9-2023

# Detecting Early-Stage Dementia Using Naturalistic Driving

Brian M. Wotring M.S.
*Virginia Tech Transportation Institute*

Jonathan F. Antin Ph.D.,CHFP
*Virginia Tech Transportation Institute*

## Recommended Citation

Wotring, Brian M. M.S. and Antin, Jonathan F. Ph.D.,CHFP, "Detecting Early-Stage Dementia Using Naturalistic Driving" (2023). *Center for Advanced Transportation Mobility*. 19.
https://digital.library.ncat.edu/catm/19

# DETECTING EARLY-STAGE DEMENTIA USING NATURALISTIC DRIVING

FINAL REPORT

SEPTEMBER 2023

Brian M. Wotring, M.S. and Jonathan F. Antin, Ph.D., CHFP
Virginia Tech Transportation Institute
Blacksburg, VA 24060

US DEPARTMENT OF TRANSPORTATION GRANT 69A3551747125

# DISCLAIMER

|  |  |  |
|---|---|---|
| 1. Report No. | 2. Government Accession No. | 3. Recipient’s Catalog No. |

|  |  |
|---|---|
| Title and Subtitle<br>Detecting Early-Stage Dementia Using Naturalistic Driving | Report Date<br>September 2023 |
|  | 4. Source Organization Code |
| Author(s)<br>Wotring, Brian M. Antin, Jonathan F. | Source Organization Report No.<br>CATM-2023-R5-VTTI |
| Performing Organization Name and Address<br>Center for Advanced Transportation Mobility<br>Transportation Institute<br>1601 E. Market Street<br>Greensboro, NC 27411 | Work Unit No. (TRAIS) |
|  | 5. Contract or Grant No.<br>69A3551747125 |
| Sponsoring Agency Name and Address<br>University Transportation Centers Program (RDT-30)<br>Office of the Secretary of Transportation–Research<br>U.S. Department of Transportation<br>1200 New Jersey Avenue, SE<br>Washington, DC 20590-0001 | Type of Report and Period Covered<br>Final Report:<br>July 2020 – September 2023 |
|  | 6. Sponsoring Agency Code<br>USDOT/OST-R/CATM |

7. Supplementary Notes:
This work was supported by funding provided by the Center for Advanced Transportation Mobility (CATM), a Tier 1 UTC consortium led by North Carolina A&T State University. Cost share funding was provided by the National Surface Transportation Safety Center for Excellence.

8. Abstract

Age-related cognitive decline may present unique challenges for aging drivers. The goal of this effort is to explore the use of naturalistic driving data to identify those with pre-diagnosis cognitive decline (i.e., pre-mild cognitive impairment, pre-MCI). Researchers relied on naturalistic driving data collected in the New River Valley area of Virginia, San Antonio, Washington, D.C., and Northern Virginia. Metrics revealed differences in driving patterns and advanced driver assistance system (ADAS) use between the pre-MCI and cognitively normal groups. A second analysis was conducted incorporating data from the Second Strategic Highway Research Program (SHRP 2), affording comparisons between participants driving vehicles equipped with ADAS and those without. Results trended towards those with pre-MCI demonstrating modest differences compared to cognitively normal individuals in terms of mobility related metrics, especially when driving vehicles equipped with L2 technology (regardless of the fact that these technologies were not frequently deployed). In addition, driving safety performance metrics may one day be able to serve as the “canary in the coal mine” for the detection of pre-MCI.

|  |  |
|---|---|
| 9. Key Words<br>Pre-MCI Diagnostic, Dementia, Older Adult Driver Safety, Naturalistic Driving Study | 10. Distribution Statement<br>Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT. |

|  |  |  |  |
|---|---|---|---|
| 11. Security Classif. (of this report)<br>Unclassified | 12. Security Classif. (of this page)<br>Unclassified | 13. No. of Pages<br>57 | 14. Price<br>… |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## EXECUTIVE SUMMARY

### Introduction

Today, there are 56 million individuals aged 65 and older in the United States, some 17% of the population. That number is expected to rise to 22% by 2050 (Vespa, Medina, and Armstrong, 2018). Given that driving remains the primary mode of transportation for older adult mobility (Payyanadan, Lee, & Grepo, 2018), and when coupled with a lack of additional options, especially in rural communities (Douthit et al., 2015; Mattson, 2017), older adults may face increased levels of isolation (Federal Highway Administration, 2017; Lam et al., 2018). Associated age-related decrements are also likely and may lead to driving and mobility concerns (Antin et al., 2020; Charlton et al., 2003; Evans, 1999; Oxley et al., 2006; Vrkljan and Polgar, 2007). Specifically, age-related cognitive decline may present a unique challenge. The goal of this effort is to explore the use of naturalistic driving data to identify those with cognitive decline that has not yet been diagnosed via standardized testing (pre-mild cognitive impairment or pre-MCI).

### Methods

To assess the utility of naturalistic driving data in identifying individuals with pre-MCI (the "cases"), the researchers relied on two datasets. The first represents people identified as having pre-MCI in the New River Valley area of Virginia. The second utilizes data from an on-going data collection effort in three sites across the United States (San Antonio, TX; Washington, D.C., and Northern Virginia). Participants in this data collection were delineated into either case or control groups based on answers to memory impairment questions during screening. For all participants, the Self-Administered Gerocognitive Exam (SAGE) was used as a cognitive assessment along with other memory-based and driving-avoidance-based metrics collected during intake (Scharre, 2007).

Using these sources of data, metrics were calculated to evaluate the differences in driving patterns and advanced driver assistance system (ADAS) use between the groups. ADAS included such features as adaptive cruise control (ACC) and lane centering (LC). Additionally, a second analysis was conducted incorporating data from the Strategic

Highway Research Program (SHRP 2 to make comparisons between participants driving vehicles equipped with ADAS and those without.

## Results

### Analysis 1

*ADAS Use*

Overall, results showed very low LC usage rates – of the seven participants with access to an LC system, only three ever used the system during the study period. This was true even though every participant drove within the operational design domain (ODD) for LC at least 20% of the time. ACC was used by 6 of the 14 participants whose vehicles were so equipped.

*System Alerts*

The forward collision warning (FCW) analysis revealed a strongly skewed distribution of events across participants. One participant was responsible for 13 of the 20 events. Lane departure warning (LDW) activations were much more common than FCW activations; however, no reliable difference was found between the groups. Additionally, an initial hypothesis was that drivers utilizing the LC system would experience fewer lane departure warning (LDW) activations than those not using the LC system. Results did not support this hypothesis; those that used the LC system had the lowest and second highest rates of LDW activation.

*Safety-Critical Events*

In none of the events was ACC or LC active at the time of, or shortly before, a safety-critical event (SCE). In 6 of 10 cases, had ACC been active, it may have played a beneficial role in helping to mitigate the situation. Such events were those in which a lead vehicle slowed or stopped in the lane ahead – had ACC been active, it may have started slowing prior to the point at which the participant ultimately intervened.

### Analysis 2

This set of analyses was conducted to compare mobility and crash rate data between case and control groups driving vehicles equipped with Level 2 automation (L2) and those driving vehicles which were not so equipped. Two analyses revealed statistically reliable results:

average number of trips per day and average trip duration. The results showed the lowest average number of trips per day for those in the pre-MCI group who drive vehicles with L2 features (3.59 trips) compared to those without L2 features (4.66 trips). These results are inconsistent with other findings that there is no significant difference in driving exposure between those with MCI and those without (Feng et al., 2021) or that those with MCI may even engage in a greater number of trips (Staplin et al., 2019). However, in both of those prior efforts, none of the vehicles were L2. It is conceivable that those with pre-MCI may have enough meta-awareness to self-restrict driving, while those who have progressed to a diagnosis of MCI have lost such awareness to one degree or another, and, so, resume driving at prior levels. It is worth considering the low use of both ACC and LC  in the current effort may not be sufficient to boost the number of trips undertaken (i.e., presuming that such technologies boost driver confidence).

When evaluating average trip duration, those in the pre-MCI group with L2 technologies available tended to drive for longer (13.34 minutes) than those in the pre-MCI group without L2 technologies (11.69 minutes). These results suggest the presence of L2 features may support engagement in longer trips. However, when taken with the overall low utilization of ACC and LC, these results may better be explained by other factors.

An analysis of SCE data produced results which were nearly statistically significant, showing that with more data collected in future research efforts, this metric could become statistically significant and important.

## Conclusion

The goal of this effort was to investigate driving differences between older drivers with and without pre-MCI. We found trends that those with pre-MCI demonstrated modest differences compared to cognitively normal individuals in terms of mobility related metrics, especially when driving vehicles equipped with L2 technology (regardless of the fact that these technologies were not frequently deployed). It is feasible that as these technologies become more widespread, those with and without pre-MCI may utilize them with greater frequency. In addition, this study showed that driving safety may one day be able to serve as the “canary in the coal mine” for the detection of pre-MCI.

# DESCRIPTION OF PROBLEM

## Introduction

### Aging Population

There are 56.1 million adults aged 65 and older in the U.S., making up approximately 17% of the population, and that proportion is expected to rise to 22% by 2050 (Vespa, Medina, and Armstrong, 2018). Driving remains the primary mode of transportation for older adults (Payyanadan, Lee, & Grepo, 2018). When coupled with a lack of additional options, especially for those older adults in rural communities (Douthit et al., 2015; Mattson, 2017), these individuals may face increased levels of isolation (Federal Highway Administration, 2017; Lam et al., 2018). As we age, functional capability tends to decrease, leading to driving safety and general mobility concerns (Antin et al., 2020; Charlton et al., 2003; Evans, 1999; Oxley et al., 2006; Vrkljan and Polgar, 2007). Specifically, age-related cognitive decline may present the greatest challenge to older adult mobility and independence.

### MCI

When faced with a patient who exhibits signs of cognitive decline, a clinician may first administer tests to rule out other psychiatric, neurological, or medical reasons for the complaints. Criteria for diagnosing MCI vary (Albert et al., 2011; American Psychiatric Association, 2013; Nelson and O'Conner, 2008; Petersen, 2004; Petersen et al., 1999; Portet et al., 2006; Winblad et al., 2004). However diagnostic criteria that tend to be common across sources include:

- Self-reported cognitive or memory concerns (sometimes corroborated by a stakeholder)
- Objective decrements in one or more cognitive domains or memory performance
- Decrements observed do not match typical expectations for aging
- Minimal or no impacts on daily activities
- No presence of dementia

The prevalence of Mild Cognitive Impairment (MCI) is difficult to determine due to individual differences in presentation and identification of cases. It has been estimated that around nine percent of those aged 69-88 meet the criteria for dementia and around 21 percent of those 69 and older suffer from MCI (Knopman et al., 2016). A meta-analysis also showed that overall, prevalence tends to increase with age, especially in men (Sachdev et al., 2015).

### Pre-MCI

For those with cognitive complaints who do not meet the diagnostic criteria for MCI, a designation of pre-MCI may be more informative. Pre-MCI describes individuals who are fully functional but have subjective memory concerns or biological markers of impairment (Chipi et al., 2019; Duara et al., 2011; Hendrix, 2012). Others have described individuals with pre-MCI as experiencing greater limitations in the performance of daily tasks and producing worse scores than neuro-typical individuals on cognitive tests (Seo et al., 2016; Verghese, De Sanctis, & Ayers, 2022). On the other hand, Nunes et al. (2010) found that pre-MCI may be detectable by decreased hippocampal volume, even in the absence of significant changes in neuropsychological tests. Additionally, biomarkers for amyloid and tangled tau proteins are characteristic of the condition. Unfortunately, these markers have not yet proven reliable in assessing severity or measuring progression (Zhou, Benoit, and Sharoar, 2021). However, self-ratings of impairment, have been shown to be reasonable determinates of pre-MCI, primarily in the earlier stages (Jessen, 2014). At very early stages of impairment, patients may retain the insight needed to notice changes over time. However, as the disease progresses, a loss of insight can affect subjective ratings at which point objective cognitive testing may be necessary.

