impaired drivers were 1.4 times more likely to sustain TBI than other injuries compared to non-impaired drivers (IDPH, 2007a). However, because the CODES data only contains data about injuries associated with traffic crashes, it is difficult to quantify the likelihood of sustaining a TBI when compared to crashes that do not result in injuries.

Methods

Data sources

In order to address the goals of this study, two data sources were used; the Brain Injury Registry maintained by the Iowa Department of Public Health and the SAVER (Safety Analysis Visualization Exploration Resource) crash database maintained by the Iowa Department of Transportation.

Crash Database

The Iowa crash database consists of police reported crashes with property damage of at least 1,000 US dollars. The database includes information about environmental, roadway, vehicle, driver, and crash factors for each entry. When responding to a crash, police document these factors on paper reports that then populate the database. This study uses crash data between 2001 and 2006. Only the overlapping years between the brain injury registry and the crash data (2001-2006) are used for the examination of the crashes associated with TBIs. To examine the crashes of TBI survivors, the brain injury registry data was used beginning with 1995, because drivers with prior TBIs were of interest for this analysis of crashes.

The crash characteristics includes identifying the manner in which the vehicle(s) collided, the severity of the crash, the location and time of the crash, and the major causes for the crash (e.g. improper lane change, failure to yield right of way). Specific to the individual information, the database contains information about the individual’s age, gender, impairment status (e.g. under the influence of alcohol), whether citations are given, the injury level sustained in the crash, and driver contributing circumstances. Driver distraction-related variables within crash databases are known to be under-represented in crash data due to the nature of self-reporting and police documentation, however, the data that is collected can provide a means to understand the role that documented driver distraction has in crashes. Table 1 shows the driver distraction related variables in the Iowa crash data.

The specific crash types included in this analysis include: angular collisions with other vehicles, rear-end collisions head-on collisions, and single vehicles crashes (e.g., collisions with fixed objects). These are the most common crash types for all drivers (NHTSA, 2008).

TBI Registry

The Brain Injury Registry in the State of Iowa was initiated in 1988 (Harrision & Dijkers, 1992). This registry contains information on all of the individuals who have experienced a TBI in the state of Iowa. During this period (1995-2006) there is data for 22,929 individuals who have sustained a TBI (including those with missing data). This data includes individuals of all ages, with a mean age of 38.0 years-old (SD=26.8) at the time of injury (Figure 4). Of all of the individuals in the database, 65.6% are male.

The Glasgow Coma Scale (GCS) is a tool used to assess the level of consciousness of patients with head injury based on three characteristics: eye opening, verbal response, and motor response (Rowley & Fielding, 1991; Teasdale & Kannett, 1974). The score can range from 3 to 15: with scores less than 9 indicating severe injuries, 9-12 indicating moderate injuries, and greater than 12 representing mild or minor injuries (NINDS, 2007). Table 2 shows the specific ratings. The Glasgow Coma Scale (GCS) score of those in the database appears to be a bimodal distribution with two maxima at GSC scores of 3 and 15 with a mean of 12.6 (SD=4.1) but is missing in almost 12% of the database. This demonstrates that the database has many individuals with mild TBIs and many with very severe TBIs (see Figure 5). The GCS and the time since injury are important indicators of injury severity and potential recovery times for individuals with TBI. These variables are available in the Iowa Brain Injury Registry.

Table 1. Crash data parameters used to define driver distraction in the Iowa crash data

Database table	**Variable**	**Values**	**Used in this analysis**
Crash Parameters 1	Major cause		
		Inattentive/distracted by passengers	X
		Inattentive/distracted by use of phone or device	X
		Inattentive/distracted by fallen object	X
		Inattentive/distracted by fatigued/asleep	
Driver Crash Parameters 1	Driver contributing circumstances 1		
		Inattentive/distracted by passengers	X
		Inattentive/distracted by use of phone or device	X
		Inattentive/distracted by fallen object	X
		Inattentive/distracted by fatigued/asleep	
Driver Crash Parameters 2	Driver contributing circumstances 2		
		Inattentive/distracted by passengers	X
		Inattentive/distracted by use of phone or device	X
		Inattentive/distracted by fallen object	X
		Inattentive/distracted by fatigued/asleep	

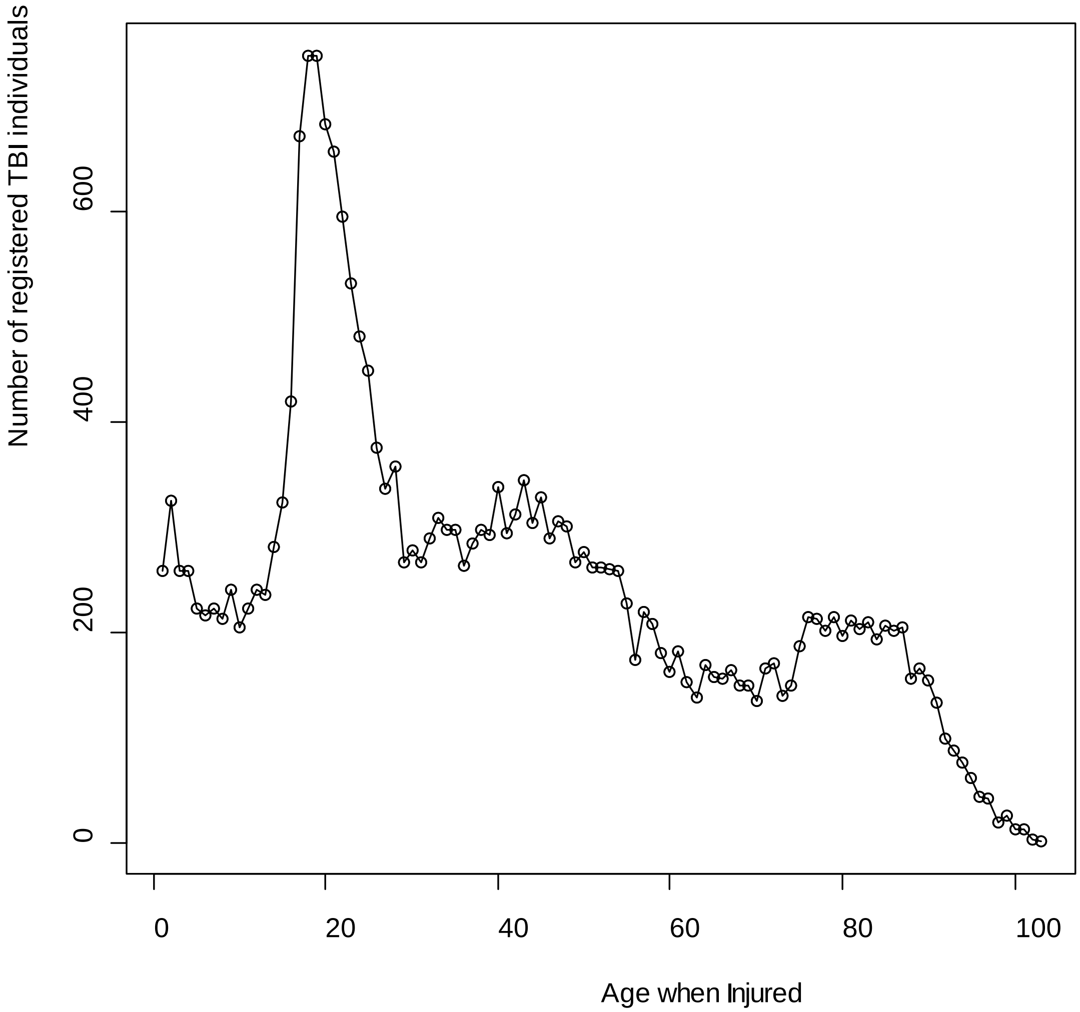


Figure 4. The age distribution of the individuals within the TBI Registry at the time of the injury (for the State of Iowa between 1995 and 2006)

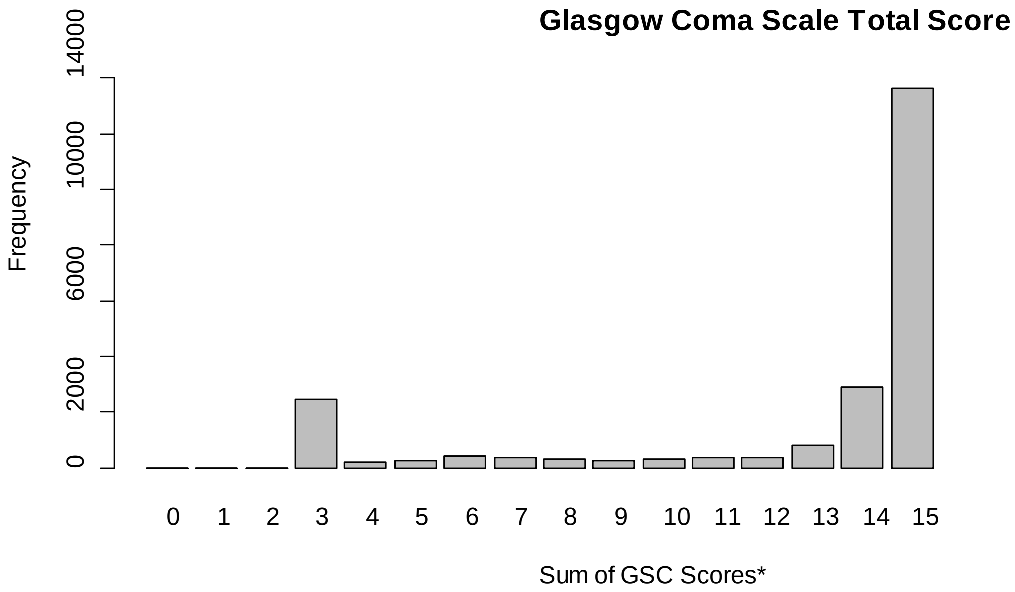


Figure 5. The total Glasgow Coma Scale Rating (The summation of the eye opening, verbal response, and best motor response scores) *Note: Missing values for 3,027 out of 22,929 records)

Table 2. Glasgow Coma Scale composition and rating scale

Score	Description
Eye Opening	
4	Spontaneous
3	To Voice
2	To Pain
1	None
0	Preorbital swelling
Verbal Response	
5	Oriented
4	Confused
3	Inappropriate words
2	Incomprehensible words
1	None
T	Intubated
Best Motor Response	
6	Obeys Commands
5	Localized pain
4	Withdraw (on pain)
3	Flexion (on pain)
2	Extension (on pain)
1	None

Merging databases

Personal identifying information was matched to link the registry and the crash database [IRB #200708724]. The crashes that involved individuals in the TBI registry were identified using three unique identifiers: the individual’s last name, first name, and date of birth (see Figure 6). Cases that had birth dates that did not match perfectly or differences in spelling of first or last names were excluded. The matching was relatively strict to control for type one error in the identification of the cases, that is, no non-TBI drivers in crashes were identified as TBI drivers. The databases were merged using SQL in MS Access 2007, as it is insensitive to character case in the data. The merging of the databases was verified by manually checking the matching of these variables. The matching resulted in 2,817 crashes that were associated with an individual experiencing a TBI because of the crash (as the crash and injury occurred on the same day), and 1,591 crashes involving drivers who are TBI survivors.

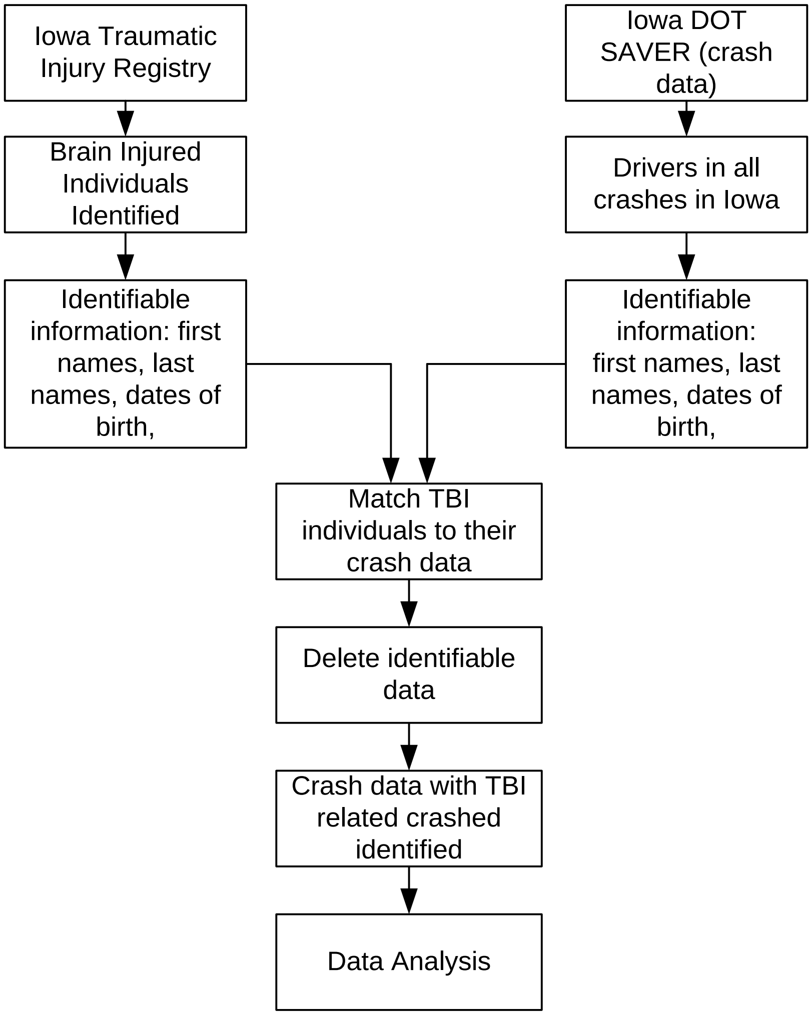


Figure 6. Process used for linking TBI registry data to Iowa crash data

Matching and selecting controls

For both objectives of this chapter, case-control methods were used to match individuals with TBI involved in crashes to non-TBI individuals involved in crashes. Case-control methods are particularly well suited for investigating risk factors on relatively rare diseases or injuries (Woodward, 2005), as observed in this study. The matching was based on the individual's date of birth and gender, the setting of the crash (rural or urban), and the speed limit of the roadway at the crash location for each year of data. For the first goal of the study, crashes involving an individual who sustained a TBI as a result of a crash [case] were matched with crashes that did not result in a TBI [control]. For the second goal of this study, crashes involving TBI drivers [case] were matched to crashes that did not involve TBI drivers [controls]. The second objective is only concerned with drivers so passengers with TBIs were excluded. The controls were randomly selected from the crashes that met the matching criteria (using a random seed to sort the matching records) from the crash database using SQL.

<u>Analysis methods</u>

Data analysis

Binary logistic regression models were used to address both objectives of this chapter. The logistic regressions were conducted using the GLIMMIX procedures in SAS 9.2. This modeling technique generates parameter estimates that can be used to predict the logit-transformed probabilities of an explanatory factor being more likely associated with one outcome compared to another (see Equation 1). Conditional logit models were not used because there were insufficient category level variables to warrant the use of this type of model.

$$y_i = \ln\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_n X_{ni} \qquad \text{(Eq. 1)}$$

The parameter estimates are used to calculate adjusted odds ratios (AOR) that take into account effects of the other model parameters that may be significant and provides a more comprehensive assessment of the associated likelihoods. The parameter estimates are used to calculate adjusted odds ratios (AOR) that take into account effects of the other model parameters that may be significant and provides a more comprehensive assessment of the associated risks. For the first objective, the model was designed to predict the likelihood of a crash that resulted in a TBI [case] when compared to a crash that did not result in a TBI [control]. For the second objective, the model predicted the likelihood of a crash involving a driver who was a TBI survivor [case] compared to a crash that did not involve a TBI survivor [control]. Initial examination of the crude proportion of each crash factor related to individuals with and without TBI was examined using the chi-squared tests for proportion.

Explanatory factors

Crashes were categorized into four types: angular, rear-end, head-on, or single vehicle crashes. These categories were based on the existing nomenclature for crash types in the database. To ensure that the dataset used for the analysis was comprehensive, additional variables were also reviewed including direction of impact, sequence of events, the manner of the crash, and the first harmful event. These variables were used to determine the crash type if it was not identified in the data directly. Single vehicle crashes are defined as collisions with only the driver's vehicle (e.g., crashes with fixed objects, run off the road crashes, and rollover crashes). Angular crashes are defined as involving two or more vehicles that are not traveling in parallel to each other prior to the crash. Rear-end collisions and head-on collisions are defined as collisions where the vehicles are traveling in parallel to each other, either in the same direction or the opposite direction, respectively.

The severity of a crash is an important factor related to the type of injuries sustained in a crash. The change in the velocity during a crash (delta-V) is a common indicator for crash severity (Segui-Gomez, 2000). However, this information was not available in the crash data used for this study. Therefore, the damage to the vehicle is used as a proxy variable for the crash severity and has been used for this purpose in other crash-based studies (Grossman, Sugarman, Fox, & Moran, 1997; MacLennan, G. McGwin, Metzger, Moran, & III, 2004). The categories in the database for vehicle damage include minor, functional, disabling, and severe (vehicle totaled). There were no crashes classified as "minor" damage in the crash data and this category was therefore, not included in any subsequent analysis.

There were also several other crash, vehicle, and person-related variables included in the analysis. Vehicle-related variables include vehicle type (e.g., passenger car, truck, SUV or motorcycle) and number of occupants in the vehicle (e.g., passengers involved or not). Passenger vehicles and SUVs were identified as such in the crash data. Trucks were categorized as light trucks/pickups and single-unit trucks (with two or more axes). Motorcycles included both motorcycles and mopeds. Person-related variables included seatbelt or helmet use, driver distraction (see Table 1), fatigue and drug or alcohol use. The analysis also considered whether the crash also involved drugs or alcohol. Several studies demonstrate the impact of these variables on crashes (Lowenstein & Koziol-McLain, 2001; McGwin & Brown, 1999; Neyens & Boyle, 2007, 2008; Peek-Asa & Kraus, 1996).

All of the explanatory factors were set up as dichotomous variables with dummy variables indicating if the variable is true [1] or false [0] for each record. For example, a rear-end crash was identified as true [1] if it was a rear-end or false [0] if it was not one, a vehicle was a passenger car [1] or not a passenger car [0], and an individual was a driver [1] or not the driver of a vehicle [0]. This allows comparison between explanatory factor levels, and allows for combinations of factors to be compared to all other crashes (e.g., crashes of un-helmeted motorcycle riders).

Results

Crashes resulting in TBIs

Of the 2,817 TBI crashes observed, only 2,382 cases were used in this study. The cases that were omitted (435) contained missing data (e.g., speed limit not identified, gender missing or not specified, or the data related to crash characteristics missing), incorrect data for matching factors (e.g., speed limit for a road identified as 43 MPH) or did not result in a match in a control (e.g., a individual who was greater than 90-years old given the factors used to match cases and controls). Non of the matching variables were included in the subsequent models, as there were no significant differences between the TBI drivers and the non-TBI drivers for these variables.

There were 1,654 (69.4% of the total) males in this sample, of whom 60% sustained a TBI in a rural setting. Similarly, 62.5% of the females (455 out of 728) sustained a TBI as a result of a crash in rural setting. The mean age of the case group was 37.3 years-old (SD=18.2 years). The age distribution of the controls was identical to the cases, which was expected based on the matching criteria. The posted speed limits at the location of the crashes ranged from 20 MPH to 70 MPH and matched exactly between the cases and the controls.

The average Glasgow Coma Scale (GCS) of the individuals who experienced a TBI as a result of a crash was 12.5 (SD=4.1) (missing in 72 cases). As shown in Table 3, crashes that resulted in a TBI were associated with more vehicle damage, more motorcycle riders, and less restraint use as demonstrated with the chi-square test for proportions. Crashes that resulted in a TBI included more single vehicle and head-on crashes than the control group. There were also fewer crashes resulting in TBIs in adverse weather conditions than the control group.

The vehicle type significantly differed between the crashes that caused TBI and the control crashes group as riding a motorcycle represented 17.63% and 1.39% of the cases and controls, respectively ($\chi2$=444.85, p<0.0001). In about 7% of the crashes resulting in a TBI and 16% of the control crashes, the vehicle type was either not identified in the data, or was not one of the vehicle types investigated as part of this study. In about 30% of the control group crashes involved vehicles with passengers compared to about 25% of the cases ($\chi 2=13.08$, $p=0.0003$).

Of the crashes resulting in a TBI, 92.8% of the individuals sustaining the injury were the driver of a vehicle compared to 86.2% of the individuals involved in control crashes ($\chi 2=55.18$, $p<0.0001$). Additionally, driver fatigue was more prevalent in TBI causing crashes (3.4%) than in the control group (1.9%). Drugs or alcohol were involved in 16.12% of the crashes that caused a TBI, opposed to 3.44% for the control crashes ($\chi 2=216.94$, $p<0.0001$). In only 67.55% of crashes that caused a TBI, the driver was using some safety-protective devices (i.e., seatbelt or helmet), compared with 94.79% of the control crashes ($\chi 2=578.49$, $p<0.0001$). The airbag deployed in about 24% of the crashes resulting in a TBI compared with about 9% in the control crashes ($\chi 2=196.57$, $p<0.0001$). Additionally, driver fatigue was more prevalent in TBI causing crashes (3.40%) than in the control group (1.89%) ($\chi 2=10.56$, $p=0.0012$). The number of crashes that involved driver distraction did not significantly differ between the crashes resulting in a TBI compared to the control crashes.

Table 3. Factors related to the crashes that result in an occupant sustaining a TBI and the matched control

Crash Factor	**TBI, n (% of column)**	**Controls, n (% of column)**	**Chi-Squared Statistic**	***p*-Value***
Crash type			181.15	<0.0001
Angular crash	495 (20.8)	606 (25.4)		
Head-on crash	184 (7.7)	114 (4.8)		
Single vehicle crash	1249 (52.4)	785 (33.0)		
Rear-end crash	454 (19.1)	877 (36.8)		
Vehicle damage*			1469.11	<0.0001
Functional	261 (11.0)	1369 (57.5)		
Disabling	415 (17.4)	525 (22.0)		
Severe (totaled)	1681 (70.6)	456 (19.1)		
Adverse weather	298 (12.5)	420 (17.7)	24.41	<0.0001
Weekend	780 (32.8)	610 (25.6)	29.36	<0.0001
Poor surface conditions	497 (20.9)	674 (28.3)	35.47	<0.0001
Daylight conditions	1385 (58.1)	1583 (66.5)	35.04	<0.0001
Fatal crash	296 (12.4)	25 (1.0)	245.32	<0.0001
Vehicle Type			444.85	<0.0001
Passenger car	1200 (50.4)	1194 (50.1)		
Motorcycle	420 (17.6)	33 (1.4)		
SUV	229 (9.6)	243 (10.2)		
Truck	368 (15.5)	535 (22.5)		
Other vehicle type	165 (6.9)	377 (15.8)		
Passengers in vehicle	591 (24.8)	702 (29.5)	13.08	0.0003
Driver	2211 (92.8)	2045 (86.2)	55.18	<0.0001
Drug or Alcohol related	384 (16.1)	82 (3.4)	216.94	<0.0001
Seatbelt/helmet used	1609 (67.6)	2258 (94.8)	578.49	<0.0001
Airbag deployed	572 (24.0)	213 (8.9)	196.57	<0.0001
Driver fatigued	81 (3.4)	45 (1.9)	10.56	0.0012
Distraction related	31 (1.3)	46 (1.9)	2.97	n.s.
Glasgow Coma Scale†	M=12.5 (SD=4.3)			
Total crashes in sample	2382	2382		

NOTE: †missing in 57 records

*n.s. indicates a not significant result at p<0.05

The logistic regression model predicted the likelihood of an individual sustaining a TBI as a result of a crash [case] compared to an individual not sustaining a TBI [control] (Table 4). Higher likelihood of sustaining a TBI was associated with severe (total) vehicle damage (adjusted odds ratio, AOR=28.60) and disabling vehicle damage (AOR=5.02). Further, individuals were more likely to experience a TBI if they were the driver in the crash (AOR=1.75) or if drugs or alcohol were present (AOR=2.79). Motorcycle riders that did not wear a helmet at the time of the crash were much more likely to sustain a TBI (AOR=40.54) when compared to all other individuals included in the analysis.

Those factors that were associated with a decrease in the likelihood of an individual sustaining a TBI (when compared to non-TBI) were rear-end crashes (AOR=0.75) (compared to other crash types), truck occupants (AOR= 0.72), and the presence of passengers (AOR=0.80). Wearing a seatbelt also reduced the likelihood of an individual experiencing a TBI (AOR=0.63).

Table 4. Logistic regression estimates and adjusted odds ratios for sustaining a TBI from a crash

Variable	**Contrast estimate**	**Standard error**	**t-Value**	**p-Value**	**AOR***	**95% Wald CI on AOR**
Intercept	-2.33	0.15	-15.24	<0.001		
Driver of vehicle	0.56	0.13	4.22	<0.001	1.75	(1.35, 2.28)
Drug or Alcohol related	1.02	0.15	6.75	<0.001	2.79	(2.07, 3.75)
Used seatbelt	-0.47	0.08	-5.8	<0.001	0.63	(0.53, 0.73)
Rear end crash	-0.29	0.09	-3.14	0.002	0.75	(0.63, 0.90
Total vehicle damage	3.35	0.10	32.59	<0.001	28.60	(23.38, 34.99)
Disabling vehicle damage	1.61	0.11	14.29	<0.001	5.02	(4.03, 6.27)
Truck	-0.33	0.10	-3.31	0.001	0.72	(0.60, 0.88)
Passengers in vehicle	-0.22	0.09	-2.5	0.013	0.80	(0.68, 0.95)
Motorcycle with no helmet	3.70	0.23	16.18	<0.001	40.54	(25.89, 63.49)
Number of observations		4764				
-2 Log-likelihood at intercept		6604.31				
-2 Log-likelihood at convergence		4165.13				
Likelihood ratio		$\chi 2=2439.18$	$p<0.0001$			

Note: *AOR=Adjusted Odds Ratio

Crashes of TBI survivors

There were 1,591 crashes involving a driver who was also a TBI survivor. Of these, eight were removed from subsequent analysis due to missing data, incorrect data, or no case and control matches. The mean age of the TBI survivors was the same as the controls used for the analysis (mean=33.4 years-old, SD=17.3). The posted speed limits at the location of the crashes ranged from 20 MPH to 70 MPH and were identical between the cases and the controls. Of the TBI survivors involved in crash, 26% of the males and 17.8% of the females were involved in crashes in rural settings.

The average Glasgow Coma Scale (GCS) of the drivers who survived a TBI and became involved in crashes afterward was 13.2 (SD=3.5). Compared to the control group, the TBI drivers were not involved in more severe crashes (as defined by the amount of vehicle damage) (Table 5). The control group had more crashes during daylight conditions and more crashes that included passengers than the TBI drivers. However, TBI drivers were in more crashes that involved drugs or alcohol. Protective devices (e.g., seatbelts or helmets) were worn by 96.65% of the drivers in the control crashes compared to 93.3% of the drivers in the TBI survivors group.

The regression model (Table 6) confirmed that TBI drivers were less likely to wear a seatbelt at the time of the crash when compared to the non-TBI drivers (AOR=0.89). Crashes involving TBI drivers were less likely to occur during daylight hours (AOR=0.88), and less likely to have passengers in their vehicle at the time of their crash (AOR=0.88) when compared to the drivers in the control group.

Table 5. Factors related to crashes of TBI survivor and the matched control

Crash Factor	**TBI, n (% of column)**	**Controls, n (% of column)**	**Chi-Squared Statistic**	**p-Value****
Crash type*			7.47	n.s.
Angular crash	443 (28.0)	506 (32.0)		
Head-on crash	44 (1.4)	42 (1.3)		
Single vehicle crash	427 (27.0)	380 (24.0)		
Rear-end crash	668 (42.2)	653 (41.3)		
Vehicle Damage‡			7.45	n.s.
Functional	979 (61.8)	1030 (65.1)		
Disabling	333 (21.0)	336 (21.2)		
Severe (totaled)	247 (15.6)	200 (12.6)		
Weekend	394 (24.9)	355 (22.4)	2.66	n.s.
Adverse weather	220 (13.9)	249 (15.7)	2.11	n.s.
Poor surface conditions	385 (24.3)	380 (24.0)	0.04	n.s.
Daylight conditions	1051 (66.4)	1137 (71.8)	10.94	0.0009
Fatal crash	21 (1.3)	14 (0.9)	1.42	n.s.
Vehicle Type			19.06	0.0008
Passenger car	920 (58.1)	897 (56.7)		
Motorcycle	45 (2.8)	27 (1.7)		
SUV	144 (9.1)	155 (9.8)		
Truck	355 (22.4)	324 (20.5)		
Other vehicle type	119 (7.5)	180 (11.4)		
Passengers in vehicle	435 (27.5)	516 (32.6)	9.86	0.0017
Drug or Alcohol related	83 (5.2)	52 (3.3)	7.44	0.0064
Seatbelt/helmet used	1,477 (93.3)	1,530 (96.7)	18.60	<0.0001
Driver fatigued	35 (2.2)	23 (1.5)	2.53	n.s.
Distraction related	37 (2.3)	31 (2.0)	0.54	n.s.
Glasgow Coma Scale†	M=13.2 (SD=3.5)			
Crashes in sample	1,583	1,583		

Notes: *Crash type not classified in three records

**n.s. indicates a not significant result at p<0.05

‡ missing in 41 records

†missing in 204 records

Table 6. Logistic regression estimates and adjusted odds ratios for crashes of TBI drivers

Variable	**Contrast estimate**	**Standard error**	**Wald Chi-Squared***	***p*-value**	**AOR**	**95% Wald CI on AOR**
Intercept	0.30	0.09	11.72	0.0006		
Seatbelt used	-0.11	0.09	15.32	<0.0001	0.89	(0.70, 0.92)
During daylight	-0.12	0.04	9.40	0.002	0.88	(0.68, 0.92)
With passengers	-0.13	0.04	9.70	0.002	0.88	(0.67, 0.91)
Number of observations			3166			
-2 Log-likelihood at intercept			4389.01			
-2 Log-likelihood at convergence			4351.45			

Note: AOR=Adjusted Odds Ratio

TBI drivers involved in multiple crashes

The matches between the two databases also revealed that several individuals were involved in multiple crashes after their injuries. In fact, there were 187 (13.7%) TBI drivers involved in multiple crashes and they accounted for 405 (25.6 %) out of the 1,581 crashes of TBI drivers. All other drivers in the database (not just the crashes selected for the control group) were involved in significantly less multiple crashes (10.4%) during the same study time period (2001-2006) ($\chi2=16.17$, $p<0.001$). The TBI drivers involved in multiple crashes had an overall mean GCS score of 13.0 (SD=3.6) and the details associated with each set of multiple crashes are shown in Table 7.

Table 7. Characteristics of TBI survivors involved in vehicular crashes

Number of crashes	N	**Age at time of injury** Mean (sd)	**Year of injury** Median (IQR)*	**Gender** % Male	**GCS** Score (sd)**
1	1,176	31.6 (18.0)	2001 (5.0)	71.7	13.3 (3.5)
2	160	25.5 (14.8)	2000 (4.0)	75.6	13.0 (3.7)
3	23	26.6 (16.9)	2000 (7.0)	56.5	13.5 (2.2)
4	4	24.8 (13.6)	2002 (2.0)	50.0	7.5 (6.4)

Notes: *IQR= interquartile range

**GSC scores were not report for 165 individuals,

An ordered logistic regression model was used to estimate the logit-transformed probability that the individual was involved in multiple crashes. Explanatory factors for this model included the survivor's age at injury and the date of the injury (Table 8). Gender and an the individual's GCS score were included in the model to account for the effects associated with these variables that have been demonstrated in the literature (Formisano, et al., 2005; Massie, et al., 1995). There were 165 observations with missing data (no GCS score reported) so they were excluded from the model. The date of the injury was used to crudely control for driving exposure following the injury during the study period. In fact, individuals with more recent injuries were less likely to have multiple crashes (AOR=0.94), which may relate to a reduction in exposure to driving since their injury.

Individuals who sustained a TBI at an older age were less likely to have multiple crashes when compared to individuals who sustained a TBI at a younger age (AOR=0.98). However, no significant differences were observed for an individual's GCS score or gender. Additionally, no other factors significantly affected the likelihood of a TBI driver being involved in multiple crashes.

Table 8. Likelihood of repeat crashes among TBI drivers

Variable	**Contrast estimate**	**Std. error**	**Wald Chi-Sq**	**p-value***	**AOR‡**	**95% Wald on AOR**
Intercept-4 crashes	125.30	56.76	4.88	0.027		
Intercept-3 crashes	127.70	56.76	5.06	0.025		
Intercept-2 crashes	129.90	56.76	5.23	0.022		
Age at injury	-0.02	0.01	13.48	0.0002	0.98	(0.97, 0.99)
Gender	0.02	0.10	0.06	n.s.	1.05	(0.72, 1.54)
GCS score	-0.01	0.02	0.24	n.s.	0.99	(0.94, 1.04)
Year of Injury	-0.07	0.03	5.32	0.0211	0.94	(0.89, 0.99)
Baseline (1 crash)						
Observations			1,198			
-2 Log-likelihood at intercept			1,063.32			
-2 Log-likelihood at convergence			1,038.95			
Likelihood ratio		$\chi 2=24.37$		$p<0.001$		

NOTE: *n.s. indicates a not significant result at p<0.05

‡Adjusted Odds Ratio

Discussion

There were two main objectives of this chapter. The first objective was to examine the factors influencing the likelihood of an individual experiencing a TBI in a crash. Those factors observed to increase the likelihood of an individual experiencing a TBI in a crash included alcohol and drug use, fatigue, motorcycle, being the driver (as opposed to a passenger), more damage to the vehicle, and not wearing seatbelts or helmets. These results are consistent with other studies (Javouhey, et al., 2006; Viano, et al., 1997) and therefore, confirm the usefulness linking the Iowa crash data to the Iowa

Brain Injury Registry for the second goal of this study, which was to examine the factors that influence the crashes of TBI drivers.

One of the factors that increased the likelihood of sustaining a TBI in a crash was driving/riding a motorcycle: this has been well documented (Javouhey, et al., 2006). Iowa does not currently have a mandatory helmet law for motorcycle, mopeds, or bicycles for any age group, but does have mandatory seatbelt laws (IIHS, 2009). The results of this study showed that wearing a seatbelt decreased the likelihood of sustaining a TBI and un-helmeted motorcycle drivers had a higher likelihood of a TBI, both of which are consistent with the literature (Javouhey, et al., 2006).

The models presented in this chapter used a proxy for crash severity since it is difficult to quantify this measure from crash databases of police accident reports. The delta-V of the crash can only be obtained during a crash investigation, but is not available when a police officer arrives at the scene. However, this information is highly relevant in explaining the impact that was sustained by the driver (Farmer, 2003). In crash databases, the definition of severity is typically based on the number of fatalities and injuries sustained in a crash. Hence, it is circular to use this definition of crash severity to predict injury severity. This creates an endogeneity bias with a correlation between an explanatory factor and the error term of the model. Hence, a proxy variable (i.e., vehicle damage) was used in the model to minimize omission bias, which can lead to inappropriate and misleading results. Likewise, airbag deployment was not included in the logistic regression because it is highly correlated (i.e., multicollinear) with crash severity (and the corresponding proxy variable). The initial chi-squared tests provided a crude estimate of the effect of crash severity. The data was also matched on individual's age, gender, urban or rural status of the crash, and the speed limit of the roadway. The matching enabled better insights on other crash factors, but limits statistical conclusions related to the matched variables.

The second objective of this chapter was to examine crashes that involved TBI drivers. Many studies have examined driving behavior after an individual sustained a TBI (Brenner, et al., 2008; Formisano, et al., 2001; Formisano, et al., 2005; Katz, et al., 1990; Schultheis, et al., 2002; van Zomeren, et al., 1988). However, few studies examine factors related to the crashes of TBI drivers (e.g., Formisano, et al., 2005). When involved in a crash, TBI drivers were less likely to be wearing seatbelts and less likely to have passengers in the vehicle. The crashes of TBI drivers were also more likely to occur at night. Individuals who do not wear seatbelts have been shown to have a higher level of sensation seeking and risk tasking than individuals who do wear seatbelts (Jonah, Thiessen, & Au-Yeung, 2001). Therefore, TBI drivers in crashes may be more likely to be exhibiting a higher level of risk taking than the non-TBI drivers in crashes.