#### *Driving Behavior as a Marker for Pre-MCI*

Errant driving behaviors may also serve as an early warning sign for pre-MCI, the virtual ‘canary in the coal mine’ (Babulal, Johnson et al., 2021; Davis et al., 2020; Roe, Barco, et al., 2017). Using naturalistic driving data collected from neurotypical adults aged 65 and older, along with imaging for Amyloid, CSF measurements for tau, genetic testing for Apolipoprotein E (APOE), and psychological testing, Babulal, Johnson et al., (2021) were able to accurately predict driving performance. Results suggest that driving behaviors such as hard braking and acceleration, travel time, and speeding may function as an early indicator for pre-AD. Using the same data, Roe, Barco et al. (2017) showed that CSF biomarkers with amyloid and tau taken together proved to be correlated with driving errors. An additional analysis showed that higher values of tau collected via CSF and phosphorylated tau both were predictive for time to marginally pass or fail an on-road driving test using Cox proportional hazards. Finally, the Amyloid/Tau/Neurodegeneration (A/T/N) classification system has been used to describe the various combinations of relevant biomarkers (Delmotte et al., 2021). Using this system, abnormal levels of amyloid and tau were predictive of time-to-fail (or marginally passing) during on-road testing (Roe, Babulal, 2018). However, neither self-reported driving patterns nor time to receive a failing during on-road driving evaluations revealed a difference between the neurotypical and suspected AD groups.

Amyloid levels detected via imaging have also been shown to be related to traffic violations and crashes (Ott et al., 2017). Using driving questionnaires in conjunction with such imaging, the authors showed that those with both pre-MCI and dementia had a higher rate of crashes than the neurotypical group (9.5 and 9.2 crashes per 1000 miles compared with 2.5). Additionally, results showed a non-linear relationship between the standardized uptake value ratio (SUVR – a method of determining brain activity in imaging) and the proportion of participants with any traffic violation or crash. As the SUVR increased, so did the proportion of participants with violations or crashes, until a peak where it decreased again as SUVR continued to increase. However, this pattern was not a differentiator between groups, as it was evident for both neurotypical adults as well as adults with MCI and dementia.

Clinical dementia rating (CDR) scores have shown predictive power in determining time to failure of an on-road driving test both over a two-year term (Duchek et al., 2003) and a 24-year term (Stout et al., 2018). While both studies produced similar results, Stout and colleagues also found that higher levels of CDR and biomarkers predicted driving cessation. Predictions were valid, even for drivers in the preclinical stage of the disease; that is, levels not typically associated with symptomatic disease still predicted a faster rate of driving cessation.

### Self-Regulation

Naturalistic driving studies have shown an increase in self-regulation in older adults with pre-clinical or AD (Davis et al., 2020; Roe, Stout et al., 2019). When drivers with and without cerebral amyloidosis were compared against symptomatic AD patients, results showed higher rates of hard braking, hard accelerating, and instances of speeding for both control groups (i.e., those with or without amyloid plaques, but not symptomatic early AD) and those with early AD. Those who tested positive for cerebral amyloidosis (but no diagnoses of AD) showed lower rates of events than either those with early AD or those without amyloidosis. This suggests self-regulating behavior may be occurring prior to developing symptomatic illness (Davis et al., 2020). In a naturalistic study, cognitively normal drivers with pre-clinical AD, as evidenced by the presence of brain amyloid, also showed elements of self-regulatory behavior. Participants drove to fewer places or unique locations, traveled fewer days, and took fewer trips than those without pre-clinical AD. Additionally, drivers with pre-clinical AD noted more reliance on others for transportation as well as showing a greater reduction in the number of days traveled per month (Roe, Stout et al., 2019). CSF amyloid has also been associated with self-reported navigation difficulties in neurotypical older adults. Those with self-reported poorer navigation abilities likewise were also more likely to have reported reduced driving, potentially self-restricting exposure (Allison et al., 2018).

## Advanced Driver-Assistance Systems

Vehicles equipped with advanced driver assistance systems (ADAS) or automated driving features may afford additional driving safety benefits for the older driver (Classen et al., 2019; Liang, Antin, Lau & Stulce, 2021). Extrapolating, these may also support independent mobility for those with pre-MCI. The Society of Automotive Engineers (SAE) J3016 describes the taxonomy of automated driving from Level 0 (no automation) to Level 5 (full automation; SAE, 2021). A vehicle with level 2 automation features both lateral (e.g., lane centering, LC) and longitudinal (e.g., adaptive cruise control, ACC) automated driving elements operating simultaneously; however, under Level 2, the driver/operator is still required to maintain supervision over the vehicle at all times.

How drivers interact with these systems has been explored with neuro-typical older adults. Results have shown that older adults prefer systems that inform the driver (such as blind spot warnings [BSW]) as opposed to those that intervene and take control (such as lane keep assist [LKA]). However, of note is that older adults expressed increased confidence and openness to using such systems over a six-week period suggesting exposure is a key factor of acceptance (Liang et al., 2018). Other factors deemed important for older driver acceptance include demonstration and video-based training (Zahabi et al., 2021). Older drivers have reported difficulties interacting with ADAS, even in the absence of trust or acceptance disparities with younger drivers (Neuhuber, et al., 2020).

However, the interaction between older adults with pre-MCI and vehicles equipped with Level 2 features has not been explored.

## APPROACH AND METHODOLOGY

### Analysis 1

### Objective

The objective of this research effort is to compare the driving behaviors of those with pre-MCI to those without, both with and without the benefits of ADAS. In addition to the use of driving behaviors and safety outcomes as tools for early dementia detection, we were also interested in examining whether the presence of pre-MCI has a meaningfully detrimental effect on driving safety for these individuals and all those with whom they share a vehicle or the road.

To this end, two analyses were conducted. Analysis 1 evaluated newly collected data; Analysis 2 evaluated previously collected data.

### Method

Data for this analysis were gleaned from two naturalistic driving studies (NDS):

1. Pre-MCI – These data were collected from participants dwelling in the New River Valley area of Virginia from September 2021 to November 2021.
2. VTTI L2 NDS – These data were collected from participants dwelling in San Antonio, TX and in the Washington, D.C. and Northern Virginia areas from January 2020 to April 2023.

### *Participants*

Subjective complaints of memory or cognition problems were used to determine pre-MCI status. Potential participants were screened prior to enrollment based on answers to the following questions:

1. Do you find yourself forgetting appointments, meetings, or important events?
2. Do you often lose items and cannot find them?
3. Do you suffer from increased irritability, anxiety, or depression?
4. Have you gotten lost, turned around, or confused while driving in familiar areas?
5. Do you find it difficult to use a GPS or similar type of device?

Those that answered *yes* to one or more questions were placed into the pre-MCI group (n=7) while those who did not answer *yes* to any of these questions were placed into the control group (n=8). Below presents participant source and breakdown of those into experimental and control groups while Table 1 shows participant demographics and vehicle details.

Table 1. Participant Selection Source and Group Allocation

| **Participant Source** | **Cases** | **Controls** | **Total** |
|---|---:|---:|---:|
| New River Valley, VA | 6 | 0 | 6 |
| San-Antonio, TX; Washington, D.C. | 1 | 8 | 9 |
| **Total** | **7** | **8** | **15** |

### *Apparatus*

The current effort consisted of two primary data collection modalities, the VTTI Data Acquisition System (DAS) and the Self-Administered Gerocognitive Exam (SAGE – Scharre, 2007). This research was approved by the Virginia Tech Institutional Review Board (IRB 20-699 and IRB 20-887).

A VTTI DAS unit was installed in the participants’ primary vehicle to collect driving data from sensors (e.g., GPS, accelerometer, rate-gyro), vehicle network (e.g., speed, L2 status), and video camera views (e.g., face, forward, and instrument panel - Figure 1). All sensors collected data at their native frequency and aligned based on a universal time stamp in VTTI’s proprietary data analysis software (Figure 2). All data were continuously collected from key-on to key-off and were written to an encrypted local drive in the DAS. Vehicle data were collected for approximately one month per participant; however, the amount varied due to data gaps for some participants. In such cases, an estimated “month” of trips was analyzed.

Figure 1. VTTI DAS camera views: face, instrument panel, and forward.

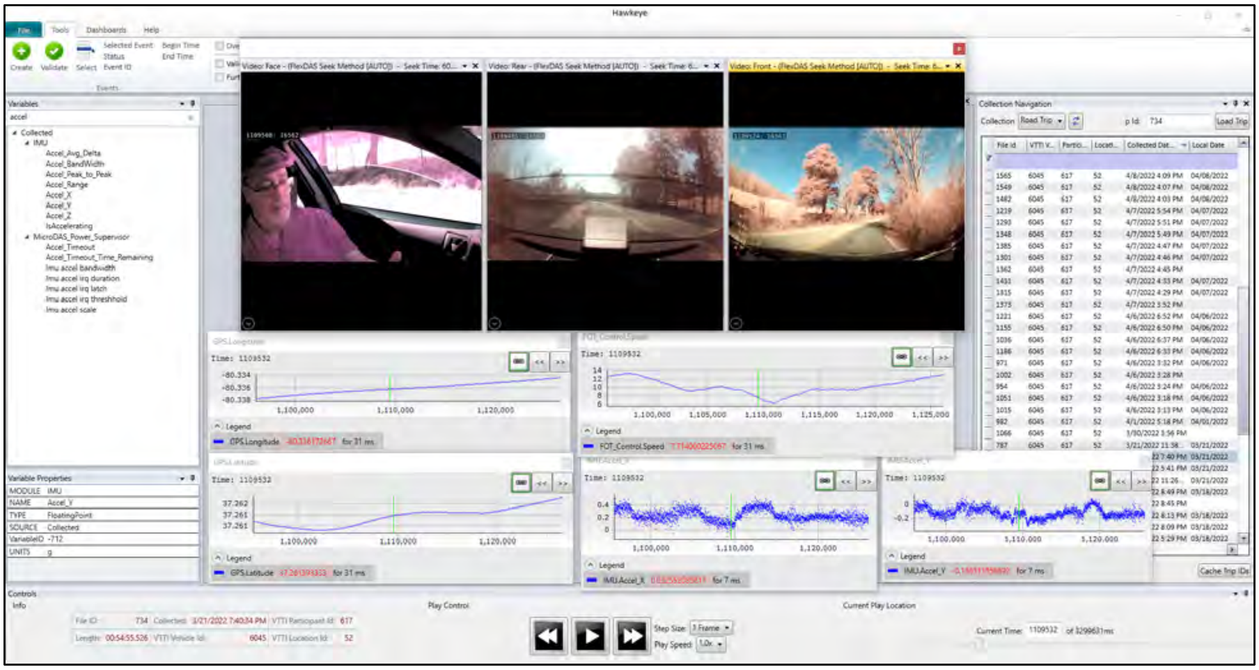

Figure 2. Proprietary VTTI analysis software allows researchers to step through time-aligned video and data for analyses.