Limitations

There are several limitations associated with anises within this chapter. For example, while the risks associated with engaging in distracting tasks may have increased for TBI drivers, the prevalence of such tasks may be reduced because of differences in willingness to engage. Additionally, the analyses presented in this chapter are from a statewide perspective and do not represent all individuals with traumatic brain injuries. In particular, because mild-TBIs are difficult to diagnose (McCrea, 2007) and often go untreated, these individuals may not be in the TBI registry, and therefore, are not included in this analysis. The study was also dependent on the quality of the data in the crash database and the TBI registry. There may be systematic errors, accuracy issues, and underreporting in behavioral data (e.g., driver distraction) such that significant outcomes would be difficult to discern (Bunn, Slavova, Struttmann, & Browning, 2005; Stutts, et al., 2003). The crash database also contains only police documented crashes that involved more than $1,000 of damage, so minor or non-reported crashes are most likely not included in the study. There may also be differences between severe and mild TBIs (as indicated by the GCS) in terms of the crashes that result in a TBI and the crashes of TBI drivers. Given the fact that there was a large number of missing data for the GCS in the TBI registry, it was not feasible to conduct an analysis comparing TBI severities for Iowa but should be considered in future analyses that include more comprehensive injury severity data.

Conclusions

This chapter showed that a larger proportion of TBI drivers are involved in multiple crashes than in the general driving population. As noted earlier, TBI drivers may adapt their driving style to accommodate for their limitations. These findings indicate that there is a greater likelihood of being involved in a crash among TBI drivers at night. However, studies have shown that individuals with TBI prefer (and feel safer) driving during the day (Dimarco & Cantagallo, 2001). Hence, some TBI drivers may not be adapting as expected. This analysis also showed that younger TBI drivers are more likely to be involved in multiple crashes and hence, may be less aware of their limitations. Similar lack of awareness have been observed in other studies on young drivers (Donmez, et al., 2010).

A key result within this chapter is identifying TBI drivers who have a higher likelihood of being involved in multiple crashes. It is important to quantify accurately the risks of these drivers, as there are substantial public health benefits in terms of driving rehabilitation and driving restrictions. This study provides some insights on factors that may differ between drivers with and without TBI but additional studies are needed to assess whether the findings are statistically consistent across other jurisdictions and over a greater period. Driver distraction-related factors did not significantly differ between the crashes that result in TBIs and the control crashes, nor did they differ between the crashes of TBI drivers and control crashes. This leads to the need to quantify TBI drivers' willingness to engage in distracting activities and the effect of distracting tasks on driving performance.

In the next chapter, a survey is used to gain insights into the driving behavior associated with TBI drivers and driver distractions. The survey evaluates the association between a TBI drivers' willingness to engage in distracting activities and the likelihood of an individual being involved in a crash or receiving a speeding ticket after their TBI (Specific Aim 2). This builds on the results related to this chapter (Specific Aim 1) in that TBI drivers involved in crashes were more likely to exhibit risk taking than non-TBI drivers.

CHAPTER 4.
ENGAGEMENT IN NON-DRIVING ACTIVITIES: A SURVEY OF TBI DRIVERS

This chapter addresses the second aim of this dissertation. Specifically, the objective of this chapter is to examine the TBI drivers' willingness to engage in distracting tasks. The willingness to engage in distracting tasks is then used to predict the likelihood that an individual is involved in a crash or receive speeding tickets after their brain injury. TBI drivers willingness to engage in distracting tasks is also compared to a teenage drivers willingness to engage in distracting tasks. TBI drivers are typically identified as having quadruple risk (Hopewell, 2002) and therefore are compared to another high risk group; teenage drivers. Younger drivers are a well known high-risk driver group and exhibit the highest level of risk taking of all driver groups (McKnight & McKnight, 2003). This comparison is done in an effort to further understand the TBI drivers propensity to take risks.

Methods

Participants

The target population for the survey includes individuals with brain injuries who have resumed driving following their TBI in the US. As it is difficult to recruit participants with TBIs, there were two main methods used to recruit participants for this survey. Initially, participants were recruited through an email distributed on listservs maintained by the Brain Injury Associations of Iowa, Washington, and North Carolina, and Wyoming, and a post on the Brain Line website. The email and post contained a link to the online survey (University of Iowa IRB ID#200808764). The website and email lists serve as a means for organizations to communicate with brain injury survivors and their families. In order to attempt to increase the sample size of the survey, a paper version of the survey was then distributed in conjunction with a driving simulator study at the University of Washington (Human Subjects Division: 2009-37323). Participants for the study at the University of Washington were recruited through the Brain Injury Association of Washington, the Washington TBI Strategic Partnership Advisory Council, the South Puget Intertribal Planning Agency, the Washington Division of Vocational Rehabilitation, and through flyers posted at the University of Washington Medical Center in the Department of Rehabilitation Medicine. As the participants were initially recruited nationally, it is appropriate to use the second recruitment method to increase the sample size. It was not expected that there would be regional differences in responses to the survey questions.

Survey design

As mentioned earlier, the survey was constructed as both an electronic survey maintained on a server within the University of Iowa and as a paper survey administered at the University of Washington. The survey was originally developed in 2008 as part of my Master’s in Public Health (MPH) practicum work with the Brain Injury Association of Iowa. The survey included demographics, information about driving evaluations and instruction following the TBI injury, driving exposure, exposure to complex driving situation (e.g. driving in snow or ice, in busy intersections, on highways) based on Priddy et al. (1990), and if the respondents were involved in crashes or received speeding tickets following their injury (see Appendix A). The survey also assessed respondent’s subjective ratings of their willingness to engage in distracting activities (e.g., talking on cellular phones, text messaging, reading, using other electronic devices, and cognitive distractions).

Analysis

The analysis was conducted in R 2.10.1. Cluster analysis is a multivariate statistical approach that is used to identify homogeneous groups within a population or dataset. The survey respondents were initially clustered on several of the questions related to their willingness to engage in distracting tasks using Ward’s hierarchical method with a distance specified as the squared Euclidean distance was used to form the clusters. Clustering data is useful for observing common patterns in behavior data (Aldenderfer & Blashfield, 1984) and is widely used for transportation based surveys including willingness to engage in distracting tasks (Westlake, 2009), responses to driver distraction and collision warning systems (Lee, McGehee, Brown, & Reyes, 2002), and use of motorist information on computer behavior (Conquest, Spyridakis, Haselkorn, & Barfield, 1983). The clusters membership was then used as an explanatory factor for predicting the likelihood of that an individual received a speeding ticket or was involved in a crash following their TBI.

Results

In total, 79 individuals accessed the online survey or the paper version of the survey, with 41 individuals completing the survey (a survey completion rate of about 52%). Females represented 23 (about 56%) of the survey respondents. The average age of the survey respondents as 47.9 years-old (SD 12.8 years) and the respondents reported that they experienced their injury 12.9 years (SD 9.74 years) prior to completion of the survey. Survey respondents represented every major geographical region of the continental US (e.g., Midwest, Northwest, Northeast, and South).

There were a few participants that reported experiencing brain injuries that were non-traumatic (as defined within this dissertation) but were included in the study (e.g., AVM rupture, massive cerebral hemorrhage). There were a few that reported experience brain injuries from cancer, did not indicate their type of injury, or did not answer the questions that were included in this analysis and were therefore excluded from the analysis. Additionally, several were excluded because they reported that they do not currently drive a car. Therefore, 32 survey respondents are included in the following analysis.

The survey respondents were clustered on their responses to their engagement in distracting tasks. The distracting tasks used for the cluster analysis included: cell phone usage, dialing a cell phone, text messaging eating or drinking, changing cassettes or CDs, tuning the radio, changing the heating or air conditioning, looking for an item in a wallet or purse, daydreaming or thinking about something complex. Several related survey questions were not included in the cluster analysis because of very similar results across all participants (e.g., willingness to apply makeup, shave, read, or using a device brought into the vehicle while driving). The dendogram of the clusters with the two groups identified is in Figure 7. The “engagers” (Cluster 1) were consistently more likely to engage in distracting tasks than the “avoiders” (Cluster 2) (see Table 9). The age of the “engagers” (mean age=58.4, SD=6.7) was significantly older than the “avoiders” (mean age=43.8, SD=13.6) (t=4.1, p<0.05). The “avoiders” drove significantly more miles in the previous day (29.8, SD=37.1 miles) (a crude measure of driving exposure) than the “engagers” (12.4, SD=7.5 miles) (*t*=-2.1, p<0.05).

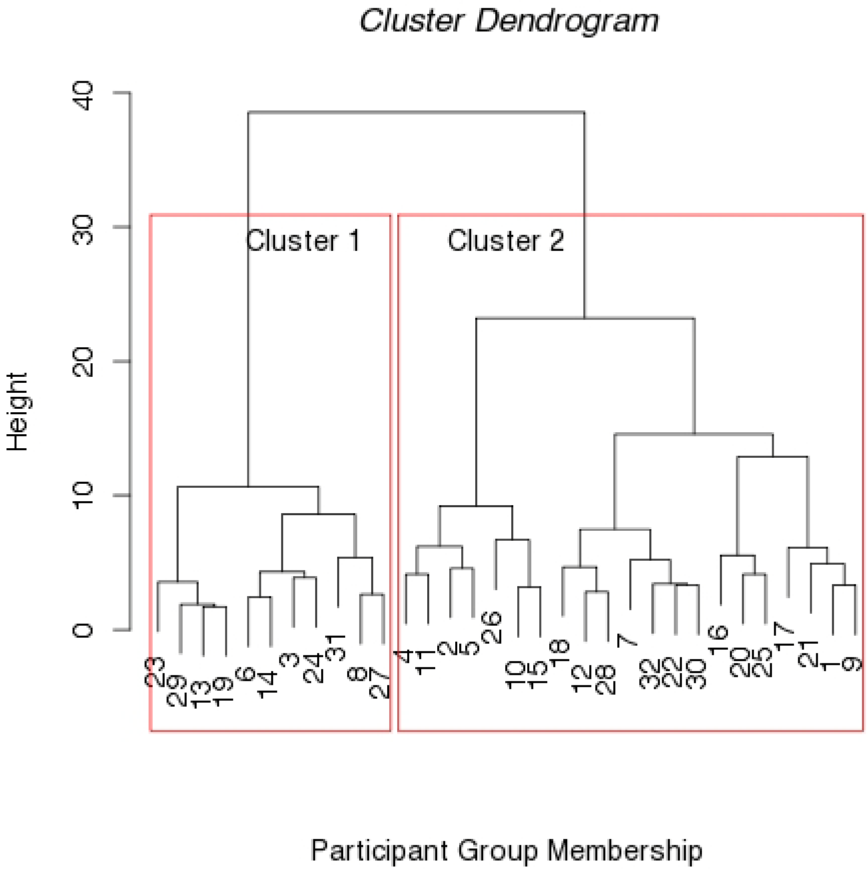


Figure 7. Dendogram of the survey respondent’s willingness to engage in distracting tasks with Cluster 1 identified as the “Engagers” and Cluster 2 as the “Avoiders”

Table 9. Cluster profiles of TBI Engagers and Avoiders of distracting activities

	Cluster 1: Engagers (n=21) median (range)	Cluster 2: Avoiders (n=11) median (range)	Wilcoxon signed rank statistic (W), p-value
Engagement in distracting tasks*			
Talk on a cell phone	4 (1,7)	2 (1,4)	67, $p<0.05$
Dial a cell phone	3 (1,7)	1 (1,4)	57, $p<0.05$
Text message	1 (1,7)	1 (1,1)	77, $p<0.05$
Eat or drink	5 (1,7)	2 (1,6)	45.5, $p<0.05$
Change CD/cassettes	4 (1,7)	1 (1,2)	66, $p<0.05$
Tune Radio	4 (3,7)	2 (1,4)	13.5, $p<0.05$
Change climate controls	4 (1,7)	3 (1,4)	44, $p<0.05$
Look for an item in the vehicle	3 (1,4)	1 (1,4)	53.5, $p<0.05$
Daydream	4 (1,7)	2 (1,4)	36.5, $p<0.05$
Think about complex problem	4 (2,7)	2 (1,4)	24, $p<0.05$
Demographics			
Age [mean, (sd)]	58.4 (6.7)	43.8 (13.6)	$t=4.1$, $p<0.05$
Miles driven yesterday [mean, (sd)]	12.4 (7.5)	29.8 (37.1)	$t=-2.1$, $p<0.05$
Involved in crash after injury (%)	33.3%	27.1%	$\chi^2=0.002$, n.s.
Received tickets after injury (%)	57.1%	18.1%	$\chi^2=3.5$, n.s.
Sex (% female)	57.1%	72.7%	$\chi^2=0.01$, n.s.

NOTE: * Medians are presented based on Likert scale (1=Never, 7=Always).

Comparison of clusters to teenage drivers

Teenage drivers have been shown to be the most willing to engage in new technologies and distracting activities while driving (Young & Lenné, 2010). It is useful to compare this group to TBI drivers to teenage drivers provide prospective on the level of willingness to engage when compared to a very high-risk, high-willing to engage group.

Westlake (2009) surveyed 1,893 teenage drivers in the State of Iowa to solicit their perceptions of driver distraction survey contained the same series of questions regarding the frequency to which the survey respondent engaged in distracting or distracting tasks that was included in the survey of TBI drivers. A cluster analysis of the teenage drivers provided three cluster groups, referred to as: infrequent engagers, moderate engagers, and frequent engagers (Westlake, 2009). The responses of the TBI drivers were compared to the responses in the three clusters. As expected, the frequent teenage engagers were significantly more likely to engage in all of the tasks than TBI engagers. It is interesting to note that the TBI engagers were similar to the teenage moderate engagers in terms of their willingness to talk on a phone, eat or drink, and change CD/cassettes while driving (Table 10). The TBI avoiders were very similar to the teenage infrequent engagers in terms of their willingness to talk on a cell phone, dial a cell phone, eat or drink, look for items in the vehicle, daydream and thinking about complex problems (Table 11). Additionally, based on the age differences it is not surprising that teenagers were more willing to text message while driving (Young & Lenné, 2010).

Table 10. Comparison of TBI Engagers cluster to teenage moderate engagers cluster from Westlake (2009)

	TBI “Engagers”	Teenage “Moderate engagers”	
	(n=21) median (range)	median (range)	Wilcoxon signed rank statistic (W)
Engagement in distracting tasks			
Talk on a cell phone	4 (1,7)	4 (1,7)	3800.5, n.s.
Dial a cell phone	3 (1,7)	4 (1,7)	3385, p<0.05
Text message	1 (1,7)	3 (1,7)	2989.5, p<0.05
Eat or drink	5 (1,7)	5 (1,7)	5344, n.s.
Change CD/cassettes	4 (1,7)	4 (1,7)	3811, n.s.
Tune Radio	4 (3,7)	6 (1,7)	3119, p<0.05
Change climate controls	4 (1,7)	6 (1,7)	3213.5, p<0.05
Look for an item in the vehicle	3 (1,4)	4 (1,7)	2937, p<0.05
Daydream	4 (1,7)	5 (1,7)	3407, p<0.05
Think about complex problem	4 (2,7)	5 (1,7)	2998.5, p<0.05

Table 11. Comparison of TBI Avoiders cluster to teenage infrequent engagers cluster from Westlake (2009)

	TBI “Avoiders”	Teenage “Infrequent engagers”	
	(n=11) median (range)	median (range)	Wilcoxon signed rank statistic (W)
Engagement in distracting tasks			
Talk on a cell phone	2 (1,4)	2 (1,7)	3821.5, n.s.
Dial a cell phone	1 (1,4)	2 (1,6)	3143.5, n.s.
Text message	1 (1,1)	1 (1,7)	2348.5, p<0.05
Eat or drink	2 (1,6)	3 (1,7)	3338, n.s.
Change CD/cassettes	1 (1,2)	2 (1,7)	1516.5, p<0.05
Tune Radio	2 (1,4)	4 (1,7)	1627, p<0.05
Change climate controls	3 (1,4)	4 (1,7)	2474, p<0.05
Look for an item in the vehicle	1 (1,4)	2 (1,7)	3016.5, n.s.
Daydream	2 (1,4)	2 (1,7)	3541, n.s.
Think about complex problem	2 (1,4)	3 (1,7)	2833, n.s.

Willingness to engage in distractions and outcomes

A logistic model was used to predict the likelihood that a TBI driver had been involved in a crash (Table 12). There was no significant effect of the cluster membership on the likelihood that an individual was involved in a crash. There were also no other significant predictors of the likelihood of crashes collected as part of the survey. Another logistic model was used to predict the likelihood that a TBI driver received a speeding ticket. Membership in the group of individuals who were more likely to engage in distracting activities were more likely to receive a speeding ticket following their injury (OR=6.75, 95%CI [1.14, 39.79]).

Table 12. Logistic regression estimates and adjusted odds ratio for survey respondent receiving speeding ticket following injury

Variable	**Contrast estimate**	**Standard error**	**z-value**	***p*-value**	**Odds ratio (OR)**	**95% Wald CI on OR**
Intercept	0.04	0.46	0.89	n.s.		
Cluster 1: “Engagers”	1.91	0.91	2.11	0.035	6.75	(1.14, 39.79)
Number of observations*			30			
Null Deviance			42.68			
Residual Deviance			37.35			

Note: *Two observations excluded due to missing data

Discussion

In this chapter, TBI drivers' willingness to engage in distracting activities was examined with respect to likelihood to incur a traffic infractions and crashes. While this analysis is limited by the sample size, two distinct populations of TBI drivers emerge; those who are more willing and those that are less willing to engage in distracting activities. The more willing to engage in distracting activities cluster tends to be older and drive less than those less willing to engage. As mentioned earlier, the clusters of TBI drivers were compared to similar young driver clusters. The TBI driver clusters also showed some consistency with the willingness of teenage drivers to engage in these same distracting tasks (Westlake, 2009).

There was no difference in crash involvement between the cluster groups. However, the more willing group was more likely to have received a speeding ticket. Hence, there is a tendency to be more risky among TBI drivers in the willingness to engage group. In fact, receiving speeding tickets has been shown to be associated with sensation seeking and risk taking behaviors (Ayvaşık, Er, & Sü mer, 2005; Jonah, et al., 2001), and this chapter demonstrates that there are some TBI drivers who exhibit higher risk taking than other TBI drivers. TBI drivers were less likely to wear seatbelts when in a crash which indicates a group of TBI drivers who exhibit risk taking as indicated by a higher likelihood of engagement in distracting activities, a lower likelihood of wearing a seatbelt and an increased likelihood of speeding tickets. This may not be related to the TBI, but rather a propensity for risk taking of individuals who also experienced a TBI.

Limitations

There are several limitations associated with this survey and the analyses presented here. Access to the survey was limited to those who had access to the online survey or participated in the study at the University of Washington. The questionnaire may have been challenging to complete, as there were several questions that were not clearly communicated and thus were not included in this analysis. The survey also did not include a time frame for the specific questions. This may have created issues because the involvement in crashes or receiving speeding tickets were not specified as occurring following the TBI. Finally, the survey was self reported behavior and may have caused over- or under-reporting of specific behaviors (i.e., recall bias), especially related to driver distraction variables. This issues need to be considered when interpreting the results of the analysis presented in this chapter.

The next two chapters examine the effect of distracting tasks on the driving performance of both TBI and non-TBI drivers to address Specific Aim 3 of this dissertation.

CHAPTER 5.
THE EFFECT OF NON-DRIVING-RELATED TASKS ON DRIVING PERFORMANCE

The objective of this chapter is to examine the effect of simple distracting tasks on the driving performance of non-TBI drivers. While this chapter does not support one of the specific aims directly, it facilitates the use of Bayesian methods in the next chapter to address Specific Aim 3. Bayesian statistics is an appropriate method to generate more precise estimates given fewer data points and uses knowledge gained in previous studies. Hence, the study conducted in this chapter provides the prior distributions for the effects to be examined in the following chapter.

Study design

A fixed based driving simulator was used for this study. The simulator uses a 1992 Mercury Sable cab with a functional radio. The simulator had a 50-degree visual field and was powered by Global Sim, Inc.'s DriveSafety^{TM} Research Simulator. In addition to collecting data from the driving simulator, video from three cameras and the video projected for the driving simulator were recorded. The driving scenario was a rural two-lane highway with no other traffic and consisted of straight segments with an equal number of 400-meter radius left and right curves. The participants were asked to drive at a comfortable speed but not to exceed a speed of 45 MPH (about 73 km/h). The participants drove for approximately 2 minutes to become accustomed to the driving simulator prior to the start of the study. The experimenter sat in the passenger seat of the simulator to provide the task instructions, to verify that the tasks were completed correctly, and because there would be an experimenter in the passenger seat in the on-road study.

Participants

Twenty-five young right-handed drivers were recruited from the University of Iowa undergraduate population. There were 13 males and 12 females with a mean age of 19.48 (S.D. 1.0). All participants held a drivers license, had at least one year of driving experience, and were native English speakers. Participants also had no driving simulator experience within the last 6 months. The participants were compensated for their time at $15 per hour. The study took about one hour to complete.

Study procedure

The distracting tasks included in this study consist of three separate non-driving-related tasks. These tasks included selecting a CD from a CD case, tuning a radio station, and making change from an array of coins. These tasks are similar to those used in other studies (Jäncke, Musial, Vogt, & Kalveram, 1994; Jenness, Lattanzio, Raymond, O'Toole, & Taylor, 2002; Wikman, Nieminen, & Summala, 1998).

- *Selecting a CD*. Eight CDs were placed in a single row CD case. Participants were requested to select a specific CD from the case and hand it to the experimenter. The CD case was initially positioned near the arm rest for all participants.

- *Radio Tuning*. The manufacturer’s radio was set to AM frequencies. The radio was not able to receive AM stations and only static noise was produced from different frequencies. The radio was initially positioned to the same frequency prior to the experiment. Participants were asked to turn the radio on and tune to a specific frequency using the search or seek buttons. Once the specific frequency was reached, the experimenter turned off the radio. This simulates the task required to tune to weather or traffic advisory stations common on interstates.

- *Making Change*. Sixteen coins [4 quarters ($0.25), 4 dimes ($0.10), 4 nickels ($0.05), and 4 pennies ($0.01)] were placed in the coin tray within the vehicle. The participants were requested to make $0.85 from these coins. The task is based on the actions needed to drive through toll roads.

Each participant completed each of the tasks randomly to control for any order effect. Each task was only conducted on the straight segments of the road, and the curve segments were not included in the analysis. A short time interval (about 30 seconds) of driving on a straight road segment before the tasks were started (but after the participants became comfortable with the control of the vehicle) is used for a baseline measure of driving performance.

Dependent measures and analysis methods

For the analysis, the dependent variables include the mean speed (MPH), the standard deviation of speed (MPH), and maximum lateral acceleration (ft/s^2) during the experimental conditions. As participants were instructed to maintain a specific speed in the simulator, the variability in the speed maintained may provide a measure of the effects of the distracting tasks on driving performance at the operational level of driving control and has been shown to be an important measure of safety and provides an indication of speed control (Reed & Green, 1999). Maximum lateral acceleration is another measure of operational levels of driving and relates to the lateral control of the vehicle and has been used as a driving performance measure in other studies (Classen, et al., 2006; Reymond, Kemeny, Droulez, & Berthoz, 2001). There are also several eye movement related variables included in this analysis. The eye gaze related variables include the percentage of time that the participants look at the distracting task, the total number of glances to the distracting tasks, and the duration of the longest glance to the distracting task. These measures have been used in other studies (Hoffman, et al., 2005; Sodhi, et al., 2002) and only apply to the engagement in distracting tasks but not the baseline driving segment. Therefore, the comparisons for these dependent variables are only compared across the distracting tasks.

Several one-way repeated measures linear models were conducted using the lme function in R (version 2.9.1) (see Equation 2). Separate models were constructed for each dependent variable for each task. Each model consisted of a dichotomous independent variable indicating engagement in the task or the baseline.

$$y_{ij} = \alpha_i + \beta_{ij}(task_j) + \varepsilon_{ij} \qquad \text{(Eq.2)}$$

The analysis of the eye data was similar, however no baseline measurement as included in the analysis as the eye movement measures only apply while engaged in the distracting tasks. Therefore, the independent variable is a categorical variable identifying which task the participant was doing during that segment.

Results

Driving performance measures

The tasks were defined as starting with the beginning of the instructions for each task and ending when the participant returns their hands to the steering wheel following the task. The durations of the tasks is presented in Table 13. Box plots of the dependent measures during the engagement of the distracting tasks and the baseline segment are shown in Figure 8. The linear model parameter estimates for each of the models associated with engagement in the tasks variable for the nine separate models is shown in Table 14. These parameter estimates are then used to generate informative prior distributions for use in Study 2.

The effect of the three distracting tasks did not result in consistent effects on driving performance. There was no significant effect on the mean speed of the coin task. However, engagement in the coin sorting task did result in larger standard deviation of speed ($t(24)=2.09$, $p=0.048$) and larger maximum lateral acceleration ($t(24)=3.21$, $p<0.05$). The CD selecting task did not affect the mean speed or the standard deviation of speed, but did result in larger maximum lateral acceleration ($t(24)=3.44$, $p<0.05$). The radio tuning tasks resulted in lower mean speed ($t(24)=-2.28$, $p<0.05$), larger standard deviation of speed (t(24)=2.92, p<0.05), and larger maximum lateral acceleration (t(24)=3.00, p<0.05). Regardless of statistical significance, each of these parameter estimates contains information about the expected effects of these tasks on driving performance.

Table 13. Mean and standard deviation (SD) of the task duration in seconds

Task	**Mean duration (SD) (seconds)**
Coin sorting	8.59 (6.06)
CD selecting	3.32 (1.10)
Radio tuning	6.52 (3.20)

Table 14. Parameter estimates used to generate prior distributions from individual repeated measures linear models.

Task type	**Dependent measure***	**Parameter estimate**	**St. Error**	**DF**	**t-stat**	***p*-value**
Coin sorting	Speed	0.12	0.35	24	0.34	n.s.
	SD Speed	255.95	122.52	24	2.09	p<0.05
	Max. Lateral Acceleration	658.20	204.83	24	3.21	p<0.05
CD selecting	Speed	0.44	0.34	24	-1.29	n.s.
	SD Speed	-1.93	54.54	24	-0.03	n.s.
	Max. Lateral Acceleration	182.68	53.10	24	3.44	p<0.05
Radio tuning	Speed	-0.79	0.35	24	-2.28	p<0.05
	SD Speed	319.35	109.30	24	2.92	p<0.05
	Max. Lateral Acceleration	178.32	59.40	24	3.00	p<0.05

*NOTE: for the dependent measures SD Speed and Max. Lateral Acceleration, the dependent variables were scaled by 1,000 to facilitate their use as priors in Chapter 6.

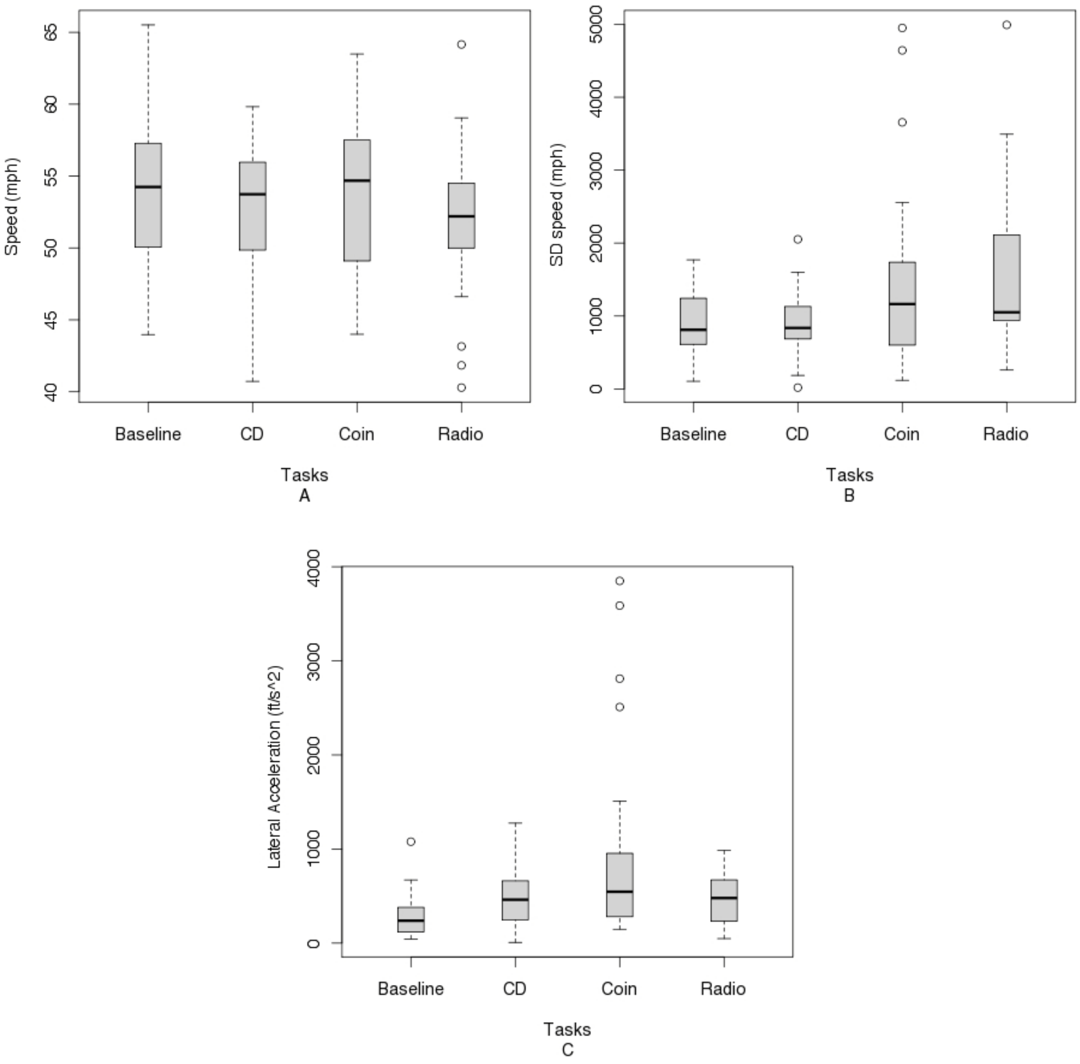


Figure 8. Box plots of the dependent measures during the distracting tasks and baseline for the mean speed (A), standard deviation of speed (B), and the maximum lateral acceleration (C)

Eye movement measures

Number of glances

The number of glances towards the distracting tasks is shown in Figure 9(A). Two participants were excluded from the analysis because they did not have eye data. There were significantly more glances toward the distracting tasks during the radio task (mean=7.32 (SD=3.26)), (*t*(46)=5.27, *p*<0.05) and the coin task (mean=8.72 (SD=5.79)), (*t*(46)=4.00, *p*<0.05) than during the CD sorting task (mean=2.91 (SD=1.70)), (see Table 15).

Table 15. Model parameters for the model of the number of glances to the distracting tasks

Variable	**Parameter estimate**	**St. Error**	**DF**	**t-stat**	***p*-value**
Intercept	2.95	0.84	46	3.53	p<0.05
Coin Sorting task	5.77	1.09	46	5.27	p<0.05
Radio tuning task	4.37	1.09	46	4.00	p<0.05

Duration of longest glance to task

The duration of the longest glace to the distracting task is shown in Figure 9(B). Both the coin sorting (mean=1.74 (SD=0.60)), (*t*(46)=4.70, *p*<0.05) and the radio tuning task (mean=1.70 seconds (SD=0.53)), (*t*(46)=4.45, *p*<0.05) resulted in longer glances to the distracting task than the CD task (mean=1.09 seconds (SD=0.32)), (see Table 16). It has been shown that glances away from the roadway for greater than two seconds results in twice the risk of a crash as baseline driving (Klauer, et al., 2006). There were many participants that had maximum glances away from the roadway during the coin sorting task and the radio tuning task that were greater than two seconds.

Table 16. Model parameters for the model predicting the duration of the longest glance to the distracting task

Variable	**Parameter estimate**	**St. Error**	**DF**	**t-stat**	***p*-value**
Intercept	1.10	0.10	46	10.50	$p<0.05$
Coin Sorting task	0.64	0.14	46	4.70	$p<0.05$
Radio tuning task	0.60	0.14	46	4.45	$p<0.05$

Percentage of time looking at task

Box plots of the percentage of time during the engagement in the distracting task that the participants were looking at the distracting task are shown in Figure 9(C). The radio task required that the participants spend a higher percentage of time looking at the distracting task (mean=51.9% (SD=10.0%)), than either the coin sorting (mean=39.1% (SD=13.1%)), or the CD selecting task (mean=37.7% (SD=9.84%)), ($t(46)=4.70$, $p<0.05$) (see Table 17). The coin sorting task did not significantly differ from the CD sorting task in the percentage of time spent looking at the distracting task.

Table 17. Model parameters for the model predicting the percent of task time spent looking at the distracting task

Variable	**Parameter estimate**	**St. Error**	**DF**	**t-stat**	***p*-value**
Intercept	0.38	0.02	46	16.5	$p<0.05$
Coin Sorting task	0.01	0.02	46	0.41	n.s.
Radio tuning task	0.14	0.02	46	5.46	$p<0.05$

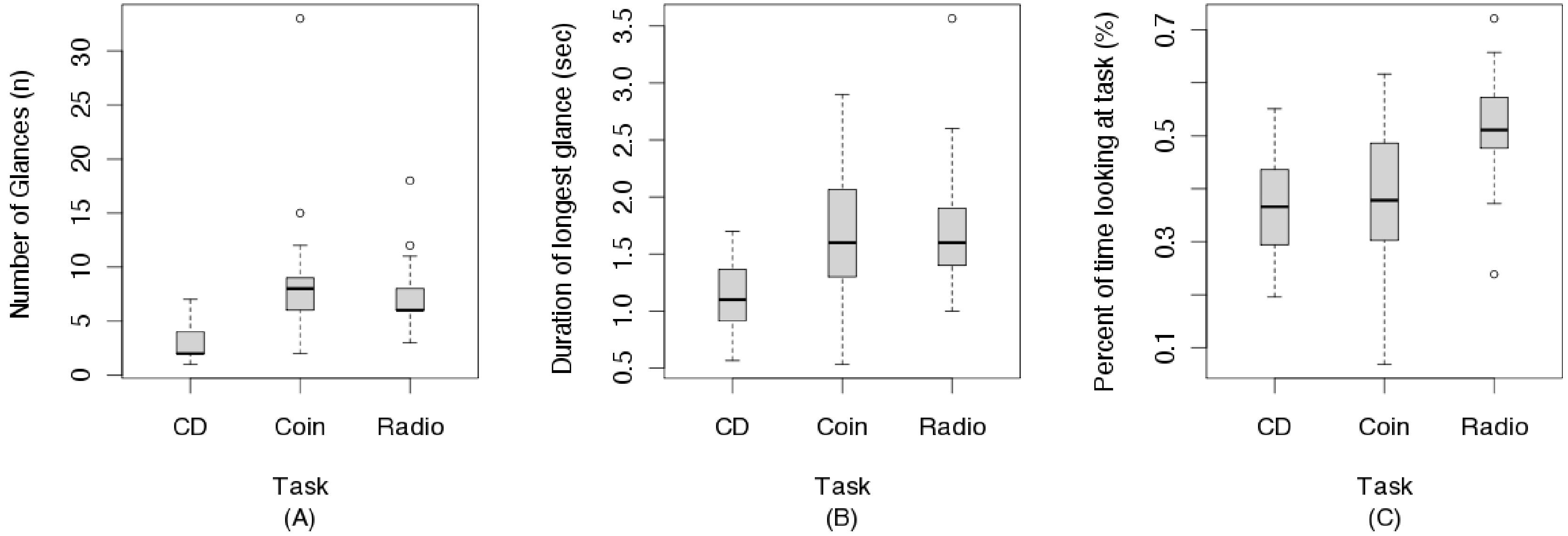


Figure 9. Box plots of the number of glances to the distracting task (A), the duration of the longest glance (seconds) to the distracting task (B), and the percentage of time spend looking at the distracting task for the simulator study.

Discussion

The results of the analysis presented in this chapter demonstrate that these simple tasks do significantly influence driving performance and provide prior distributions for use in the next chapter.