The VTTI DAS is designed to be as unobtrusive as feasible, given its robust set of capabilities. The main unit of the system was mounted under the driver footwell or in the trunk area of the vehicle. in an orientation so as to not impede driving. Participants were not required to interact with this portion of the system but were, in some instances, required to swap hard drives. In such instances, a cable was routed to relocate the USB plug to the glove box for ease of access.

### *Data*

ADAS Data obtained from the vehicle network such as ACC status, LC status, and LDW status were compared with vehicle kinematic data (e.g., lateral and longitudinal g-forces) and video (e.g., face and forward views). Vehicle network data could not be collected from one vehicle in the case group.

## Safety-Critical Events

The number of, and validity of, safety-critical events was determined by searching for longitudinal high g-force events. As noted above, each DAS installation differed to some degree, so acceleration values were not normalized across vehicles in the pre-MCI dataset. Thus, to search for relevant events, researchers sought a vehicle/driver specific criterion where there were fewer than 20 potential events to review. To do so, researchers deployed a titration-like process using 0.05 increments until the desired number of unique potential events remained.

Unlike the pre-MCI data described above, the VTTI L2 NDS accelerometer data were normalized. Therefore, threshold values of > 0.5g and < -0.65g along the longitudinal axis were used and values > 0.75g and < -0.75g were used for the lateral axis as per Perez et al. (2017). Potential events were then submitted to a video review process to determine whether it was a valid crash-relevant conflict (e.g., a near-crash or crash). Definitions utilized for these categorizations are as follows:

1. **Crash-relevant conflict:** Any circumstance that requires an evasive maneuver on the part of the subject vehicle or any other vehicle, pedestrian, cyclist, or animal that is less urgent than a rapid evasive maneuver (as defined below in Near Crash), but greater in urgency than a "normal maneuver" to avoid a crash. A crash avoidance response can include braking, steering, accelerating, or any combination of control inputs. Crash Relevant Conflicts must meet the following four criteria:
    - **a.** Not a Crash. The vehicle must not contact any object, moving or fixed, and the maneuver must not result in a road departure.
    - **b.** Not pre-meditated. The maneuver performed by the subject must not be pre-meditated. This criterion does not rule out Crash Relevant Conflicts caused by unexpected events experienced during a pre-meditated maneuver (e.g., a premeditated aggressive lane change resulting in a conflict with an unseen vehicle in the adjacent lane that requires a non-rapid evasive maneuver by one of the vehicles).
    - **c.** Evasion required. An evasive maneuver to avoid a crash was required by either the subject or another vehicle, pedestrian, animal, etc. An evasive maneuver is defined as steering, braking, accelerating, or combination of control inputs that is performed to avoid a potential crash.
    - **d.** Rapidity NOT required. The evasive maneuver must not be required to be rapid. Rapidity refers to the swiftness of the response required given the

amount of time from the beginning of the subject ’s reaction to the potential time of impact.

2. **Near-crash:** Any circumstance that requires a rapid evasive maneuver by the subject vehicle or any other vehicle, pedestrian, cyclist, or animal to avoid a crash. Near Crashes must meet the following four criteria:
   - **a.** Not a Crash. The vehicle must not contact any object, moving or fixed, and the maneuver must not result in a road departure.
   - **b.** Not pre-meditated. The maneuver performed by the subject must not be premeditated. This criterion does not rule out Near Crashes caused by unexpected events experienced during a pre-meditated maneuver (e.g., a premeditated aggressive lane change resulting in a conflict with an unseen vehicle in the adjacent lane that requires a rapid evasive maneuver by one of the vehicles).
   - **c.** Evasion required. An evasive maneuver to avoid a crash was required by either the subject or another vehicle, pedestrian, animal, etc. An evasive maneuver is defined as steering, braking, accelerating, or combination of control inputs that is performed to avoid a potential crash.
   - **d.** Rapidity required. The required evasive maneuver must also require rapidity. Rapidity refers to the swiftness of the response required given the amount of time from the beginning of the subject ’s reaction and the potential time of impact.
3. **Crash:** Any contact that the subject vehicle has with an object, either moving or fixed, at any speed. Also includes non-premeditated departures of the roadway where at least one tire leaves the paved or intended travel surface of the road.

## Safety Alerts

Two analyses evaluated the presence of vehicle-based safety alerts: LDW and FCW. In both cases, after events were identified, a member of the research team validated those events. LDW validation removed instances of:

- Purposeful lane changes
- Lane position change due to roadside threats or large passing vehicles

- No lane line visible, such as a newly paved roadway
- Temporary lane marking (e.g., construction zones)

FCW validation removed instances of:

- Parking in home garage
- Events less than five mph
- Off-road events

### Questionnaires

Additional data selected for analyses come from a questionnaire administered during the intake session and covers various topics such as demographic information, memory, and driving avoidance behaviors (Appendix A).

### SAGE

The Self-Administered Gerocognitive Exam (SAGE) assessment is self-paced and requires no specialized knowledge or experimenter intervention to complete. It is typically completed within five to ten minutes. Additionally, a scoring rubric is available to ensure consistent scoring. Validation studies have shown SAGE to be an accurate metric (Meara et al., 2018; Scharre, Chang, et al., 2010; Scharre, Nagaraja, et al., 2021).

SAGE scores range from 0 to 22 points with additional points assigned to those over the age of 80 or those with fewer than 12 years of education).

## *Procedures*

### In-Person Interaction

As noted above, the SAGE was used to categorize participants into case or control groups. In addition, SAGE scores were also used to determine study eligibility. Scores ≤ 11 (suggestive of dementia, Scharre, Chang, et al., 2010) served as the eligibility cutoff. No participant was eliminated based on this criterion. The SAGE instrument, its scoring rubric, and a contact letter in case of a low score are presented in Appendices A, B, and C, respectively.

During the first in-person visit, the research team obtained informed consent. Following the consent session, an intake questionnaire was administered, and the DAS was installed in the participant’s vehicle. Participants completed electronic assessments. Assessments collected data including self-identified memory concerns, health conditions, and driving preferences (Appendix A). As the installation process could take up to four hours, participants were offered a ride by study personnel, or they were offered compensation for rideshare transportation. Once the DAS installation was completed, the participant was given an overview of the DAS kit installed in his/her vehicle.

#### Remote Interaction

Several participants were already engaged in another data collection effort for VTTI. For these participants, a phone call was used to gauge their interest in also participating in the current effort. Following a verbal indication of interest, the research team contacted the participant for a verbal consent session via phone or Zoom. Following consent, participants completed the intake questionnaire. As the larger data collection effort had been underway for much longer than the current study, the month of driving data immediately following the return of the SAGE was utilized in the current analyses. In cases where participants' vehicles were already deinstalled from the larger effort, the last month of data collected was used.

## Analysis 2

### Objective

Analysis 2 leverages previously-collected SHRP 2 data to afford comparisons not only between those in the case and control group, but between vehicles equipped with L2 and those not so equipped.

### Method

Additional data for Experiment were extracted from the SHRP 2 NDS dataset, a large-scale NDS which collected data from six sites across the U.S. from 2010 - 2013.

#### *Participants*

Overall, 3,247 individuals aged 16-98 participated in the SHRP 2 NDS. Only those 70+ were included in the current analysis. The resulting sample is presented in Table 2 below. Participants from all sites (Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington) were included. No vehicles were equipped with ACC or LC.

Table 2. SHRP 2 Participant Demographics by Group Allocation

| Group | Age Group | Gender |  |  |
|---|---|---|---|---|
|  |  | Female | Male | Total |
| Control | 70-74 | 9 | 18 | 27 |
| Control | 75-79 | 16 | 30 | 46 |
| Control | 80-84 | 11 | 14 | 25 |
| Control | 85-89 | 2 | 11 | 13 |
| Control | 90-94 | 0 | 1 | 1 |
| Control | 95-99 | 1 | 0 | 1 |
|  | **Total** | **39** | **74** | **113** |
| Case | 70-74 | 46 | 57 | 103 |
| Case | 75-79 | 64 | 86 | 150 |
| Case | 80-84 | 51 | 36 | 87 |
| Case | 85-89 | 17 | 18 | 35 |
| Case | 90-94 | 2 | 1 | 3 |
|  | **Total** | **180** | **198** | **378** |

### *Apparatus*

A VTTI DAS was utilized to collect driving data from participants' primary vehicle. The DAS incorporated g-force, GPS, and alcohol sensors as well as video and forward radar. The resulting continuous data stream includes over 32 million miles, 900,000 hours of in-vehicle time, and 5.5 million trips (Antin et al., 2019). An example video view is presented in Figure 3. Further details about data collection methods and sampling procedures are available from Antin et al. (2019) and Blatt et al. (2014).

Figure 3. SHRP 2 video views (note face shown is that of an experimenter, not a participant).

### Data

In addition to the naturalistic data collected via the DAS above, this effort used clock drawing scores to determine the allocation of SHRP 2 participants into case or control groups. The clock drawing scoring system produces a range of one to five as shown in

Table *3* (Dingus et al., 2014). For this effort, scores of two were considered pre-MCI cases while a score of one denoted a control. Scores ≥ 3 were deemed to possibly represent MCI or dementia-level impairment, and so these individuals were not included in the current analysis.

Table 3. Clock Drawing Score Descriptions and Group Placement

| Score | Description | Group Assignment |
|---|---|---|
| 1 | Ostensibly Perfect | Control |
| 2 | Minor visuospatial errors | Case (Pre-MCI) |
| 3a | Inaccurate time, good visuospatial | Possible MCI |
| 3b | Inaccurate time, minor visuospatial errors | Possible MCI |
| 4 | Moderate visuospatial errors | Possible MCI |
| 5 | Severe visuospatial errors | Possible Dementia |
| 6 | No reasonable representation of a clock | Possible Dementia |

Therefore, the experimental design of Analysis 2 is as follows in Table *4*:

Table 4. Experimental Design

|  |  | Pre-MCI |  |
|---|---|---|---|
|  |  | Yes | No |
| ADAS Access | Yes<br>Current Collection | n=7 | n=8 |
|  | No<br>(SHRP 2) | n=378 | n=113 |

# FINDINGS, CONCLUSIONS, RECOMMENDATIONS

## Analysis I Results

### *Intake Assessment*

#### Assessment Independence

An analysis showing the relationship between the participants' score on the SAGE and their allocation to the case or control group (based on answers to screening questions) is presented below. A logistic regression was used to calculate the likelihood that SAGE score, the proportion of affirmative answers to memory questions, and the proportion of driving scenario avoidance ("often" or more frequently selected) could predict allocation into the control or case group (Table *5*).

Table 5. Logistic Regression Results for SAGE Score, Memory Answers, and Driving Avoidance

| **Variable** | **Coefficient** | **SE** | **P-value** | **Odds Ratio** | **95% Confidence Interval** | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| SAGE Score | 0.13 | 0.31 | 0.67 | 1.14 | 0.62 | 2.08 |
| Memory Answers | 2.86 | 2.74 | 0.30 | 17.51 | 0.08 | 1000 |
| Avoidance | -6.61 | 5.21 | 0.21 | 0.01 | 0.01 | 37.07 |

These results suggest that none of the three scores could accurately predict group allocation. Means and standard deviations for each of the three factors are presented in Table *6*.