The coin sorting task resulted in larger standard deviation of speed and maximum lateral acceleration but resulted in no difference in mean speed compared to the baseline. The radio tuning task resulted in a lower mean speed, but larger standard deviation of speed and larger maximum lateral acceleration. The CD selecting task only resulted in a larger maximum lateral acceleration than the baseline. Other studies have used these tasks as benchmarks to evaluate other sources of distractions and the design of in-vehicle systems, however these tasks do have consequences in terms of driving performance themselves (Jäncke, et al., 1994; Jenness, et al., 2002; Wikman, et al., 1998). Both the coin sorting and the radio tuning task resulted in more frequent and longer glances to the distracting tasks. The radio tuning task resulted in a higher percentage of time spend looking at the distracting task than the coin sorting or the CD selecting tasks. The values of the eye gaze related variables for the radio tuning task are very consistent with the measures reported for a radio tuning task in the literature (Sodhi, et al., 2002). However, the existing literature does not report the results of these tasks in a form that can be used to represent prior knowledge about their effect when compared to baseline driving. The distributions of the model parameters in the current experiment fit directly into the Bayesian analysis in Chapter 6. While there may be differences in the effect of these tasks on driving performance between the younger participants in the simulator study and the on-road study involving TBI drivers, they do include information that is useful for evaluating the on-road study data. The distributions therefore, illustrate prior knowledge about the effects of these tasks on driving performance in an effort to improve the precision of the posterior distributions that otherwise would not be available.

CHAPTER 6.
THE EFFECT OF NON-DRIVING TASKS ON DRIVING PERFORMANCE OF INDIVIDUALS WHO SUSTAINED A TBI

This chapter presents an on-road study to investigate the influence of distracting tasks on the driving performance of TBI and non-TBI drivers (Specific Aim 3). The on-road study used an instrumented vehicle with data collected with researchers at Drexel University. It is hypothesized that the effect of distracting tasks may have a larger effect on the driving performance of individuals with traumatic brain injuries than for non-TBI drivers.

There are several constraints associated with using a clinical population in an on-road study. Recruitment of drivers from a clinical population is oftentimes difficult, and inferences need to be made from smaller than ideal sample sizes. It is also not appropriate to use distracting tasks that are shown to have high crash risk and are illegal (e.g., cell phones) . Therefore, distracting tasks that are quite common (tuning the radio) were used. However, these common distracting tasks may not show as large an effect in a frequentist statistical model. Bayesian regression techniques are used in this study to account for some of these concerns. These techniques allow for the use of prior distributions to increase the precision of the posterior distributions of the parameter estimates. These prior distributions were obtained in the study described in the previous chapter.

The study presented in this chapter is an on-road study involving both TBI and non-TBI drivers as part of a National Institute of Health project and the University of Iowa Institutional Review Board (#200705762) and the University of Washington Human Subjects Division (#2009-36964) approved the data analysis. The overall goal of the NIH project is to develop a driving simulator that generates measures that are empirically and clinically relevant for driving. As part of this project, participants, in a within subject design, drove on a desktop driving simulator and in an instrumented vehicle with a professional driving evaluator. The driving simulator portion of this study was not used because it is based on the same drivers and it is inappropriate to use the same population to develop prior distribution. Further, it was important to be able to generalize the results to real world setting. Hence, the data that will be used for this dissertation will only include the data collected from the instrumented vehicle. It is hypothesized that the effect of distracting tasks may have a larger effect on the driving performance of individuals with traumatic brain injuries than for non-TBI drivers.

Methods

As mentioned earlier, the data used in this paper was collected as part of a larger study that involves individuals with TBIs and controls driving in an instrumented vehicle. As part of this study, the participants also completed the same distracting tasks that were examined in Chapter 5 (the CD selecting, coin sorting and radio tuning tasks). The only minor changes to these tasks relate to the specific radio station starting point and the station number target (based on the stations available in the area), and the specific amount of change that the participants need to make in the coin sorting task ($ 0.65).

During the larger study, participants drove an on-road course in suburban Pennsylvania. The participants were transported to the test site by Drexel University researchers in the instrumented vehicle. The participants met the certified driving evaluator in the parking lot of the Newtown, PA Recreation Center. The certified driving evaluator conducted the study and sat in the front passenger seat of the vehicle, and another researcher sat in the back seat behind the driver. The driving evaluator had the ability to take control of the vehicle if necessary (through either the steering wheel, or using the secondary brake installed on the passenger side of the vehicle). The driving evaluator gave the participant the driving instructions including when to make turns and when to start the specific distracting tasks. The route for the on-road study was designed to include residential, highway, urban and rural driving segments (see Figure 10). Each participant drove a set course twice. The distracting tasks (CD selecting, radio tuning, and coin sorting tasks) were conducted in a random order on the second lap of the course on straight segments of rural roads with a speed limit of 40 MPH (64 KPH). The baseline driving segments were selected from the first lap of the course by matching the exact location of the start and end of the tasks between the laps using the GPS locations. All tasks were completed on the second lap to allow the driving evaluator time to determine if the participants could safely attempt the tasks. The driving evaluator was not told which participants were TBI drivers and which were controls, so each participant was evaluated consistently prior to engaging in the distracting tasks.

Figure 10. On-road route for the instrumented vehicle drive in Newtown, PA. (via Google Earth, modified from that by R. Mitura, Digital MediaWorks Inc.)

Equipment

The instrumented vehicle used in this study was a 2002 Ford Taurus (Figure 11), and was instrumented with an extensive array sensors and cameras. The sensors in the vehicle measure the brake pedal and gas pedal forces, the vehicle's longitudinal and lateral acceleration, steering wheel angle, the vehicles GPS position and data from the vehicle OBD (On-Board Diagnostic) computer including the engine's RPM and the vehicle speed (see Figure 12). Data from the instrumented vehicle and the videos from seven cameras were collected at 5 Hz. The videos collected included a forward view, a face view, a foot view, two over the shoulder views (left and right), and two pavement-marking views (from both side mirrors outside of the vehicle).

Figure 11. The HFSM Instrumented Vehicle

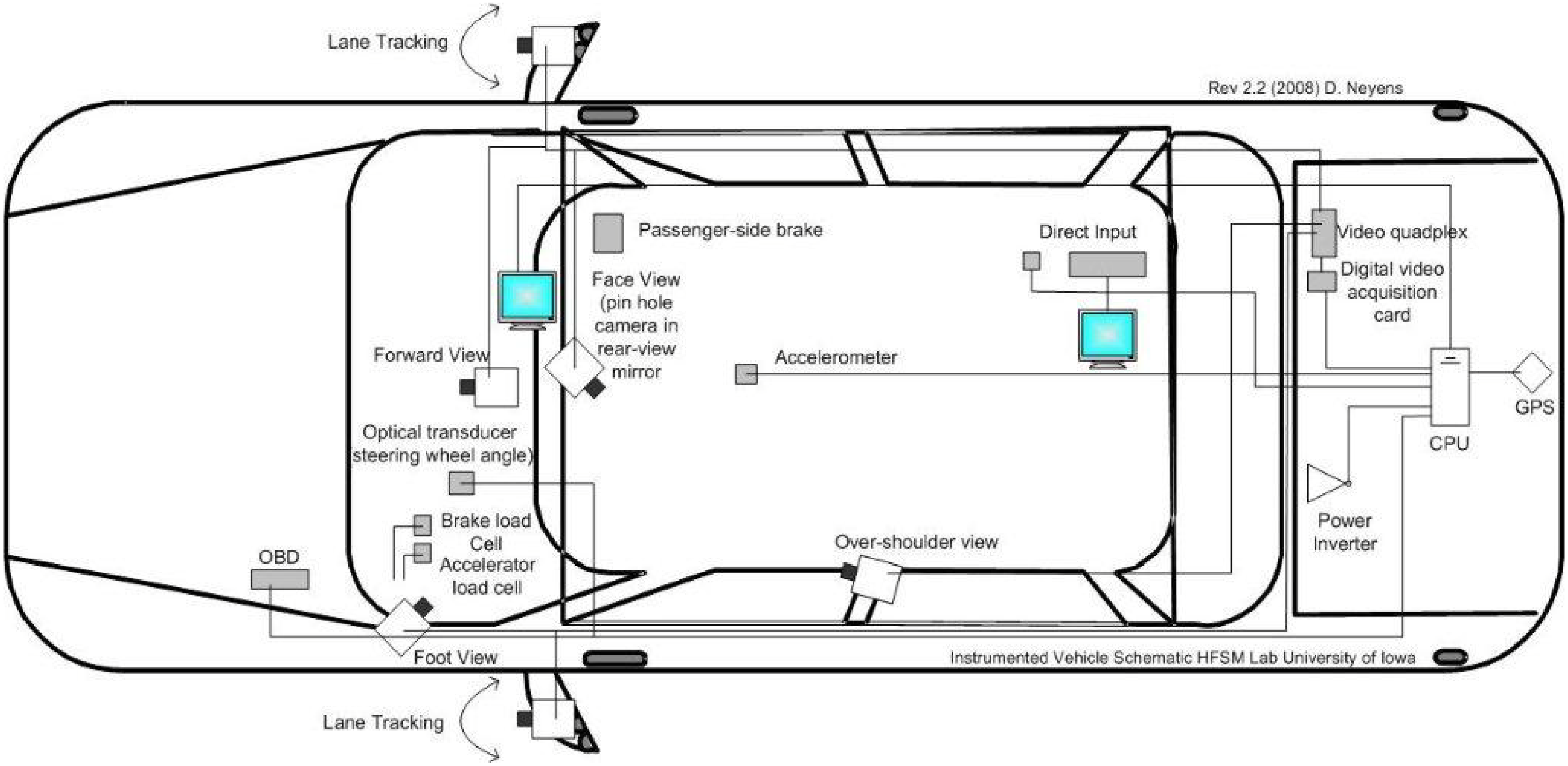


Figure 12. Schematic of the instrumentation embedded within the vehicle.

Participants

The individuals with TBI were recruited for participation in this study through rehabilitation facilities in the Philadelphia metropolis. All TBI drivers needed to be driving for at least one year following their injury. Additionally, the TBI drivers must have had a minimum of one year of driving experience prior to their injury and maintained a valid driver’s license. Drivers who required adaptive driving control (e.g. steering wheel knob, adaptive mirrors, hand controls) were excluded from the study. If the participant had a history of strokes, seizures, prior brain injury or other substantial neurological history, a history of psychiatric or substance abuse, or were taking medication with sedating effects at the time of study they were also excluded from the study. Additionally, if the participants have a history of reckless driving, a suspended license, or was an expert driver (e.g. truck driver or cab driver) they were also excluded from the study. Finally, individuals with a history of motion sickness, or who were identified as exhibiting risks for simulator sickness (through the Simulator Sickness Questionnaire) were also excluded.

Controls were selected to match the TBI drivers by age and gender. They were also required to have maintained active drivers licenses for at least one year prior to participating in the study and could not have a history or reckless driving, a suspended license, or be employed as expert drivers.

Analysis methods

Analytical Justification

Bayesian statistical methods are based on Bayes' Theorem as shown in Equation 3. This theorem states that the posterior distribution of a parameter is proportional to the distribution of the data multiplied by an a priori distribution. In other words, the posterior distribution of a parameter is the conditional distribution given the data.

$$P(\theta \mid y) \propto P(y \mid \theta) \times P(\theta) \qquad \text{(Eq. 3)}$$

Statistical analysis based on Bayes' theorem has been difficult because of the numerical integration needed to calculate the joint conditional distributions. Sampling based methods have been used to estimate these numerical integrations. The most popular sampling method used for Bayesian statistical analysis is Markov Chains Monte Carlo (MCMC). MCMC methods draws samples from a Markov chain such that the limiting distribution for the samples is the joint distribution on the parameter of interest in the model (Gelman, Carlin, Stern, & Rubin, 2004). As these are Markov Chains, the draws for each iteration are dependent only on the previous iteration. One method for conducting the sampling in the MCMC is Gibbs sampling. In Gibbs sampling random variables are used to initially estimate parameters allowing for the next iteration of the MC to be draws from distributions with defined parameters.

WinBUGS (Windows Bayesian inference Using Gibbs Sampling) is a software package that uses the Gibbs sampling methodology to fit Bayesian models through the use of MCMCs (Lunn, Thomas, Best, & Spiegelhalter, 2000). This software is freely available and has been popularly used in the transportation domain, for example, see Davis & Yang (2001) or Miaou & Lord (2003).

There are several advantages for using Bayesian methods over Frequentist methods. In Bayesian statistics the results of the analysis are more intuitively interpreted. For example the interpretability of credible intervals is more intuitive than confidence intervals. A 95% credible interval is interpreted as an interval that contains the true parameter value with approximately 95% certainty given the data. This is different than a Frequentist confidence interval which is interpreted as a long run approximation that confidence intervals based on each data set (with different confidence intervals) will contain the true parameter estimate 95% of the time (Congdon, 2006). Another benefit to Bayesian methods is that the quantities of interest can be easily obtained. For example, the posterior predictive distribution can be generated in order to produce a range of values for future observations. Bayesian methods allow for the formal incorporation of prior distributions of parameter estimates to generate posterior distributions. A prior distribution can be based on the results of previous similar studies (as in the case of this analysis) or can be based on expert knowledge, or lack thereof (which is the case of an uninformative prior distribution). There are many methods to constructing prior distributions. The precisions of the resulting posterior distributions are improved with the additional information contained in the prior distribution. It is critical that the prior distributions are selected appropriately and that they do not drive the results (see Appendix C for model comparisons). One important aspect of prior distributions is that they are conjugate priors. Conjugate priors allow the likelihood (when calculated from

Equation 1) to be a proper distribution. Therefore informative prior distributions are based on the effect estimates generated in the analysis presented in Chapter 5. These prior distributions are conjugate normal priors with the means and precisions of the estimates from the simulator study. There are many texts that provide recommendations for selecting priors and evaluating their impact on the results (Congdon, 2006; Gelman, et al., 2004; Ntzoufras, 2009).

Methods

Repeated measures Bayesian linear models are used to estimate the posterior probabilities of the parameters (see Eq. 4). The model has two independent factors, the distracting task [engaged in task or baseline driving] and the classification of the participant [TBI driver or control]. As mentioned earlier, the prior distributions of the parameter estimates for the distracting tasks parameter are conjugate normal distributions with means and precisions of the parameter estimates from the simulator study in Chapter 5. Uninformative conjugate normal prior distributions are used for the parameters associated with the TBI driver or non-TBI driver classification, as there is little information available regarding the expected distributions of these parameters.

$$f(\beta \mid \sigma^2, y_{ij}) \propto \prod_{i=1}^{n} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma^2}(y_{ij} - x'_i \beta)^2\right] \times f(\beta) \qquad \text{(Eq. 4)}$$

WinBUGS (Windows Bayesian inference Using Gibbs Sampling) is used to estimate the posterior distributions using Gibbs sampling for the Markov Chains Monte Carlo (MCMC) (Lunn, et al., 2000). Posterior predictive probabilities were calculated using the step function within WinBUGS. For each model, three chains of 100,000 iterations were run, 10,000 of which were burn-in iterations to ensure that the MCMCs had converged. In comes cases, 25,000 iterations were burnt-in to ensure convergence. Convergence was determined based on the history plots and the BGR plots (Brooks & Gelman, 1998). Significance is determined by the posterior predicative probability. Additionally, for each task and dependent measure, models with completely uninformative prior distributions were run to verify that the prior distributions for the task parameter were not driving the results but rather contributing to the distributions associated with the data.

Dependent variables

As mentioned earlier the dependent variables of interest for this analysis include the mean speed (MPH), the standard deviation of speed (MPH), and maximum lateral acceleration (ft/s^2). These dependent measures were selected, as they are consistent between the driving simulator used in the previous chapter and the instrumented vehicle used in this chapter. Additionally, the same eye gaze variables from the simulator study presented in Chapter 5 are also used in this chapter (i.e., percent time looking at task, duration of longest glance to task, and number of glances to distracting task).

Evaluating model convergence

Model convergence was determined based on the history plots and the Brooks-Gelman-Rubin (BGR) diagnostics from within WinBUGS (See Appendix B). The BGR is based on running a minimum of three separate over-dispersed MCMC chains concurrently. The 80% credible set intervals of the distribution of a given parameter for the MCMC runs are calculated for each chain separately then averaged and the 80% credible set interval is calculated for the chains pooled together. The pooled and the averaged widths should converge and the R-ratio should approach and remain near one (the rule of thumb is that it remains less than 1.1) if the model has converged (Gelman, et al., 2004).

Results

A total of 39 individuals participated in the study. Three participants were excluded from the analysis; one because they were unable to complete the distracting task, one because it started raining during the study, and one, because they experienced extraneous events during the study (i.e., church festival parade in the other lane). Therefore, the study included 17 TBI drivers and 19 healthy control (HC) non-TBI drivers. The posterior densities of the participants ages did not differ between the TBI participants with a mean age of 37.5 years-old (SD=11.4) and the controls with a mean age of 38.7 years-old (SD=12.4) (t=-0.29, n.s.). There were there were five females with TBI and eight females that were non-TBI drivers.

Global cognitive score

Both the TBI participants and the controls completed neuropsychological tests. A global cognitive score was calculated for participants based on their test scores. The specific neuropsychological tests used to calculate this score include the: Trail Making A and B, the Stroop Test, Symbol Digit Modalities, Digit Span, Rey Complex Figure Copy Score, and Block Design from the Wechsler Abbreviated Intelligence Scale. Other studies have used these neuropsychological tests to predict on-road driving evaluations of brain injured individuals (Schanke & Sundet, 2000). The scores of each of the tests were standardized using a T-score (mean=50), based on published norms. The standardized scores of each test were averaged to calculate the global cognitive score. There was no significant difference between the average global cognitive score of the controls 48.6 (SD=5.16) and the average global cognitive score of the TBI group 44.5 (SD=11.8) (z=-1.32, p=0.09) (see Figure 13).

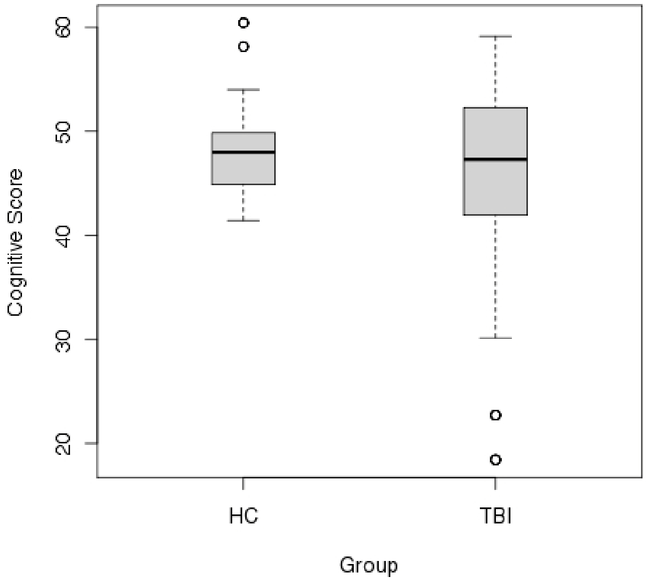


Figure 13. The global cognitive scores for the healthy control (HC) driver group and the TBI driver group.

Self-reported driving habits

A survey was distributed as part of the larger study that assess driving exposure, and a history of tickets or accidents. The non-TBI drivers and TBI drivers did not significantly differ in the number of days they reported driving each week, with the healthy controls reporting driving 3.5 (SD=2.7) days per week and the TBI drivers reported driving 4.8 (SD=2.9) days per week. Nor did they report significantly different exposure to driving as indicated by the number of miles driving during the last trip, with the controls reporting 20.4 (SD=21.8) miles in the last trip and the TBI drivers reporting 19.4 (SD=34.8) miles. Of the TBI drivers, 58.8% reported cognitive impairments following their injury and 41.2% reported changes in their driving following their injury but only 35.2% reported attending driver training following their injury.

The duration of the tasks and the corresponding baselines for the distracting tasks for both the TBI and non-TBI drivers is reported in Table 18. The coin sorting and the CD selecting tasks took longer for the TBI group than the control group (z=1.96, p=0.025; z=1.75,p=0.04, respectively). However, the durations of the radio tuning task did not significantly differ between the groups.

Table 18. The duration (and standard deviation) of the distracting tasks and the corresponding baseline road segments for the controls and the TBI group.

	Controls		**TBI Group**		**Difference in task times**
	Task	**Baseline**	**Task**	**Baseline**	**Z-score, p-value**
Coin sorting	33.95 (10.78)	31.47 (10.69)	44.82 (20.47)	37.98 (16.75)	1.96, p=0.025
Radio tuning	30.44 (12.94)	28.24 (12.94)	33.40 (12.55)	29.81 (12.54)	0.69, p>0.05
CD selecting	19.35 (5.97)	18.88 (7.59)	23.27 (7.31)	20.73 (5.75)	1.75, p=0.040

Driving performance measures

Coin sorting task

The results of the Bayesian repeated measures linear models and the interaction plots for the coin sorting task are shown in Figure 14 and Table 19. There were no significant interaction terms in the models, and therefore they are not included. There was no significant difference between the mean speed maintained by the TBI group and the healthy controls (HC) during the coin sorting task. The standard deviation (SD) of speed was significantly larger when engaged in the task compared to the baseline driving. There was also a significant difference between the HC and TBI groups, with the highest SD of speed for the TBI drivers when engaged in the coin sorting task. The maximum lateral acceleration was significantly higher for the TBI group than the HC group. The maximum lateral acceleration was also higher during the task than the baseline driving segment for all participants.

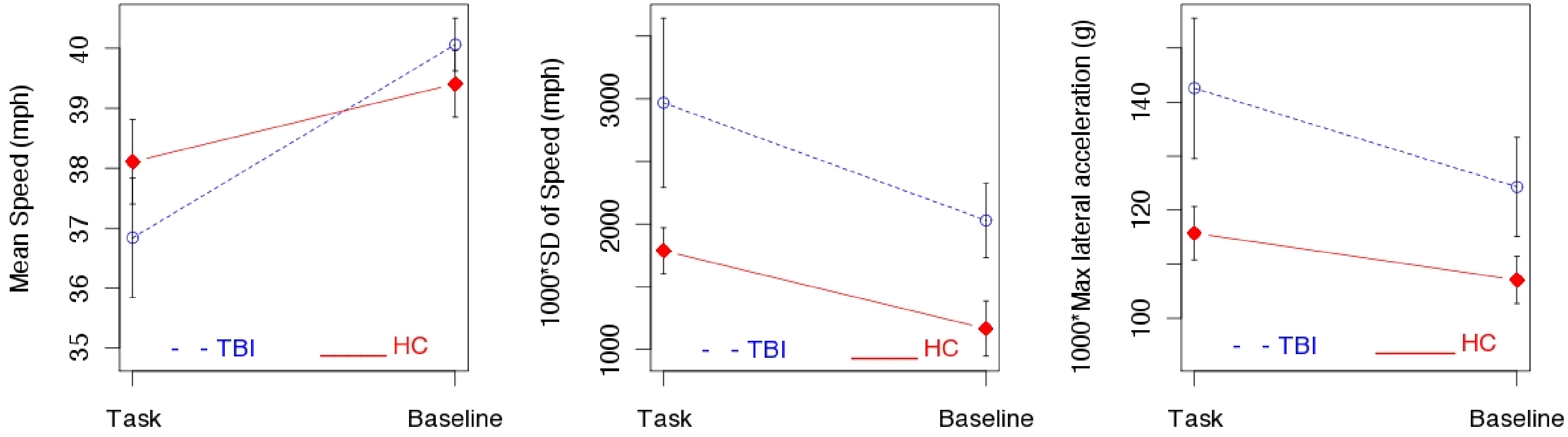
Radio tuning task

The Bayesian repeated measures linear models for the engagement in the radio tuning task and the interaction plots are shown in Table 20 and Figure 15. Similar to the other tasks, there were no significant interaction terms in the models. The mean speed did not significantly differ between the task and the baseline segment nor were there significant differences between the groups. The standard deviation of speed was significantly larger when engaged in the radio tuning task compared to the baseline. In terms of maximum lateral acceleration, there were no significant effects of either engagement in the radio tuning task or between the TBI and HC group.

CD selecting task

The Bayesian repeated measures linear models for the engagement in the CD selecting task and the interaction plots are shown in Table 21 and Figure 16. There were no significant interaction terms in the models similar to the other two distracting tasks.

There were no significant differences found between the groups or for engagement in the CD selecting task for any dependent measures.



(A) (B) (C)

Figure 14. Standard error plots of the data from Study 2 for TBI and healthy control (HC) drivers while engaged in the coin sorting task and during the baseline driving segment for (A) mean speed, (B) standard deviation of speed, and (C) maximum lateral acceleration.

Table 19. The parameter estimates for the repeated measures Bayesian model predicting driving performance measures while engaged in the coin sorting task

	Dependent measure					
Parameter estimate	**Mean speed (MPH)**		**SD Speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	39.3 (0.5)*	(38.3, 40.3)	1338.0 (248.0)*	(819.5, 1810.0)	107.0 (4.6)*	(97.8, 116.2)
Task	-0.4 (0.3)	(-1.0, 0.3)	292.1 (113.2)*	(77.2, 516.0)	9.0 (3.9)*	(1.3, 16.6)
TBI	0.4 (0.8)	(-1.3, 2.0)	765.0 (325.8)*	(137.8, 1416.0)	18.9 (11.5)*	(-3.9, 41.5)

Note: *significant with posterior predictive probability > 0.95

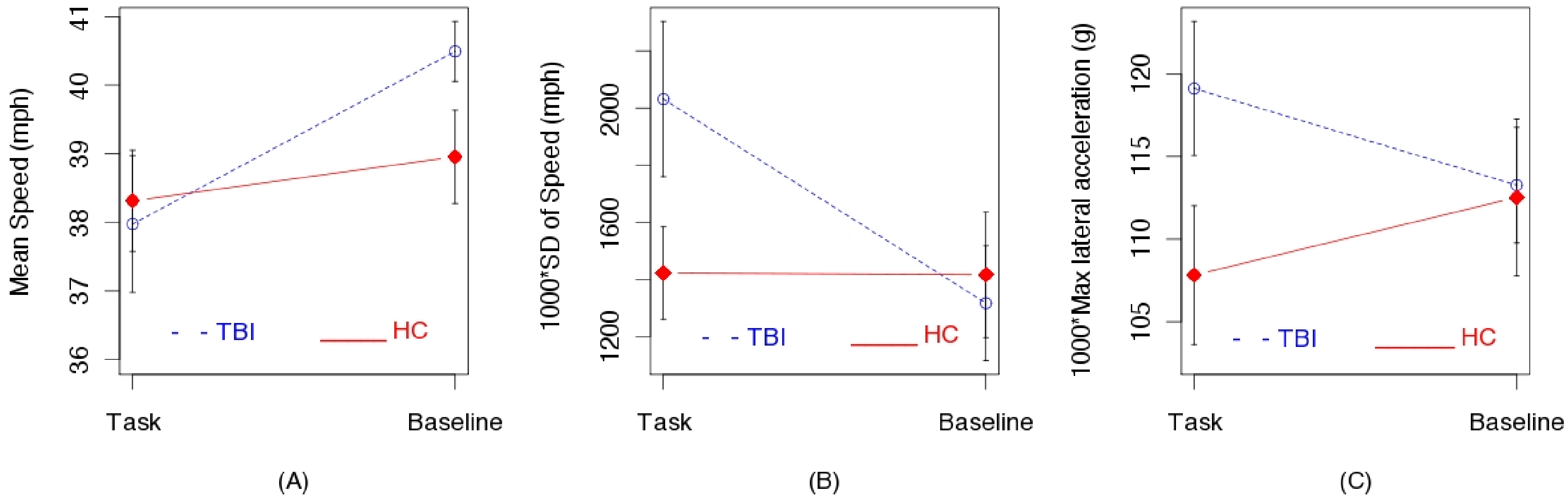


Figure 15. Standard error plots of the data from Study 2 for TBI and healthy control (HC) drivers while engaged in the radio tuning task and during the baseline driving segment for (A) mean speed, (B) standard deviation of speed, and (C) maximum lateral acceleration

Table 20. The parameter estimates for the repeated measures Bayesian model predicting driving performance measures while engaged in the radio-tuning task

	Dependent Variable					
	Mean speed (MPH)		**SD Speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
Parameter estimate	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	38.9 (0.6)*	(37.7, 40.0)	1214.0 (156.7)*	(900.1, 1516.0)	110.5 (4.0)*	(102.5, 118.4)
Task	-0.2 (0.3)	(-0.4, 0.9)	333.1 (96.9)*	(141.6, 521.1)	0.6 (3.2)	(-5.6, 6.8)
TBI	1.3 (0.9)	(-0.4, 3.1)	292.5 (209.9)	(-115.0, 706.6)	4.8 (5.6)	(-6.2, 16.1)

Note: *significant with posterior predictive probability > 0.95

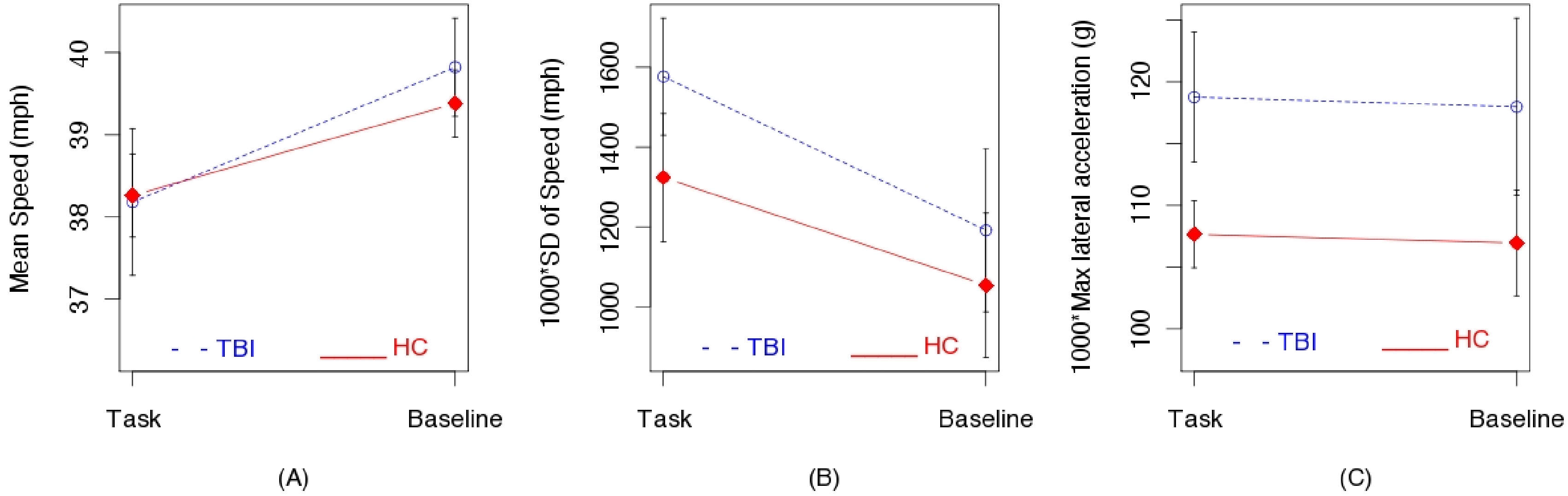


Figure 16. Standard error plots of the data from Study 2 for TBI and healthy control (HC) drivers while engaged in the CD selecting task and during the baseline driving segment for (A) mean speed, (B) standard deviation of speed, and (C) maximum lateral acceleration

Table 21. The parameter estimates for the repeated measures Bayesian model predicting driving performance measures while engaged in the CD selecting task

Parameter estimate	**Dependent Measure**					
	Mean speed (MPH)		**SD speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	39.2 (0.5)*	(38.3, 40.2)	1152.0 (127.3)*	(904.6, 1403.0)	106.9 (4.8)*	(97.4, 116.2)
Task	-0.2 (0.3)	(-0.8, 0.4)	29.7 (53.4)	(-75.9, 133.1)	9.7 (6.9)	(-3.8, 23.3)
TBI	0.3 (0.8)	(-1.2, 1.8)	200.1 (176.6)	(-147.8, 540.1)	1.6 (3.6)	(-5.4, 8.7)

Note: *significant with posterior predictive probability > 0.95

Eye gaze related variables

The mean and standard deviation of the percentage of time looking at the task, the number of glances, and the duration of the longest glance to the distracting tasks are shown in Table 22. The percent of time looking at distracting task was significantly greater for the radio task than the other two tasks (Figure 17(A) and Table 23). TBI drivers also spent a significantly longer time looking at the distracting tasks than the non-TBI drivers.

The number of glances significantly differed between all three distracting tasks with the coin tasks and radio task requiring more glances to the task than the CD task (Figure 17(B) and Table 23). TBI drivers also consistently had more glances to the distracting tasks than the controls.

The duration of the longest glance to the distracting task was longer for the coin sorting task and the radio tuning task than the CD sorting task (Figure 17(C) and Table 23). However, there were no significantly differences between the TBI drivers and the HC drivers for the duration of the longest glance to the distracting tasks.

Table 22. The mean (and standard deviation) of eye gaze related variables during the distracting tasks for the healthy controls and the TBI group.

	Percent time looking at distracting task (%)		**Number of glances to distracting task**		**Duration of longest glance to distracting task (sec)**	
	TBI	**HC**	**TBI**	**HC**	**TBI**	**HC**
Coin sorting	0.23 (0.12)	0.15 (0.08)	10.24 (6.22)	6.56 (3.01)	1.48 (0.67)	1.13 (0.34)
Radio tuning	0.51 (0.10)	0.38 (0.11)	15.18 (5.05)	11.78 (5.44)	2.16 (1.16)	1.61 (0.43)
CD selecting	0.25 (0.08)	0.20 (0.09)	5.94 (2.63)	4.39 (2.30)	1.47 (0.59)	1.36 (0.52)

Table 23. The parameter estimates for the repeated measures Bayesian model predicting eye gaze measures while engaged in the CD selecting task

	Dependent Measure					
	Percent of time looking at task (%)		**Number of glances to the task**		**Duration of longest glance to task (sec)**	
Parameter estimate	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	0.18 (0.02)*	(0.14, 0.22)	4.18 (0.51)*	(3.15, 5.16)	1.15 (0.09)*	(0.97, 1.32)
Coin task	-0.04 (0.02)	(-0.09, 0.00)	4.06 (0.70)*	(2.70, 5.46)	0.17 (0.09)*	(0.00, 0.36)
Radio task	0.22 (0.03)*	(0.18, 0.27)	6.61 (0.77)*	(5.05, 8.09)	0.60 (0.10)*	(0.40, 0.80)
TBI	0.08 (0.03)*	(0.03, 0.13)	2.11 (0.88)*	(0.40, 3.87)	0.27 (0.17)	(-0.07, 0.61)
Baseline: CD selecting task						

Note: *significant with posterior predictive probability > 0.95

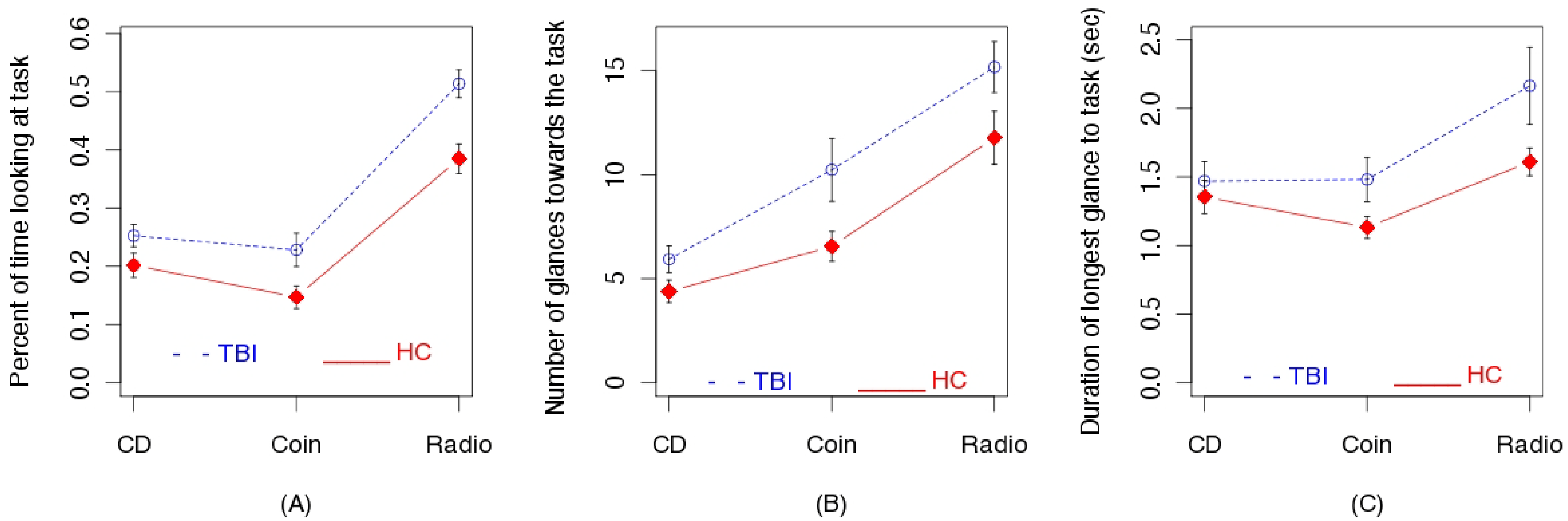


Figure 17. The percentage of time looking at the task (A), the number of glances to the task (B) and the duration of the longest glance to the task (C) for the TBI and healthy control (HC) drivers.