Table 6. Means and Standard Deviations by Group

| | **SAGE score Mean (SD)** | **Driving Scenario Avoidance Proportion Mean (SD)** | **Proportion Affirmative Answers to Memory Questions Mean (SD)** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Case (n=7)** | 20.86 (1.86) | 0.06 (0.06) | 0.40 (0.28) |
| **Control (n=8)** | 20.0 (2.98) | 0.13 (0.15) | 0.28 (0.21) |

We evaluated the relationship between SAGE scores and driving avoidance as well as affirmative answers to memory questions. A Pearson correlation was computed and showed no statistically significant correlation between the SAGE score and driving avoidance (correlation coefficient of 0.02 and p=0.93, Figure *4*) or memory answers (correlation coefficient of 0.31 and p=0.27, Figure *5*).

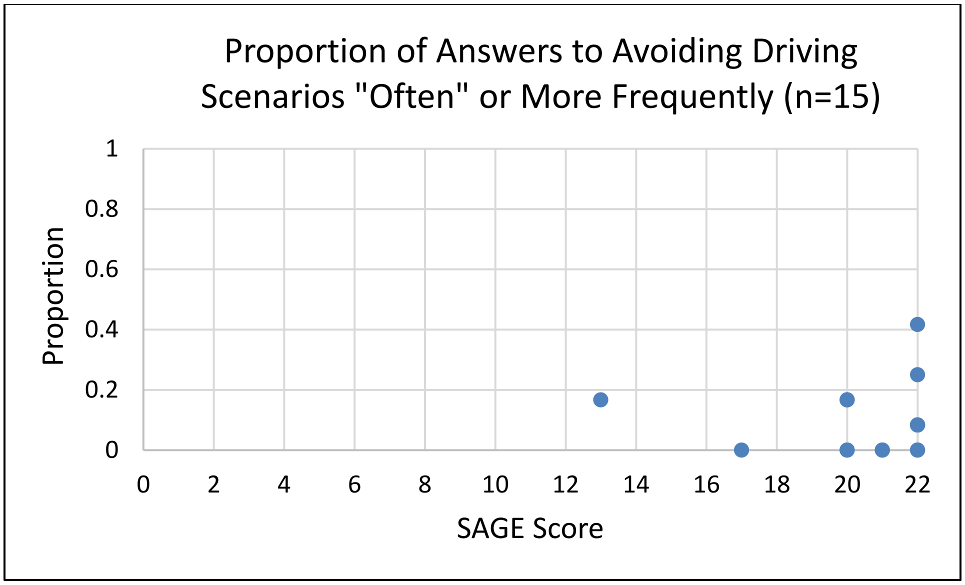

Figure 4. Driving avoidance by SAGE score.

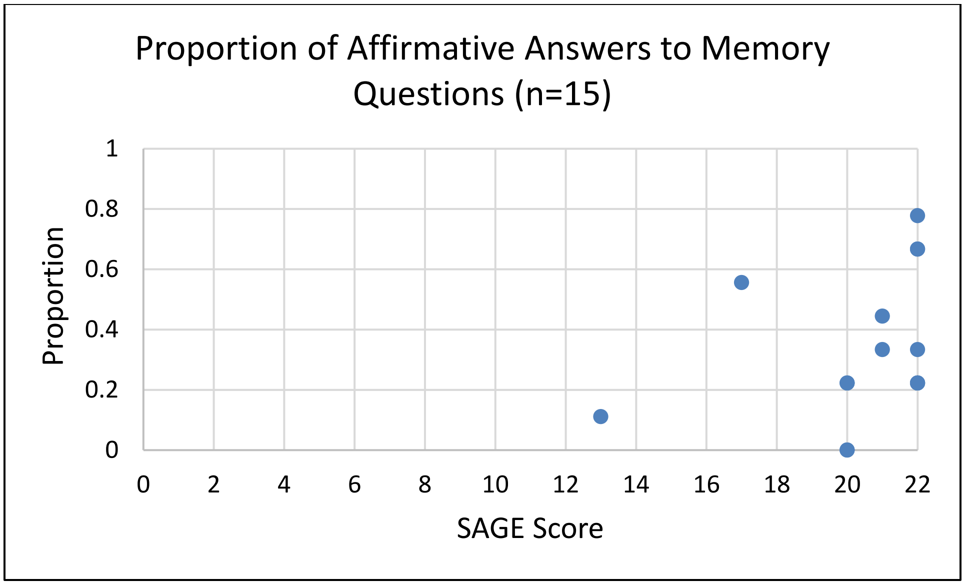

Figure 5. Affirmative answers to memory questions by SAGE score.

## *Naturalistic Data*

### Safety Critical Events

Results from the safety critical event (crash, near-crash, and crash-relevant conflict) analysis showed that very few drivers experienced such an event (Figure 6). In total, six participants contributed to the total of ten events, with four participants each responsible for two events (Table 4).

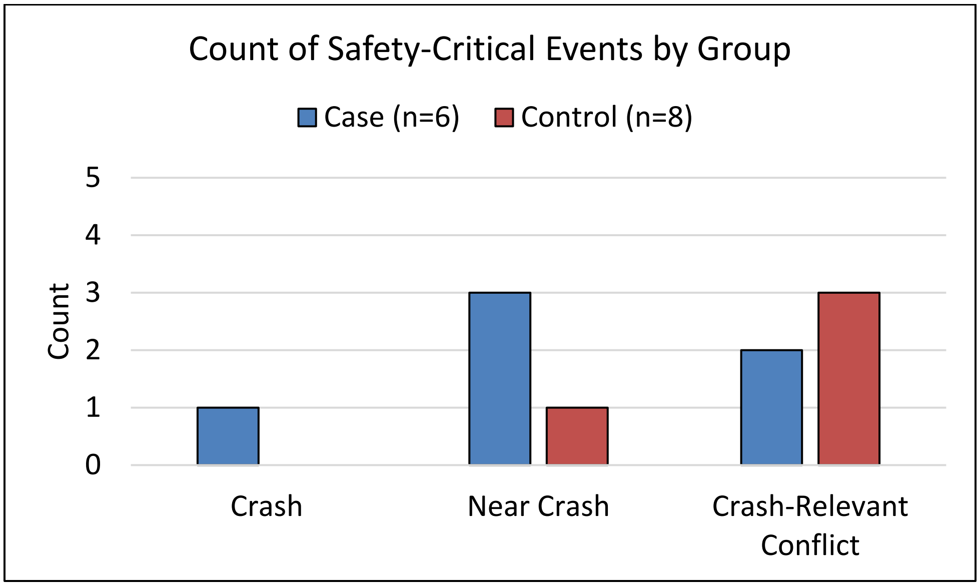

Figure 6. Count of crashes, near crashes, and crash-relevant conflicts by group.

Furthermore, Table *7* presents descriptions of each of the safety critical events along with the utilization of ACC or LC, and whether it was theoretically possible to use such systems (based on vehicle speed and roadway conditions). In no cases was ACC active immediately prior to or during any of the safety critical events.

Table 7. Description of safety-critical events and ADAS systems

| Driver | Group | Event Type | ACC or LC Possible | Scenario |
|---|---|---|---|---|
| **177** | Control | Near Crash | Yes Both | Lead vehicle slowed in lane ahead. |
| **319** | Control | Crash Relevant Conflict | Yes Both | Lead vehicle turning into parking lot. |
| **319** | Control | Crash Relevant Conflict | Yes Both | Driver slows suddenly due to unknown scenario [forward camera video not available]. |
| **992** | Control | Crash Relevant Conflict | Yes Both | Driver changes lanes to avoid vehicle on the side of roadway and encounters a slowing lead vehicle. |
| **572** | Case | Near Crash | Yes Both | Driver brakes to avoid squirrel in road. |
| **572** | Case | Crash Relevant Conflict | None | Lead vehicle slowed in lane ahead. |
| **573** | Case | Crash | None | Driver selects wrong gear and pulls forward into curb. |
| **573** | Case | Near Crash | Yes Both | Driver brakes to avoid squirrel in road. |
| **1147** | Case | Near Crash | Yes Both | Lead vehicle stopped in roadway, obscured by curve and vegetation. |
| **1147** | Case | Crash Relevant Conflict | None | Driver makes wide turn while turning onto another roadway and brakes before hitting another vehicle. |

## Mobility

### Quantity

A t-test conducted to compare the number of trips taken per driving day for the case vs. control groups revealed no significant difference (t=-1.06, p=0.308, Figure *7*).

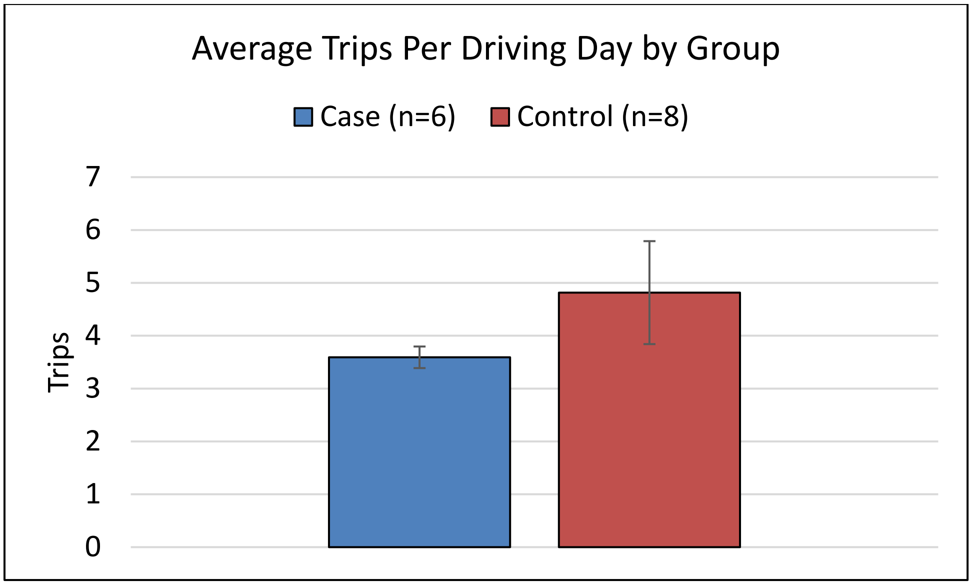

Figure 7. Average number of trips per driving day by group.

### Average Duration per Trip

T-tests revealed no significant differences for average daily duration (t=-0.29, p=0.775, Figure *8*) or average trip duration (t=0.23, p=0.823, Figure *9*).

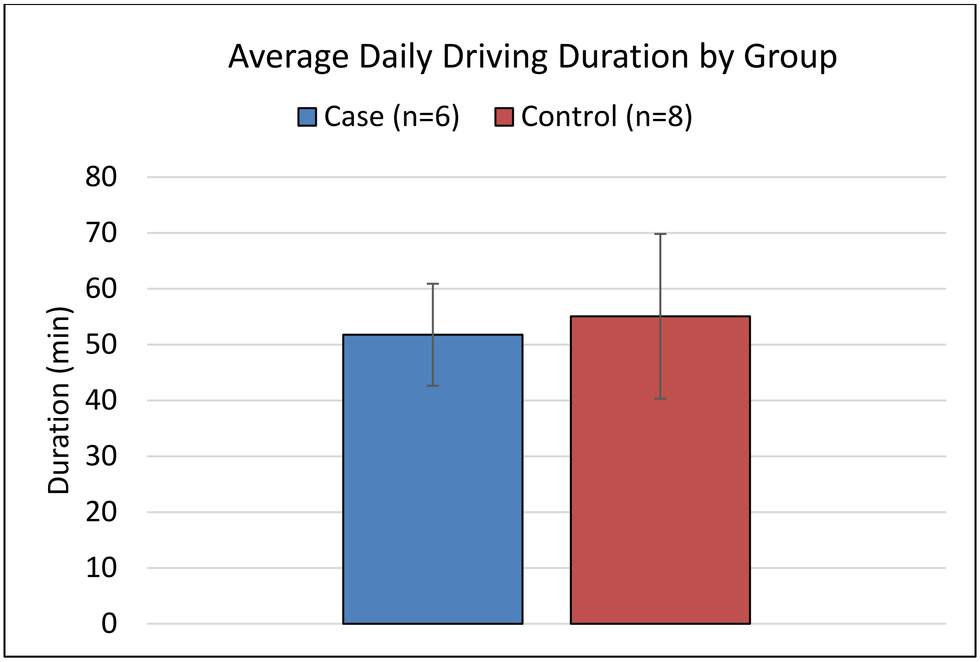

Figure 8. Average trip duration per driving day by group.

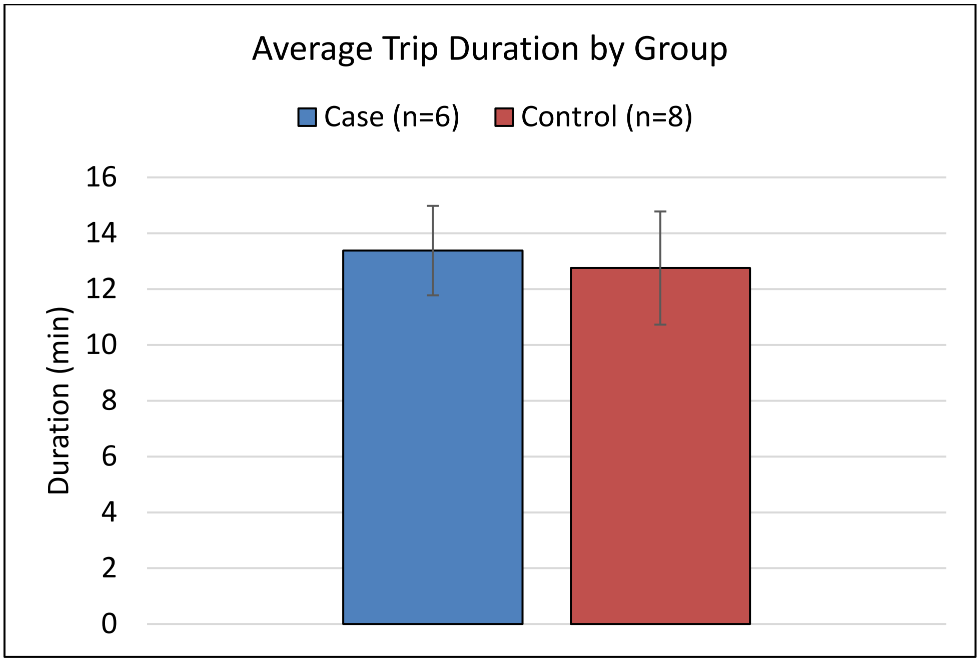

Figure 9. Average duration per trip by group.

## ADAS Use

### Proportion of Trips

Of the fourteen participants with ACC-equipped vehicles, only six ever used the system during the study period (3 each from the control and case groups). Figure *10* shows the proportion of trips in which ACC was utilized by these participants.

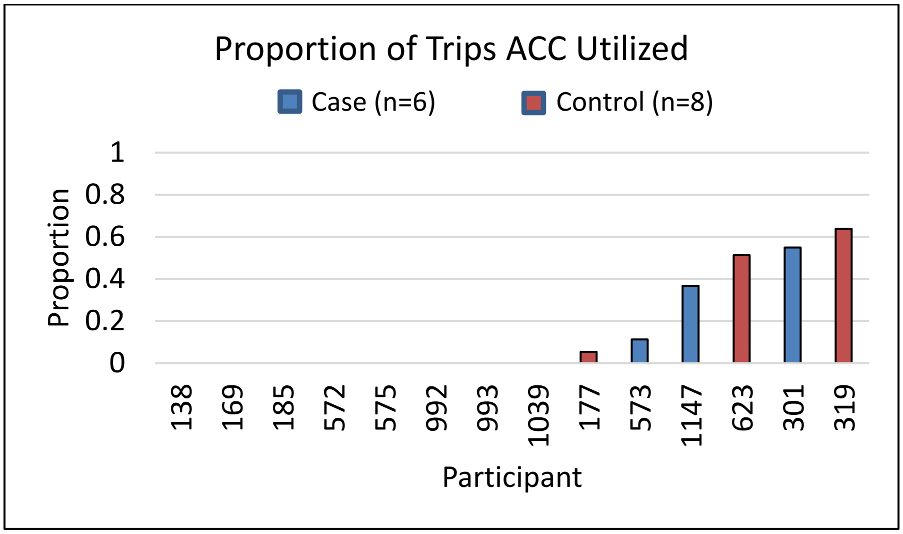

Figure 10. Proportion of trips in which ACC-equipped vehicles utilized ACC for at least part of the trip.

A similar analysis was completed to evaluate the proportion of trips where the LC system was utilized (Figure *11*). Of the seven total vehicles equipped with the LC system, only three (42.9%) used the system at any point.

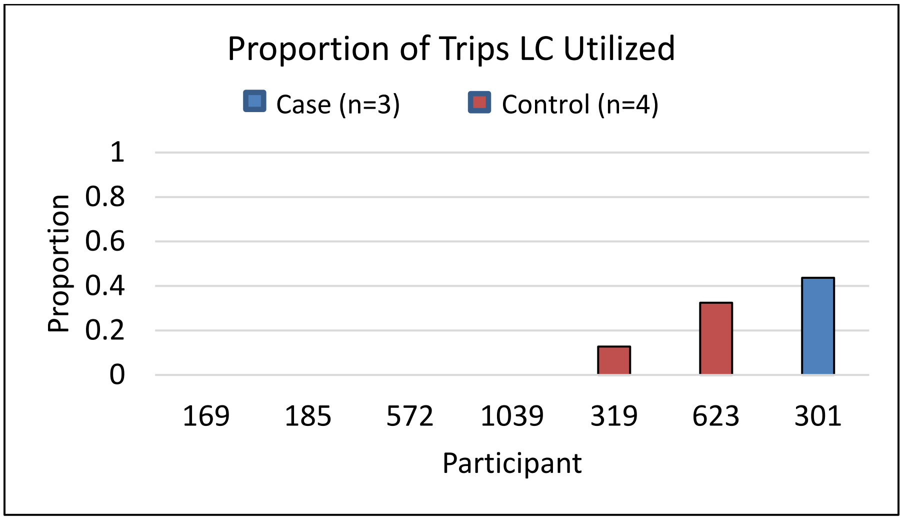

Figure 11. Proportion of trips in which LC-equipped vehicles utilized LC for at least part of the trip.

### Proportion of Time

An analysis of the proportion of time that ACC and LC systems were utilized was performed. To provide an accurate comparison, the proportion of time the vehicle traveled faster than 25 mph is also provided. Vehicle manufacturers indicated ACC system use for greater than 25 mph at initial setting and greater than 45 mph for LC. As shown in Figure *12*, the proportion of time above 25 mph was at least 0.2 for every participant except for one. Despite traveling within the operational design domain (ODD) for ACC, very little use was observed during ODD (ACC: 0.04 to 0.35 for six participants). The analysis focusing on proportion of time above 45 mph revealed that 7 of 14 (50%) of participants spent a small proportion of time (0.20) above 45 mph. For those with LC-equipped vehicles, only 3 of 7 (43%) participants spent a greater than 0.20 proportion of time above 45 mph. Overall, LC use was minimal - the greatest proportion of LC use among all participants was 0.11.

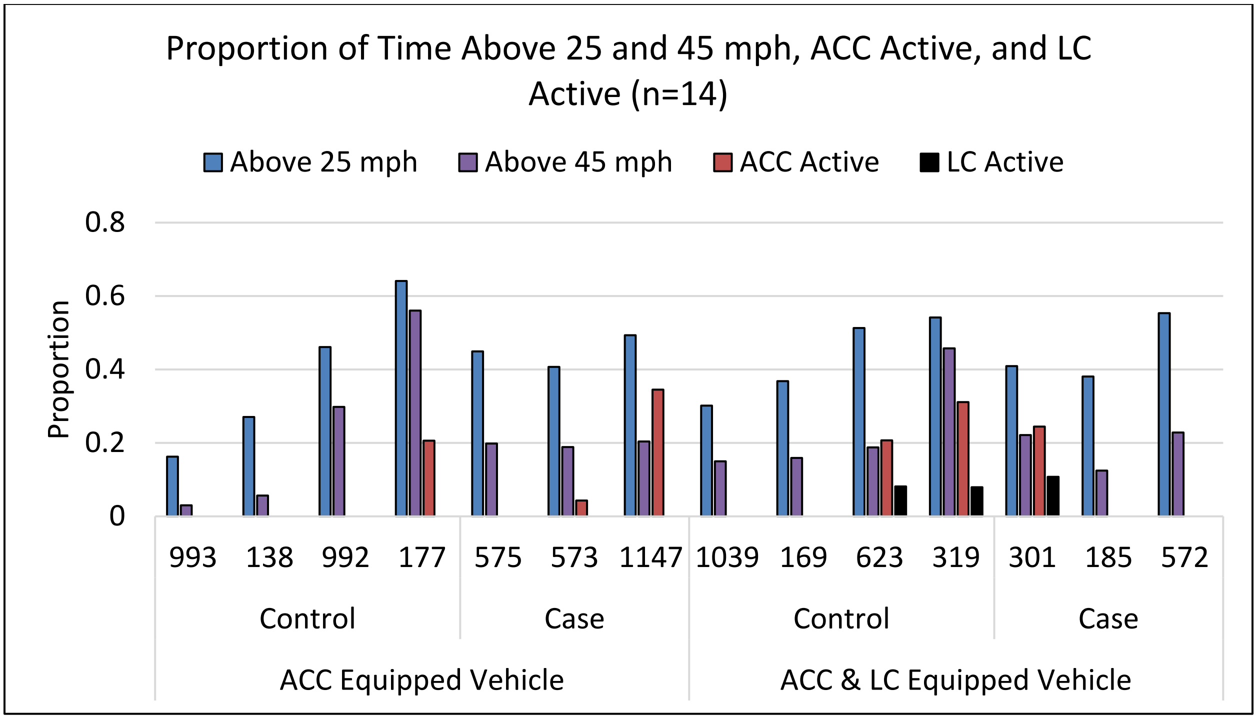

Figure 12. Proportion of time above 25 mph, ACC active, and LC active by group and system configuration.

The resulting analysis using the general linear model and a binomial distribution showed no statistically significant differences for any of the three metrics: proportion of ODD time (i.e., above 25 mph, F=0.35, p=0.564), proportion of ODD time (i.e., above 45 mph, F=0.32, p=0.585), and proportion of time ACC active (F=0.20, p=0.664 - Figure *13*). No inferential statistics were conducted for the proportion of time LC was active due to the low number of observations.