Model comparisons

As mentioned earlier, it is necessary to determine if the prior distributions are directing the results of a Bayesian model. To evaluate this, frequentist models with the same form as the Bayesian models, as well as Bayesian Models with uninformative prior distributions were conducted. These two models are compared to the models using informative prior distributions for all conditions and dependent measures. The models for the standard deviation of speed during the coin sorting, radio tuning, and CD selecting are shown in Figure 18. The 95% credible sets for the parameters from the Bayesian models with informative priors are much smaller than the other models. All other comparisons (as well as the actual model parameters) are shown in Appendix C.

As can be seen in Figure 17, the model parameters (and the 95% credible sets for Bayesian models or 95% confidence intervals for the frequentist models) do not substantially differ. The 95% CS for the task parameter in the Bayesian model with informative prior distributions is much smaller than the other intervals.

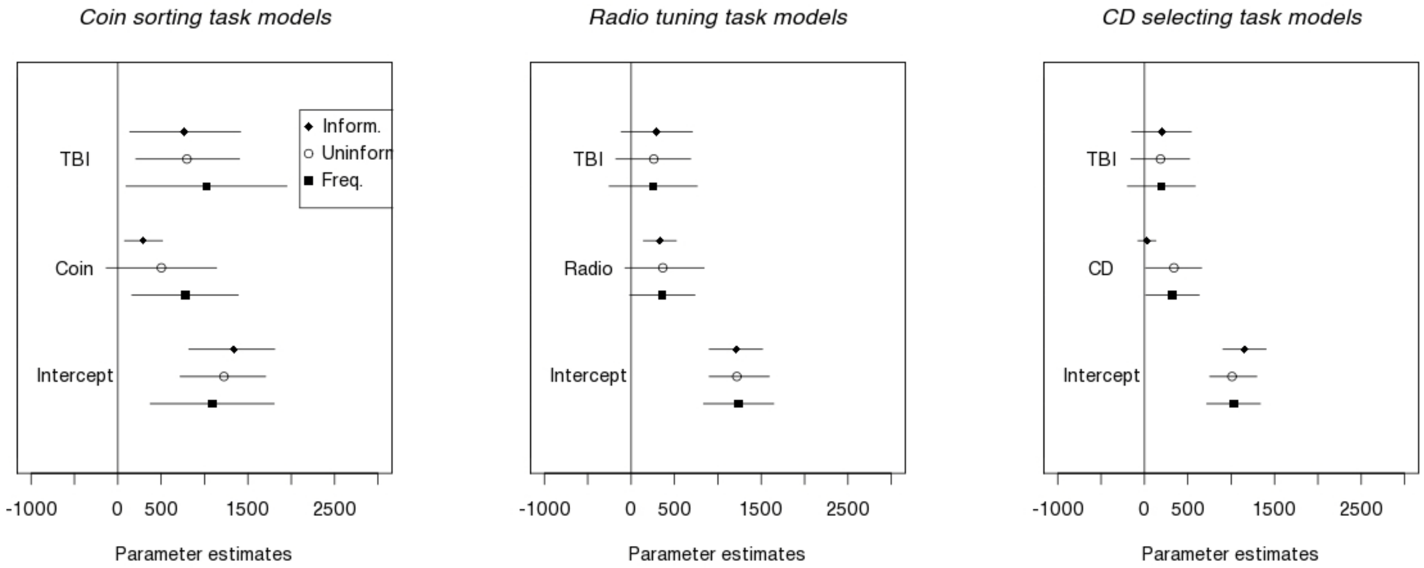


Figure 18. Comparisons of model parameters of models of the coin sorting task, radio tuning task, and CD selecting task for the dependent measure **standard deviation of speed** using frequentist models, the Bayesian models with uninformative prior distributions and the Bayesian models with informative prior distributions.

Discussion

This study investigated the effect of distracting tasks on the driving performance of individuals with traumatic brain injuries. As mentioned earlier, it is important to verify that the prior distributions do overly contribute to the resulting posterior distributions. The use of the prior distributions from the simulator study did contribute to the posterior distributions and thus resulted in more precise posterior distributions. For example, during the coin sorting task, the TBI drivers exhibited worse driving performance in terms of larger standard deviation of speed and larger maximum lateral acceleration. However, there were no differences detected in the driving performance between the TBI group and the HC group during the CD selecting or the radio tuning tasks.

These results suggest that a relatively simple distracting task affect driving performance more severely for TBI drivers than for non-TBI drivers. The coin sorting task contains cognitive, visual and manual components, whereas the CD selecting and radio tuning tasks is composed of mostly visual and manual components. The differences in decomposed distracting tasks (e.g., visual, manual, cognitive and auditory) have been used to explain some differences in performance decrements between distracting tasks (Ranney, Mazzae, Garott, & Goodman, 2001). The more complex cognitive aspects of counting the currency may have caused this task to be more difficult, which resulted in differences in driving performance between the groups. In future work, more complicated distracting tasks should be used to determine if these differences are inherently related to task complexity or some other factor causing these differences in performance. Other studies have used more complex distracting tasks with clinical patients (e.g., Parkinson disease) and found that clinical patents committed more errors during a distracting task than non-TBI drivers (Uc, et al., 2006).

Limitations

There are several limitations associated with this analysis. First, there is an inherent order effect related to the fact that the baseline segment for each task always occurred prior to the task segment. However, these segments occurred about 30 min apart within the full experiment, and it was necessary for the driving evaluator to determine if it was safe to ask participants to engage in the distracting tasks. In fact, one participant (that was excluded from this analysis) was not able to complete the tasks successfully. Another limitation is associated with the selection of the distracting tasks. It was necessary to select distracting tasks that did not result in substantial increases in risk for clinical populations. Additionally, individuals with TBIs are difficult to recruit and those that participated in the study generally exhibit only minor cognitive difficulties. Those with severe TBIs may either not be active drivers (and thus not qualified for this study) or may be unwilling to participate due to the fear of losing their drivers license. Another limitation associated with this study is the use of only three dependent measures of driving performance. While other studies typically use several variables associated with driving performance, it was necessary to select variables that were consistent between the driving simulator and the on-road study and were available on both pieces of equipment.

One of the major limitations associated with this analysis was not accounting for the severity of TBI within the TBI driver category. Most of the drivers within this category experienced mild TBIs and some of the differences may be based on individual factors rather than classification of TBI or non-TBI. There are many differences between mild, moderate, and severe brain injuries, and there were mostly mildly injured individuals that participated in this study. Accounting for the severity of injury is very important to generating appropriate conclusions, but was not possible in this study due to small sample sizes in the more severely injured categories. Future work should address the severity of injury more closely or control for its effect in the analysis of driving performance measures.

Conclusions

Across all distracting tasks, TBI drivers had a larger number of glances to the task and a higher percentage of time looking at the distracting task than the non-TBI drivers. This may indicate that drivers with TBI need more visual information processing time in order to complete the task while driving. This may relate to deficits in cognition, and information processing experienced by individuals with TBIs (Mathias & Wheaton, 2007; Park, et al., 1999).

Bayesian statistical methods provided a means to determine distributions of parameter estimates that take into account knowledge or data outside of just one experiment. The knowledge generated in Chapter 5 was used to improve the confidence of the estimated effects in the model for the on-road study. This is particularly useful in a study with the size of that presented in this chapter.

CHAPTER 7.
CONCLUSIONS

The overall goal of this dissertation was to develop a greater understanding of how driver distraction influences TBI drivers. Data from a simulator study, an on-road study, crash data, and a survey of TBI drivers were used to examine this population from different perspectives to generate a more comprehensive view of the effect of driver distraction for this population. More specifically, the driving behaviors at the three levels of driving control and crash outcomes were investigated. The summary of results from this dissertation is presented in Table 24.

Insights into the effect of driver distraction are found at each level of driving control within Michon's model of driving control. In terms of strategic control, TBI drivers that were willing to engage in distracting activities also exhibited a propensity to speed (as identified by receiving traffic infractions). This may not have directly related to the TBI injury but rather a propensity to take risks .The survey identified two groups of TBI drivers based on their willingness to engage in distracting activities. One group was very unwilling to engage in distracting tasks, and was very similar to teenage drivers who were also unwilling to engage in distracting activities. The group of TBI drivers that was more willing to engage in distracting was similar to teenage drivers who were moderately willing to engage in distracting activities. As expected, TBI drivers were not as willing to engage in distracting activities as the frequent engaging teenage drivers because teenagers in general are the most willing to engage in distracting tasks (Olsen, et al., 2005; Sarkar & Andreas, 2004). However, the more willing TBI drivers were more likely to have received speeding tickets (an indication of a propensity to speed).

At the tactical level of driving control TBI drivers engagement in distracting tasks differed from non-TBI drivers as identified by the duration and frequency of glances to the task. In other words, TBI drivers appear to engage in the distracting tasks differently than non-TBI drivers. During the radio-tuning task and the coin sorting tasks TBI drivers had longer percentage of time looking at the distracting task and a greater number of glances to the distracting task. This indicates that drivers with TBI need more visual information processing time in order to complete the task while driving. This may relate to deficits in cognition and information processing experienced by individuals with TBIs (Mathias & Wheaton, 2007; Park, et al., 1999) and that they required more time to gather visual information from the distracting task in order to complete it.

In terms of the operational control of the vehicle, TBI drivers had larger standard deviation of speed and larger maximum lateral acceleration than the controls during a coin sorting task. There were no differences in driving performance during the CD selecting or the radio tuning tasks. The coin sorting tasks may have been more complex or less compatible with the driving task for the TBI drivers who experienced driving performance decrements.

The analysis of the crash data demonstrated that TBI drivers involved in crashes were more likely to occur at night and the drivers were less likely to wear seatbelts when in crashes than the controls. Driver distraction related crashes did not significantly differ between the crashes of TBI drivers and non-TBI drivers in crashes. This may relate to the underreporting related to driver distraction variables in crashes (Stutts et al., 2001, Neyens & Boyle, 2007, 2008). This underreporting relates to self-reported information and the documenting police officer’s perceptions. Additionally, in crashes that are severe or involve other obvious factors, driver distraction variables become less critical and thus less likely noted on the crash documentation (Neyens & Boyle, 2007). Therefore, the results related to the involvement of driver distraction in crashes need to be interpreted with this in mind. Given the differences in performance at each of the levels of driving control. It is expected that with accurate reporting, there would be differences in the driver distraction related crashes between TBI and non-TBI drivers. However, given the current data availability, investigating this true effect is not currently feasible. Regardless of driver distraction involvement, TBI drivers were more likely to be involved in multiple crashes than all other drivers in the crash database. Hence, it is very interesting that there is a groups of TBI drivers that exhibit a higher risk of being involved in multiple crashes.

Practical implications of this research

This research translates into some preliminary recommendations. In the analysis of crash data, TBI drivers were less likely to wear seatbelts in crashes, which suggests that driving rehabilitation and driver evaluation should focus on the benefits of wearing seatbelts. Additionally, based on the results of the analysis of the distracting tasks, TBI drivers exhibited worse driving performance when engaged in the tasks. When resuming driving following a TBI, driving evaluators and medical personnel should discuss how detrimental distracting tasks could be for TBI drivers. More specifically, the radio tuning task resulted in durations of glanced that were longer than two seconds for TBI drivers. Glances away from the roadway for greater than two seconds results in doubling the crash risk (Klauer, et al., 2006; Wierwille, 1993). This suggests that even simple distracting tasks may result in a substantial increase in risks for TBI drivers. The coin sorting tasks resulted in a significant decrements in driving performance. With further research these decrements in driving performance may actually translate into in increased risk of crashes while engaged in distracting tasks.

Table 24. Summary of research conclusions

Chapter	Specific Aim	Data sources	Population	Analysis	Outcome	General Outcomes
3	1	Crash data and brain injury registry	TBI and non-TBI drivers	Logistic regression models	TBI drivers less likely to wear seatbelts than controls in crashes	Observational: More risk taking among some TBI drivers (strategic control)
4	2	Survey data (n=32)	TBI drivers	Cluster analysis	TBI drivers more willing to engage in distracting tasks were more likely to have speeding tickets, and are similar to teenage 'moderate engagers'	
5	(supports Aim 3)	Simulator (n=25)	Non-TBI drivers	Repeated measures linear models	Prior distributions of model parameter	Controlled: Isolating all other effects, cognitive components of distraction cause worse performance for TBI drivers (operational control) Engagement in task differed between TBI drivers and controls (tactical control)
6	3	On-road driving Test study (n=36)	TBI and non-TBI drivers	Bayesian repeated measures linear models	TBI drivers spent more time looking at, and more glances to the tasks. Addition of cognitive component of distracting task decreased driving performance (coin sorting task)	

Contribution to the field

This research examines of how driver distraction affects driving for individuals with traumatic brain injuries at three levels of driving control and with regard to crash risks. Specifically, it examines the crash characteristics of TBI drivers compared to non-TBI drivers using crash data, assesses TBI drivers willingness to engage in distracting activities, how drivers adjust and regulate the engagement of the distracting tasks, and the effects on driving performance. This research bridges a gap between research in driver distraction and research in driving following a TBI.

Understanding the characteristics of crashes involving TBI drivers can lead to insights into some driving behaviors and environmental factors that are problematic for these drivers (including seatbelt usage and driving at night). Given that TBI drivers have are more likely to be involved in multiple crashes following their injury than the rest of the driving population, there is the potential for safety-based interventions to reduce the risks for these drivers. These interventions could involve driver training, rehabilitation and ultimately the decision to resume driving. Additionally, this research identified differences in engagement (as noted by the eye gaze analyses) and the effect of distractions on driving performance for TBI drivers. A TBI drivers' willingness to engage in distracting activities and the effect of distractions on their driving performance should also further investigated in future work.

Future research

One of the more interesting findings of this research is that TBI drivers are more likely to be in multiple crashes. Future work can extend upon this finding to further identify the group of TBI drivers that is involved in crashes, and specifically those who are involved in multiple crashes. This group of drivers may exhibit identifiable behavior or characteristics that would identify those individuals who may need additional driving rehabilitation or should consider their decision to resume driving. Preventing these crashes could represent a major safety benefit due to a reduction in crashes.

Future work should also identify the differences between the TBI drivers who exhibit higher risk taking behaviors (e.g., not wearing seatbelts, and a higher willingness to engage in distracting activities) in order to understand how these populations differ and if these topics should be included in driver rehabilitation and driving evaluation programs for TBI drivers.

Given the similarities between teenage drivers and TBI drivers in terms of their willingness to engage in distracting tasks and the high incidence of TBIs in teenage populations future studies could examine the subsequent crashes of teenage TBI survivors. Little is known about teenage drivers with TBIs. Quantifying the crash risk of this population can lead to increased traffic safety with more information for physician/patient communication regarding resuming driving, driver training, and driving evaluations for teenagers after experiencing a TBI.

This research presented in this dissertation focuses on the effect of driver distraction for TBI drivers. Future work should also examine the effect of more complex driver distractions (e.g., cognitive distractions and cell phones) for TBI drivers. More complex distractions with more cognitive components are expected to increase in the future as new in-vehicle and mobile technology is developed. Based on the results of this dissertation, distracting tasks that involve cognitive components are of great concern and could have a substantial effect on safety for TBI drivers.

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APPENDIX A.
DRIVER DISTRACTION SURVEY

TBI Driving Behavior Survey

The Human Factors and Statistical Modeling Lab is conducting a project to assess driving behaviors of individuals who have experienced a traumatic brain injury. Your answers to these questions will remain completely confidential.

1. How old are you? _______

2. Are you [ ] Male [ ] Female

3. Do you currently drive a car?
   [ ] Yes [ ] No

4. Please rate how often you do the following activities while actively driving (not while stopped).

Task	Never - - Sometimes - - Frequently						
Talk on a cellular phone	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Dial a cellular phone	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Text message	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Eat or drink	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Change CDs/tapes	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Tune the radio	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Change the heat or air conditioning	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Apply Makeup	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Shave	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Read (map, printed directions, book, etc.)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Look for an item in wallet/purse	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Use a device brought into the vehicle (iPod, laptop etc.)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Day dream	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Think about something difficult (complex problem, relationship, argument, etc.)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

5. How often has the following occurred because of the activities listed in Question 2 (e.g., talk on a cellular phone, read, think about something difficult)?

Event	Never - - Sometimes - - Frequently						
Forgotten to fasten seatbelt	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Missed an exit on the highway	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Nearly hit the car in front of you	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Forgotten where you were going	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Forgot how you got to your destination	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

6. In general, how often do you avoid the following driving situations?

Event	Never - - Sometimes - - Frequently						
At night	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In heavy traffic	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In snow or ice	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In rain	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
With passengers	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In busy intersections	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
On highways	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

7. How often do you avoid the activities in Question 2 (e.g., talk on a cellular phone, read, think about something difficult) when in these driving situations?

Event	Never - - Sometimes - - Frequently						
At night	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In heavy traffic	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In snow or icy conditions	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In rain or wet conditions	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
With passengers	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
In busy intersections	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
On highways	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

8. Do you pull over or change routes when you find yourself in an unexpectedly challenging driving situation?

[ ] Always [ ] Most of the time [ ] Sometimes [ ] Rarely [ ] Never

9. In a normal week, which days do you drive?

[ ] Sun. [ ] Mon. [ ] Tues. [ ] Wed. [ ] Thur. [ ] Fri. [ ] Sat.