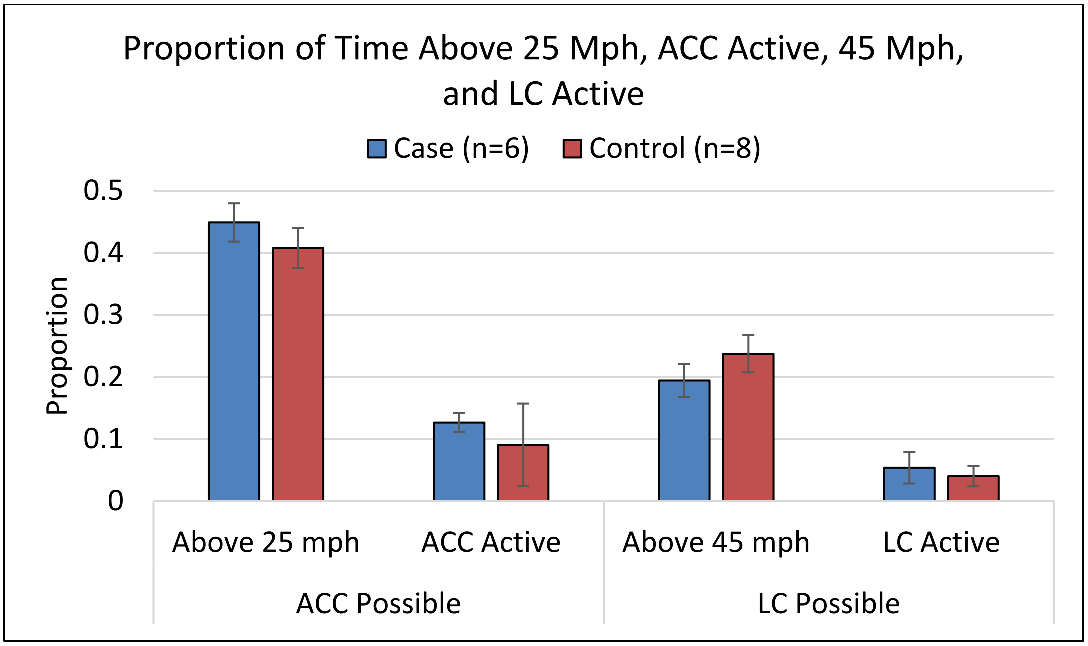

Figure 13. Proportion of time above 25 mph and 45 mph, ACC active, and LC active by group.

### LDW Rate

LDW rate per trip were compared between groups. In total, 211 valid warnings were issued across all participants. Figure *14* shows the rate of warnings per trip.

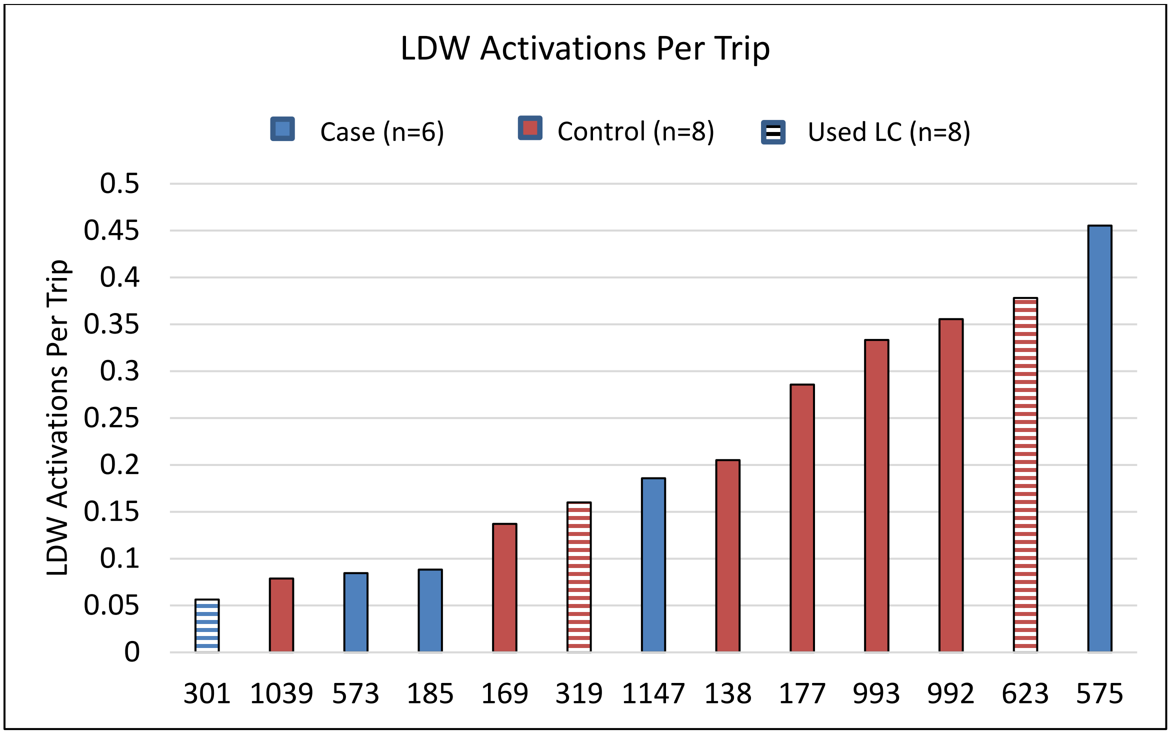

Figure 14. LDW per trip (hashed bars represent participants who engaged LC at some point during participation).

Figure 15 shows overall rate of valid warnings by group; a t-test revealed no statistically significant differences between the groups (t=-0.89, p=0.393).

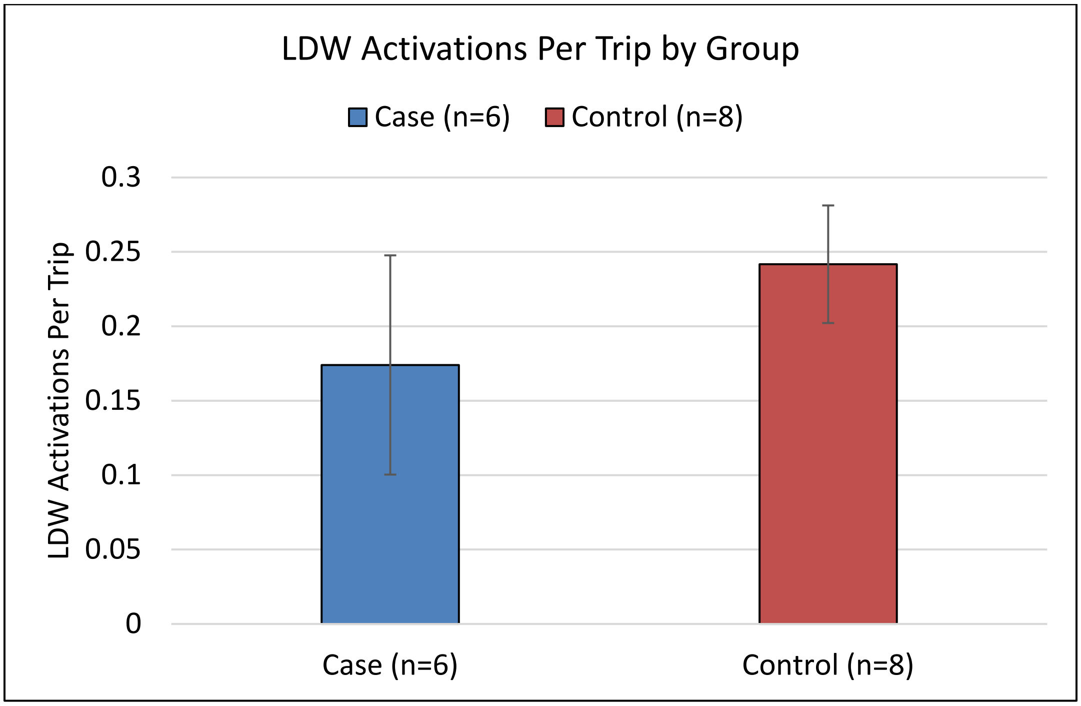

Figure 15. LDW per trip by group.

### FCW Rate

Rate of FCW were compared between groups. A total of 20 valid activations occurred across all participants. Figure *16* shows the rate of FCW activations per trip.

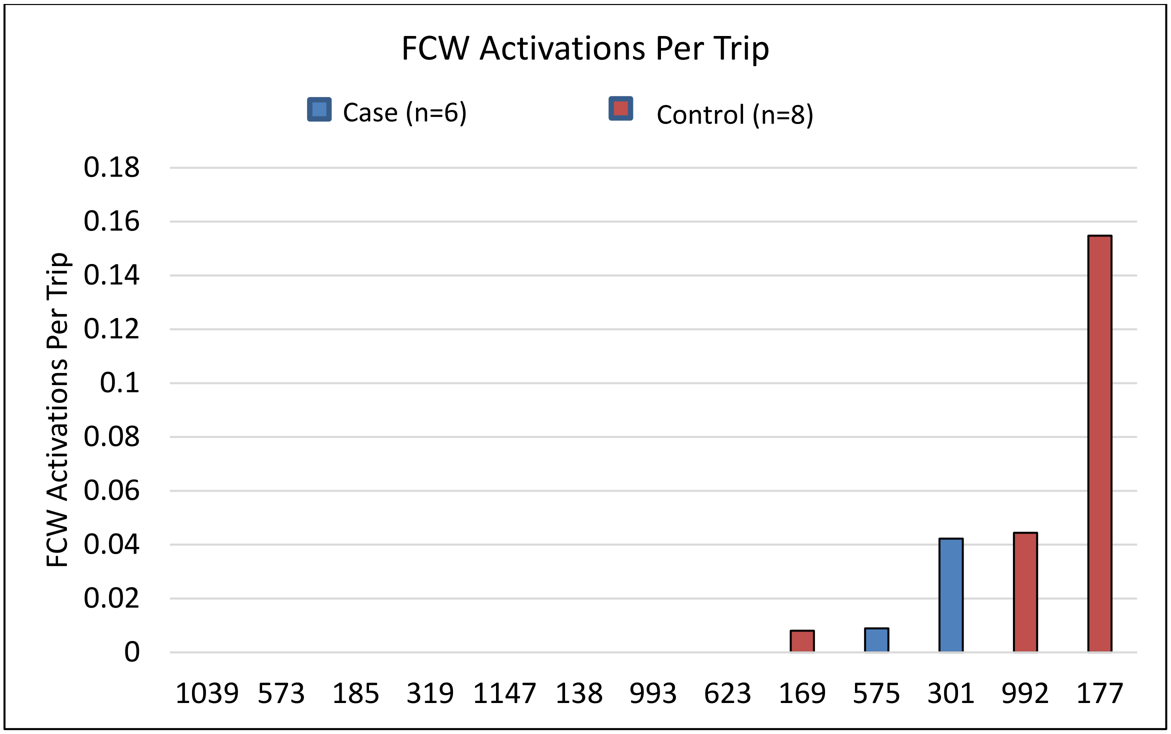

Figure 16. FCW rate per trip.

We also examined valid FCW by group (Figure *17*). It is worth noting that one participant, a control (177), accounted for 13 of 20 (65%) valid FCW.

### *Analysis 1 Discussion*

The goal of this effort was to investigate the possibility that participants with pre-MCI may exhibit differences in driving behavior compared to those without pre-MCI, prior to detection with standardized cognitive evaluations. In addition, we wanted to examine the impact of the presence and usage of ADAS features on the driving behaviors of these two groups. At a high level, the analyses did not reveal any meaningful statistically significant findings between the groups.

## ADAS Use

Overall, results showed very low LC utilization – of the seven participants with access to LC, only three activated it during the study. The lack of utilization was present even though the proportion of time above 45 mph was at least 0.2 for each participant. The authors had expected a higher proportion of participants to have used the LC system at least once during the data collection. An initial hypothesis was that drivers utilizing the LC system would experience fewer LDW activations than those not using the LC system. Results did not support this hypothesis; those that used the LC system had both the lowest as well as second highest rates of LDW activation. One participant who received several LDW, appeared to spend quite a bit of time driving on a narrow two-lane roadway. This is a location that both a) affords a high opportunity to trigger a LDW activation as well as b) a roadway in which the LC system was specifically outside of its ODD and therefore not likely to be effective in that situation.

Additionally, results showed a moderate use of ACC (6 of 14 or 42.8%). This result shows that almost half were utilizing the system at some point during trips. However, the authors expected to see higher adoption rates. It may be that participants simply did not spend as much time traveling on roadways designed for system use. For example, those in rural areas may often travel on winding roadways where they do not feel comfortable using ACC. Additionally, if a high proportion of trips are to nearby areas, there simply may be no need to use ACC.

### Safety-Critical Events

In none of the safety-critical events was ACC or LC active either at the time of or shortly before the event. Interestingly, in 60% (6 of 10) cases, had ACC been active, it may have played a beneficial role in mitigating the situation. Events were considered mitigatable if a lead vehicle slowed or stopped in the lane ahead – had ACC been active, it very likely would have started slowing prior to the point at which the participant intervened. No safety critical events were the result of a lane departure and thus it is unlikely that the presence of LC in any of the situations would have been beneficial. The only safety-critical events in which ACC would likely *not* have afforded any meaningful degree of mitigation were those caused by animal-vehicle interactions.

# Case Studies

In nearly all transportation research, participants are allocated to specific groups and analyses are conducted to determine differences between groups. While required to have a sufficient sample size suitable for inferential testing, collapsing across participants may also obscure highly relevant findings or information. This effect may be especially pronounced in exploratory works such as this. Below, two case studies are presented and the results from these individual participants can be used for hypothesis generation in future research efforts.

## Participant 177

Participant 177 is a 74-year-old male who lives in the Washington D.C. area and drives a 2018 Subaru equipped with ACC, but no LC system. He received a top score on the SAGE and only answered in the affirmative in three out of nine memory questions (forget something he just read, not as sharp as he used to be, and trouble recalling words). He noted avoiding the following driving scenarios: icy conditions, unprotected left turns, and complex intersections.

He drove the second-most trips per driving day of anyone included in the study (7) suggesting he drives frequently, despite his noted avoidances, and for an average of 21 minutes per trip. Duration is likely affected by his proximity to a major city. This participant was involved in one near-crash event which involved his slow response to a slowing lead vehicle. He was not utilizing any ADAS features at the time; however, he did have ACC available to him and it may have been beneficial in intervening sooner than he did. He was responsible for 65% of all FCWs issued and had the highest rate of anyone in the study (0.15 per trip). He was also responsible for 11% of all LDWs issued. On only four trips did he utilize ACC, each of which occurred on a major four-lane divided highway or interstate. Even though this participant was not revealed to have cognitive impairment via the SAGE assessment, he still was responsible for a large number of FCW and LDW events as well as one near crash. His driving clearly reflects someone who poses an increased crash risk, but no dementia or MCI was reflected in his cognitive evaluation. Perhaps his situation represents the proverbial ‘canary in the coal mine’, wherein cognitive tests are not sufficiently sensitive to reveal any problems, but his personal feelings and driving performance suggest that some degree of cognitive impairment may, in fact, be present (Babulal, Johnson et al., 2021; Davis et al., 2020; Roe, Barco, et al., 2017).

With a larger sample size, more such individuals may become apparent thus revealing a need to lean on driving performance data as a potential leading indicator of cognitive impairment, *prior to* that which may be revealed by standardized metrics.

### Participant 319

Participant 319 presents another interesting case study. This individual an 80-year-old male who lives in the San Antonia area and drives a 2018 Honda with ACC and LC systems. He also received a top score on the SAGE yet responded in the affirmative to memory issues in six out of the nine memory questions and indicated that he chooses to avoid driving in five of the 12 driving scenarios.

He is in the top 33% of participants for number of trips driven per day (4.5) with an average duration per trip of 16.8 minutes. In his case, duration may also be slightly elevated given his proximity to a major city. This individual was involved in two crash-relevant conflicts. The first involved a slowed reaction time to a lead vehicle slowing and turning into a parking lot while the nature of the second is unknown because the forward video was unavailable; however, the participant clearly braked hard while showing strained emotions and making utterances while traffic in the adjacent lane proceeded normally. As the true nature of the scenario could not be determined without corroborating video, a lower severity rating was assigned. In both cases an ACC system may have proved beneficial; however, neither ACC nor LC systems were active at the time of the event.

This driver was not revealed to have any cognitive impairment; however, as noted above he admitted to memory complaints as well as actively avoided driving in certain situations. A logical conclusion of such behavior is that his meta-cognitive status is such that he is aware of degraded driving performance and is taking steps to minimize exposure to the situations he finds most difficult or daunting.

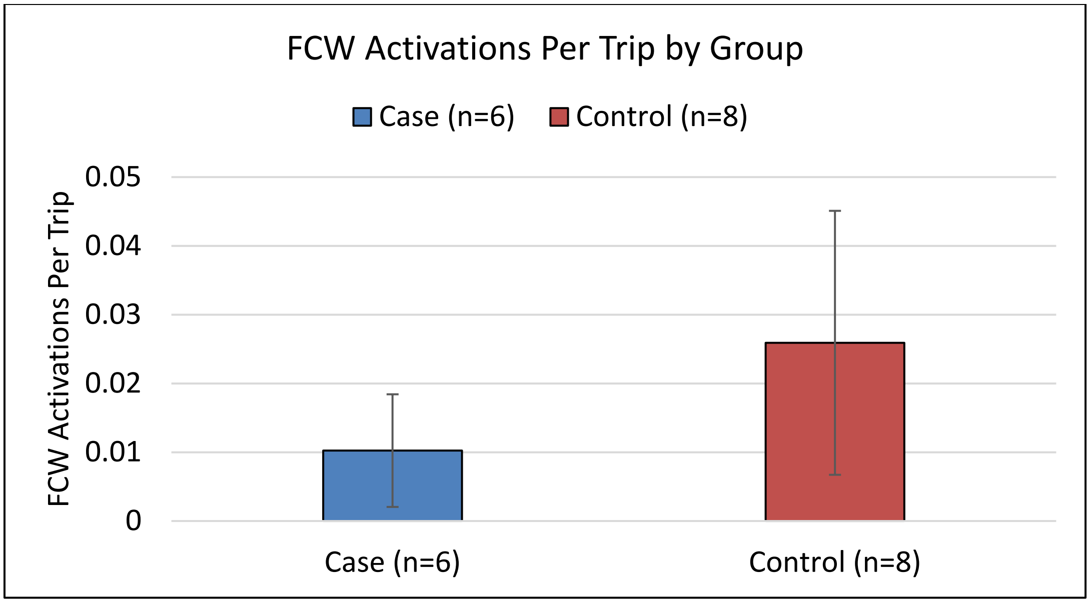

Figure 17. FCW rate per trip by group.

## Analysis 2 Results

### *Mobility*

The average number of trips taken per driving day were compared between those with access to ADAS features and those without as well as by cognitive status group. A Chi-square test of independence revealed a significant difference ($\chi^2 = 54.04$, $p < 0.001$); see (Figure 18 and 19).

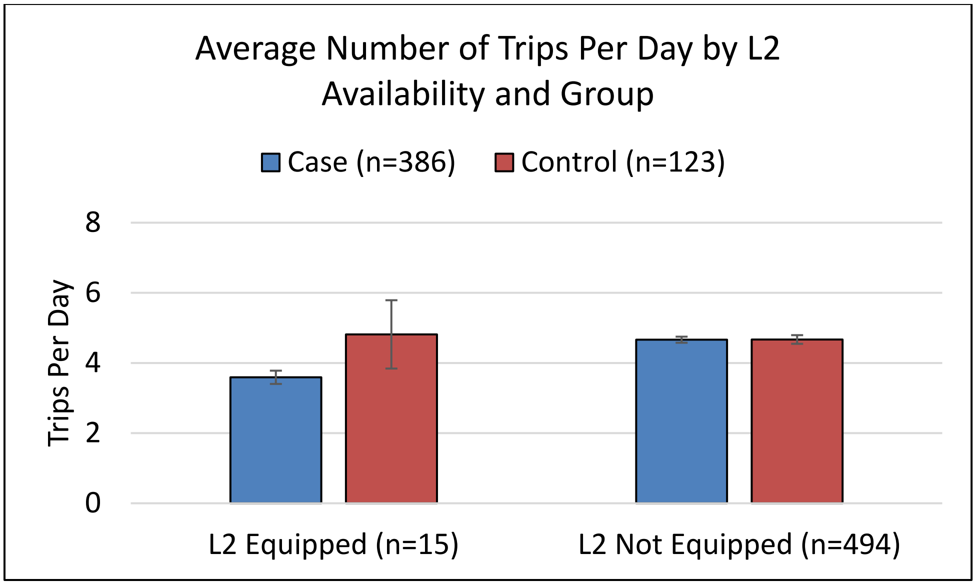

Figure 18. Average number of trips per driving day by group – group comparison.

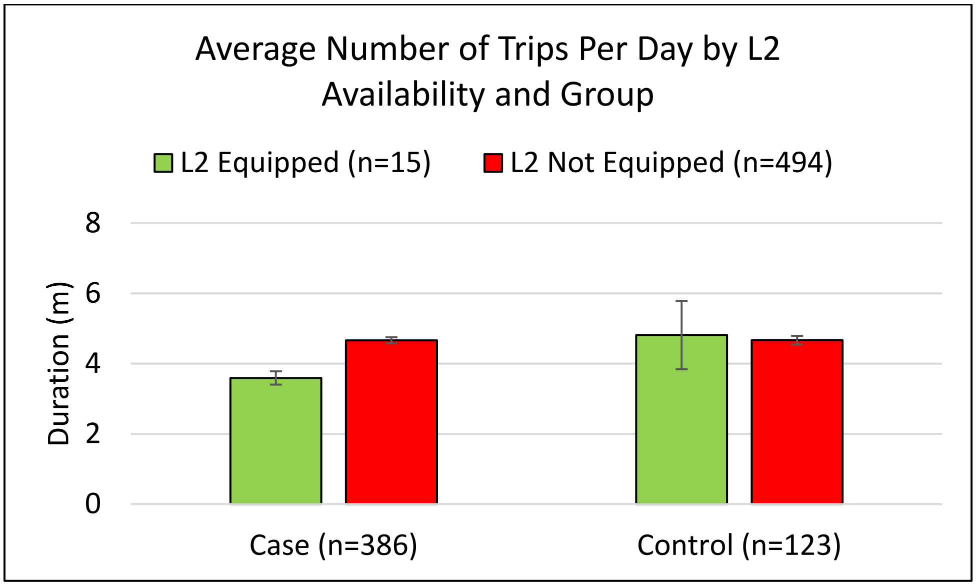

Figure 19. Average number of trips per driving day by group – L2 comparison.

### *Duration*

A Chi-square test of independence revealed a statistically significant difference comparing group membership and L2 availability ($\chi^2 = 102.93$, $p<0.001$) and is presented in Figure 20 and 21.