10. About how many miles did you drive yesterday? ___________________ miles

11. About how many miles did you drive last week? ____________________miles

12. Who are your usual passengers?

[ ] Partner/Spouse [ ] Children [ ] Relatives [ ] Friends [ ] None usually

13. How do you rate your driving skills?

[ ] Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor

14. How do you think your driving skills compare to others on the road?

[ ] Excellent [ ] Good [ ] Average [ ] Fair [ ] Poor

15. When was your current drivers license issued? ___________

16. While driving, have you ever been involved in a car crash (accident?)
[ ] Yes [ ] No

17. Have you received a speeding ticket?
[ ] Yes [ ] No

18. Have you experienced a traumatic brain injury?
[ ] Yes [ ] No
If you answered No to Question 18, then please stop here, if yes please continue. Thank you.

19. When did you experience your injury? _____________________________

20. Has your driving strategy changed since your injury?
[ ] Yes [ ] No

21. Have you had a driving evaluation since your injury?
[ ] Yes [ ] No [ ] Not yet

22. While driving, have you been in a car crash (accident) since your injury?
[ ] Yes [ ] No

23. Have you received a speeding ticket since your injury?
[ ] Yes [ ] No

24. Do you think that your transportation needs will change in the future?
[ ] Yes [ ] No

25. Did your health care professionals discuss driving with you after your injury?
[ ] Yes [ ] No [ ] I don’t remember

Please rate if you agree or disagree with the following statements.

26. Additional driving training/evaluation would be helpful for me.
[ ] Strongly agree [ ] Agree [ ] Uncertain [ ] Disagree [ ] Strongly Disagree

27. My transportation needs are being met.
[ ] Strongly agree [ ] Agree [ ] Uncertain [ ] Disagree [ ] Strongly Disagree
Thank you.

APPENDIX B.
WinBUGS CODE AND SAMPLE OUTPUT

The Bayesian model formulation used for the analysis, and some of the sample WinBUGS output is provided.

Sample repeated-measures Bayesian linear model winBUGS code:

```
----
model
    {for( i in 1 : N ) {
            for( j in 1 : T ) {
                Y[i , j] ~ dnorm(mu[i , j], tau.c)
            mu[i , j] <-alpha[i] + task[i]*coin[j] + TBI[i]*bi[i]
            resid[i,j] <-Y[i,j]-mu[i,j]
            }
            alpha[i] ~ dnorm(alpha.c,tau.alpha)
            task[i] ~ dnorm(betatask.c,tau.betatask)
            TBI[i] ~ dnorm(betaTBI.c,tau.betaTBI)
            }
        tau.c ~ dgamma(0.1,0.1)
        sigma <- 1 / sqrt(tau.c)
        alpha.c ~ dnorm(0.0,1.0E-6)

        # Prior 1: uniform on SD
        sigma.alpha~ dunif(0,100)
        sigma.betatask~ dunif(0,100)
        sigma.betaTBI~ dunif(0,100)

        tau.alpha<-1/(sigma.alpha*sigma.alpha)
        tau.betatask<-1/(sigma.betatask*sigma.betatask)
        tau.betaTBI<-1/(sigma.betaTBI*sigma.betaTBI)

        #uninformative prior distribution
        #betatask.c ~ dnorm(0.0,1.0E-6)

        #informative prior distribution .
        betatask.c ~ dnorm(255.95, 6.66E-5)

        betaTBI.c ~ dnorm(0.0,1.0E-6)
        p.betaTBI<-step(-1*betaTBI.c)
        p.betatask<-step(-1*betatask.c)
            }

#Data
```

```
list(N=34, T=2, coin=c(1,0), bi=c(1,1, .,0,0))

#Data for 1000*SDSpeed during Coin Y[,1], and Baseline Y[,2]
Y[,1]   Y[,2]
2182.32         2793.62
 .
1272.91         393.43
1343.88         818.13
END

----
```

Sample model output: History plots (Figures B1 and B2) illustrate the values used in the iterations of the MCMC to estimate the posterior distributions of the model parameters.

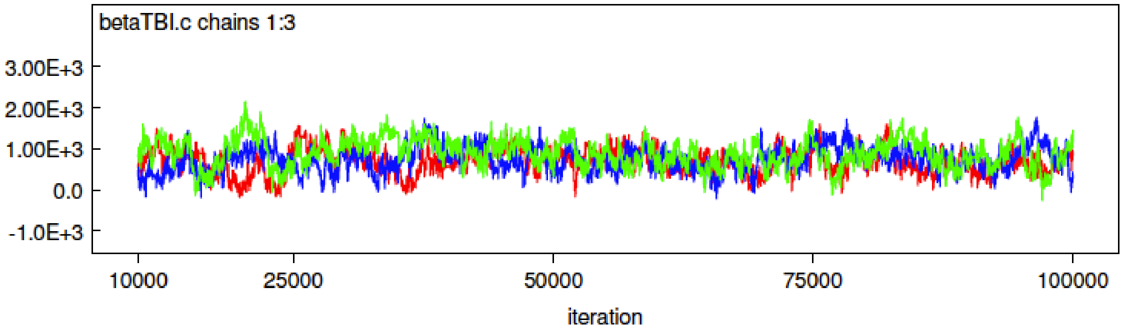

Figure B1. History plot for the group classification parameter for the three MCMC chains used to estimate the posterior distribution of this parameter.

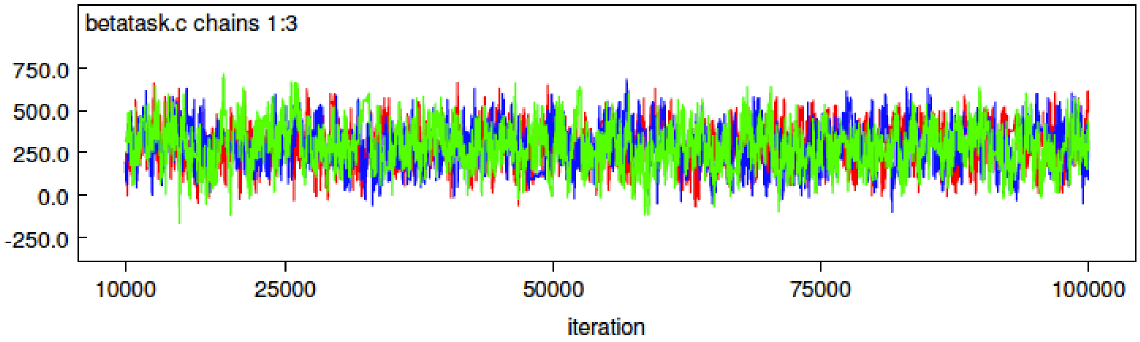

Figure B2. History plot for the task parameter for the three MCMC chains used to estimate the posterior distribution of this parameter.
The density plots are a summary of the MCMC history plots into a distribution as shown in Figure B3.

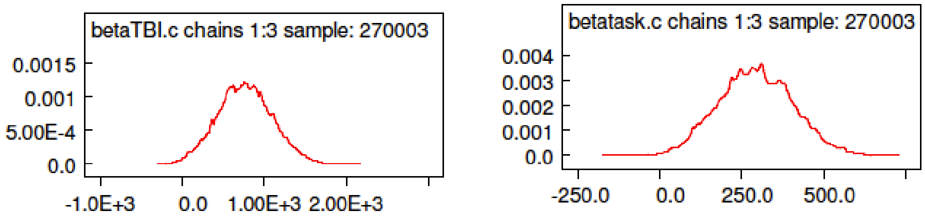

Figure B3. The density plots of the task and the TBI group parameters shown in the above history plots.

APPENDIX C.
MODEL COMPARISONS

The following figures and tables provide the models and the model comparisons between the frequentist repeated measures linear model (using the lme function in R) and the repeated measures Bayesian models with either completely uninformative prior distributions or with the informative prior distributions on the task parameter (using WinBUGS). The figures demonstrate that with informative prior distributions, the 95% credible set for the task parameter is smaller than without prior information.

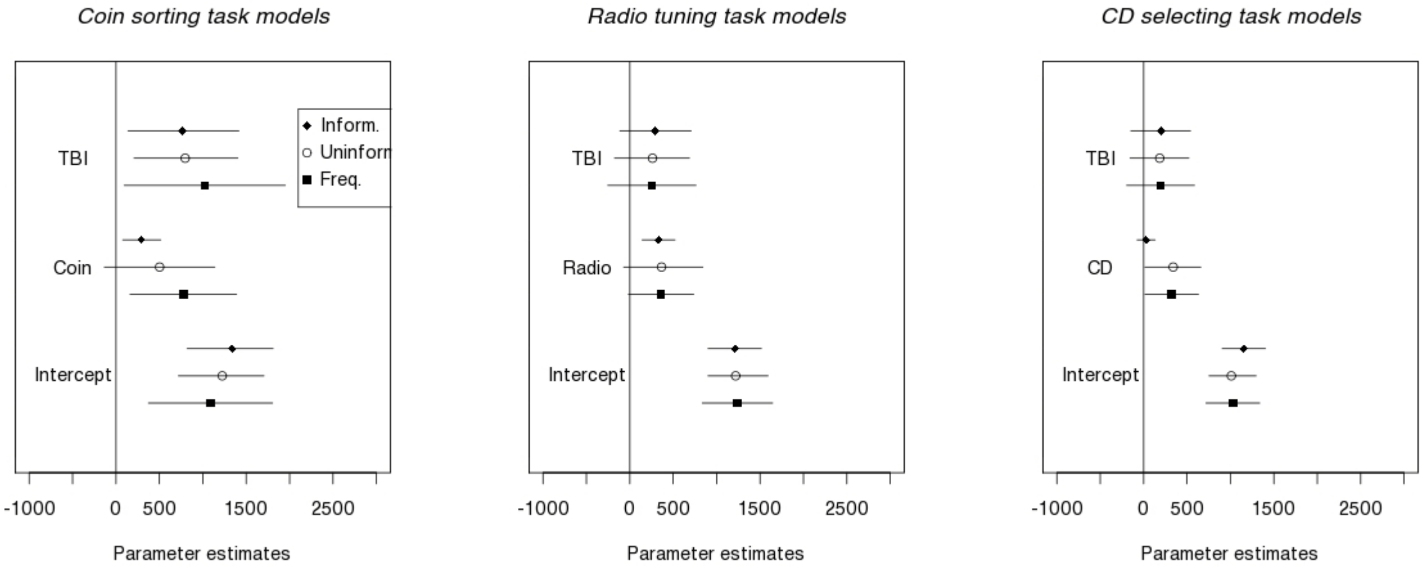

Figure C1. Comparisons of model parameters of models of the coin sorting task, radio tuning task, and CD selecting task for the dependent measure **mean speed** using frequentist models, the Bayesian models with uninformative prior distributions and the Bayesian models with informative prior distributions.

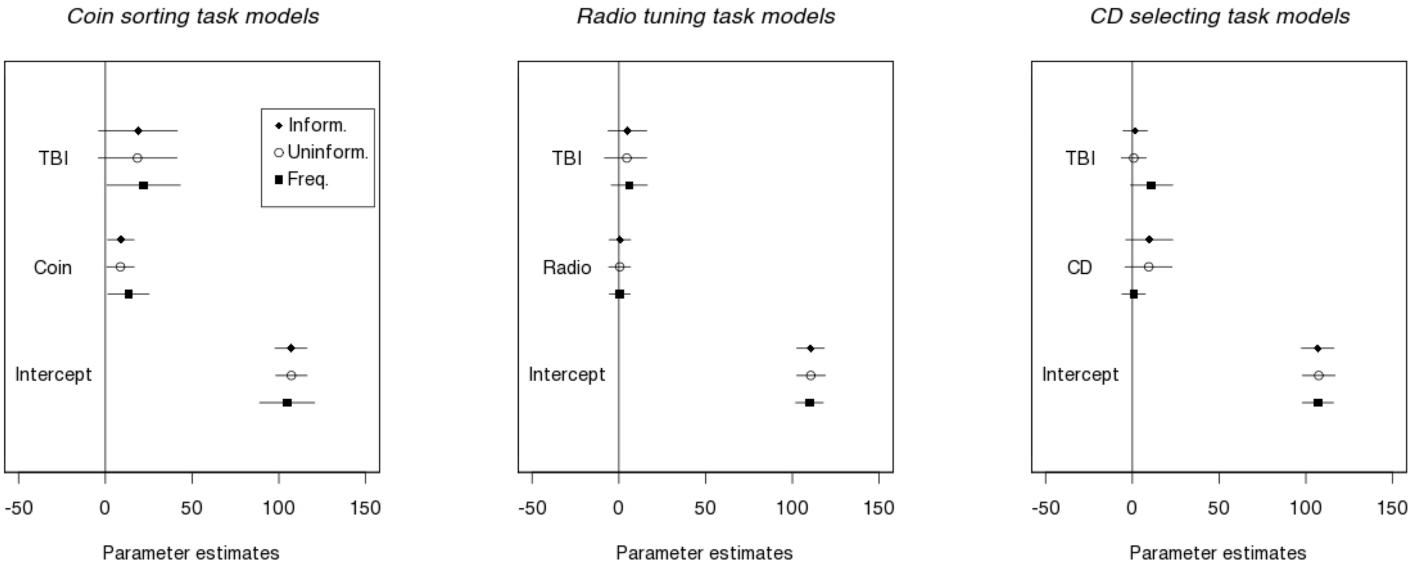

Figure C2. Comparisons of model parameters of models of the coin sorting task, radio tuning task, and CD selecting task for the dependent measure **maximum lateral acceleration** using frequentist models, the Bayesian models with uninformative prior distributions and the Bayesian models with informative prior distributions.

Table C1.The parameter estimates for the repeated measures *frequentist* model predicting driving performance measures while engaged in the coin sorting task

Parameter estimate	**Mean speed (MPH)** Mean (SD)	 95% CI	**SD speed (MPH)** Mean (SD)	 95% CI	**Maximum lateral acceleration (ft/s2)** Mean (SD)	 95% CI
Intercept	39.9 (0.6)*	(38.6, 41.1)	1088.5 (351.9)*	(373.3, 1803.7)	104.7 (7.8)*	(88.9, 120.6)
Task	-2.2 (0.6)*	(-3.4, -1.1)	775.3 (302.0)*	(161.5, 1389.1)	13.3 (5.8)*	(1.44, 25.3)
TBI	-0.3 (0.8)	(-1.9, 1.3)	1022.4 (456.1)*	(94.4, 1950.4)	22.0 (10.4)*	(0.9, 43.2)

Dependent Measure (spanning header over all measure columns)

Note: *significant at p<0.05

Table C2. The parameter estimates for the repeated measures *frequentist* model predicting driving performance measures while engaged in the radio tuning task

Parameter estimate	**Mean speed (MPH)** Mean (SD)	 95% CI	**SD speed (MPH)** Mean (SD)	 95% CI	**Maximum lateral acceleration (ft/s2)** Mean (SD)	 95% CI
Intercept	39.4 (0.7)*	(38.1, 40.8)	1239.7 (199.7)*	(834.2, 1645.2)	109.9 (3.9)*	(101.9, 117.8)
Task	-1.6 (0.5)*	(-2.7, -0.5)	359.9 (185.4)	(-16.6, 736.4)	0.57 (3.0)	(-5.5, 6.6)
TBI	0.6 (0.9)	(-1.2, 2.4)	254.4 (250.2)	(-254, 762.8)	6.0 (5.1)	(-4.4, 16.4)

Note: *significant at p<0.05

Table C3.The parameter estimates for the repeated measures *frequentist* model predicting driving performance measures while engaged in the CD selecting task

	Dependent Measure					
Parameter estimate	**Mean speed (MPH)**		**SD speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI
Intercept	39.5 (0.6)*	(38.5, 40.5)	1027.2 (152.6)*	(717.5, 1337)	106.9 (4.6)*	(97.9, 115.9)
Task	-1.4 (0.4)*	(-2.6, -0.2)	323.4 (152.1)*	(14.7, 632.2)	0.7 (3.4)	(-6.0, 7.5)
TBI	0.2 (0.8)	(-1.0, 1.4)	195.0 (192.5)	(-196.2, 586.2)	11.0 (6.2)	(-1.1, 23.3)

Note: *significant at p<0.05

Table C4.The parameter estimates for the repeated measures *Bayesian with uninformative priors* model predicting driving performance measures while engaged in the Coin sorting task

	Dependent Measure					
Parameter estimate	**Mean speed (MPH)**		**SD speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	39.5 (0.5)*	(38.5, 40.6)	1224.0 (254.7)*	(718.1, 1705.0)	107.2 (4.6)	(98.2, 116.3)
Task	-2.0 (0.6)*	(-3.2, -0.9)	502.5 (318.3)	(-134.5, 1139.0)	8.7 (4.0)	(0.9, 16.6)
TBI	0.4 (0.8)	(-1.3, 2.0)	796.9 (298.0)*	(207.4, 1404.0)	18.5 (11.4)	(-4.1, 41.3

Note: *significant at p<0.05

Table C5.The parameter estimates for the repeated measures *Bayesian with uninformative priors* model predicting driving performance measures while engaged in the Radio tuning task

	Dependent Measure					
Parameter estimate	**Mean speed (MPH)**		**SD speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	39.0 (0.6)*	(39.1, 40.3)	1219.0 (187.6)*	(900.1, 1593.0)	110.6 (4.2)*	(102.5, 119.0)
Task	-1.6 (0.6)*	(-2.7, -0.4)	365.8 (225.2)*	(-70.9, 841.7)	0.54 (3.2)	(-5.8, 6.7)
TBI	1.3 (0.9)	(-0.4, 3.0)	261.6 (219.3)	(-176.4, 687.1)	4.6 (6.1)	(-8.3, 16.0)

Note: *significant at p<0.05

Table C6.The parameter estimates for the repeated measures *Bayesian with uninformative priors* model predicting driving performance measures while engaged in the CD selecting task

	Dependent Measure					
Parameter estimate	**Mean speed (MPH)**		**SD speed (MPH)**		**Maximum lateral acceleration (ft/s2)**	
	Mean (SD)	95% CS	Mean (SD)	95% CS	Mean (SD)	95% CS
Intercept	39.4 (0.6)*	(37.9, 40.3)	1010.0 (138.4)*	(752.8, 1296.0)	107.4 (4.8)*	(98.0, 116.8)
Task	-1.4 (0.6)*	(-2.3, -0.6)	340.4 (164.7)*	(13.7, 659.3)	9.45 (6.9)	(-4.3, 22.9)
TBI	0.3 (0.9)	(-1.3, 1.8)	185.2 (171.6)	(-156.5, 521.3)	0.82 (3.6)	(-6.4, 8.0)

Note: *significant at p<0.05