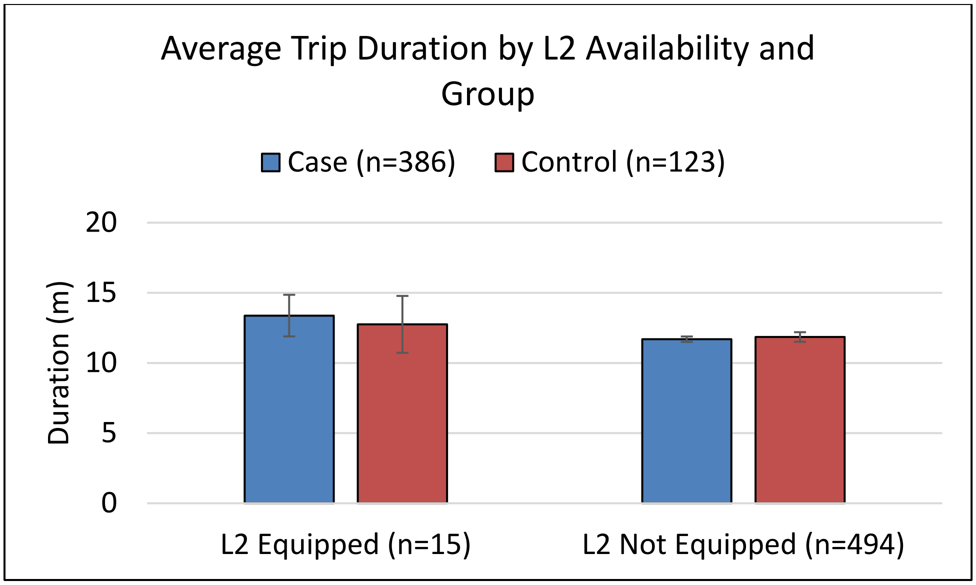

Figure 20. Average trip duration by L2 availability and group – group comparison.

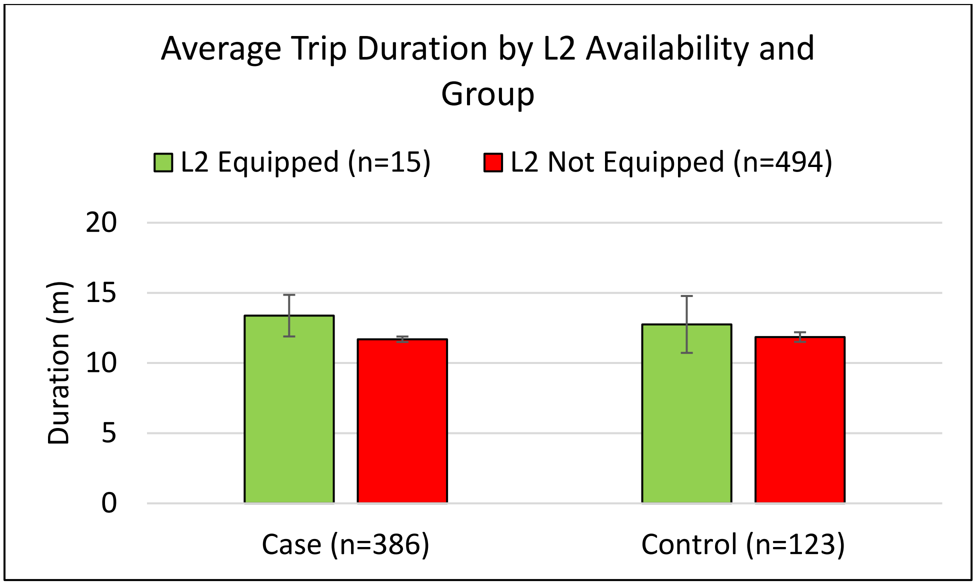

Figure 21. Average trip duration by L2 availability and group – L2 comparison.

### *Safety Critical Events*

For the following analysis, all safety-critical events were grouped together, regardless of severity, to create a large enough sample size to conduct meaningful inferential statistics. A Chi-square test of independence was conducted on group and L2 availability – it showed no statistically significant effects ($\chi^2 = 3.55$, p=0.059) and is presented in Figure 22 and 23.

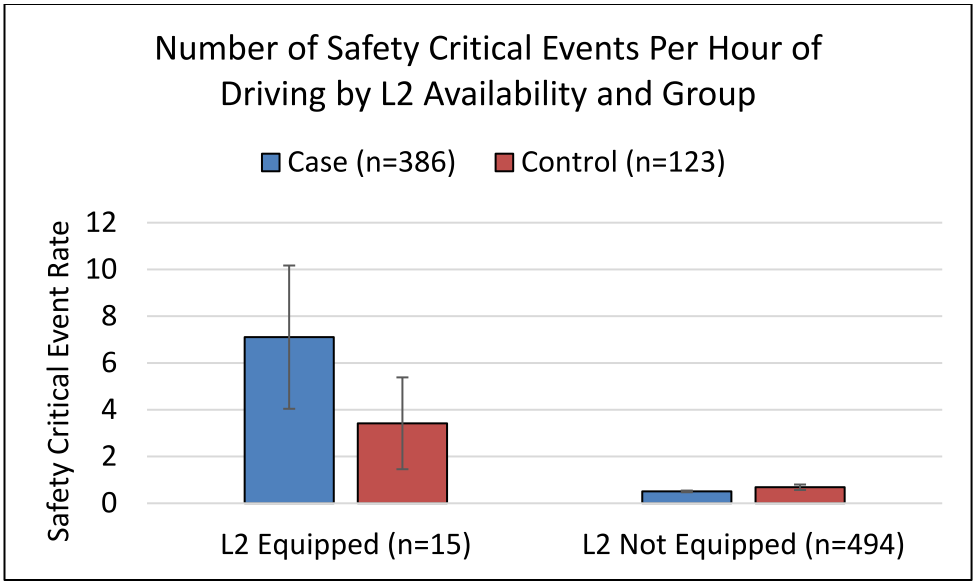

Figure 22. Safety critical event rate per 100 driving hours – group comparison.

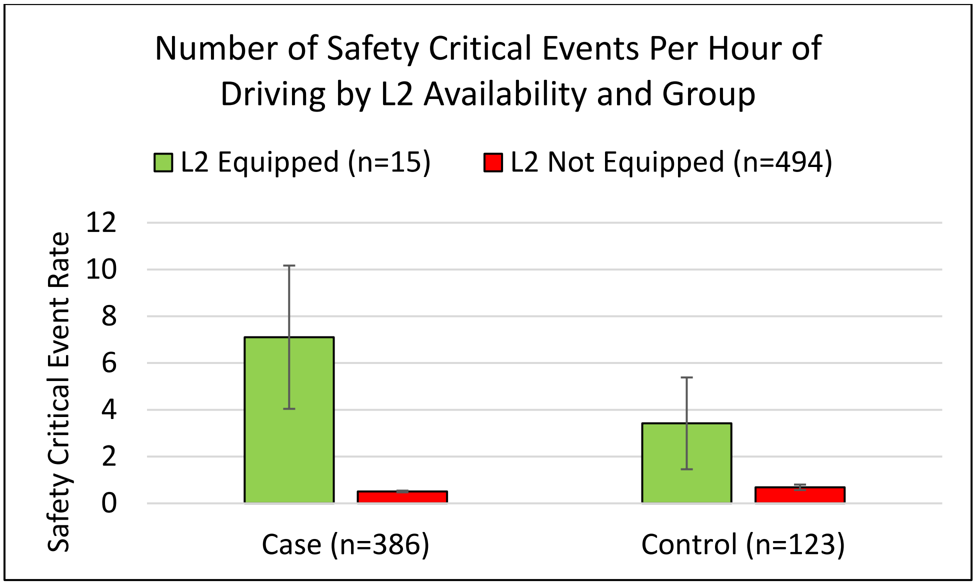

Figure 23. Safety critical event rate per 100 driving hours – L2 comparison.

## Analysis 2 Discussion

Analyses were conducted to compare mobility and safety critical event rate data by cognitive status group membership and L2 availability. Two analyses revealed statistically reliable results: average number of trips per day and average trip duration. Results showed the lowest average number of trips per day for those in the pre-MCI group driving vehicles with L2 features. Results of current analyses are not consistent with other findings. For instance, Feng et al. (2019) found no significant difference in driving exposure for those with MCI vs. those without, and Staplin et al. (2019) found that those with MCI may even engage in a greater number of trips compared with cognitively normal individuals. However, those analyses were conducted with non-L2 vehicles. It is also conceivable that those with pre-MCI may have sufficient meta-awareness to realize the safety benefits of self-restricting their driving. The SHRP 2 data (i.e., those without access to L2 features) did not show the same pattern – those in the pre-MCI group and those in the control group drove a virtually identical number of trips per day. At a high level, it appears that technologies designed to improve safety and mobility are not producing the expected results. However, low usage rates may play a large role in that outcome. As today's younger drivers age into the older adult category in coming years, they may be more used to such technologies and more willing to engage and reap their benefits.

When evaluating average trip duration, those in the pre-MCI group with L2 technologies available tended to drive for longer (13.34 minutes) than those in the pre-MCI group without the technologies (11.69 minutes). Those in the pre-MCI group driving vehicles with L2 technologies also tended to drive for longer durations than those in the respective control group (12.75 minutes). Those in the SHRP 2 collection showed no difference in trip duration by group (pre-MCI: 11.69 minutes, control: 11.85 minutes). These results suggest the presence of L2 features may support engagement in longer trips. However, when taken with the overall low L2 usage rate, these results may be better explained by other factors.
One such unexplored element may be driver confidence. The presence of safety features (used or not) may improve the participant's level of confidence, simply knowing the systems are available if needed. It is also interesting to note that those with L2 technologies tended to drive for longer durations than their non-L2 SHRP 2 counterparts. While average durations were higher regardless of pre-MCI status for the L2 group, the highest average duration was those in the pre-MCI case group with access to L2.

The safety-critical event (SCE) analysis produced results which were nearly significant and may be instructive for future research hypotheses. Results demonstrated a trend suggesting cases might have a higher SCE rate than controls, when both groups were driving L2-equipped vehicles. It is possible that that the cases had reduced understanding of the L2-equipped vehicles' capabilities and limitations as well as the L2 ODD.

### General Discussion

Even though we were unable to detect a strong trend for driving metrics serving as the "canary in the coal mine" for pre-MCI, we did find case studies that followed such a pattern. Again, with more data, future studies may be able to show this factor more definitively.

Our findings are consistent with other work *not* utilizing biomarkers which has shown that older adults with MCI have been shown to exhibit shorter time-to-collision during simulated driving than healthy controls, but otherwise have a minimal impact on driving performance (Frittelli et al., 2008). With respect to driving avoidance and affirmative answers to memory questions, a conceivable intervening variable is the level of metacognition. Presumably, as cognitive faculties decline, one's ability to accurately evaluate oneself may also decrease. A natural result may be *less* avoidance of driving scenarios and *fewer* admissions of memory issues. Older drivers have been known to self-regulate driving by avoiding or minimizing exposure to select scenarios (Gwyther and Holland, 2012). However, many may not have sufficient introspection to recognize deficits (Wood et al., 2013). Even those who do have intact introspection may choose to continue to drive out of necessity (Ng et al., 2020; Strogatz et al., 2020). Unfortunately, this effort did not have a gold-standard metric of cognitive performance such that a level of introspection could be derived. The SAGE scores exhibited a ceiling effect which either indicates the participants were more cognitively intact regardless of case versus control, or that it is not sensitive enough to reliably differentiate pre-MCI and MCI for our purposes.

### General Conclusion

The goal of this effort was to investigate driving differences between those older adults with pre-MCI and controls, both with ADAS/L2 and without. We did find evidence that those with pre-MCI demonstrated modest differences compared to cognitively normal individuals in terms of mobility-related metrics, especially when driving vehicles equipped with L2 technology (regardless of the fact that these technologies were not frequently used). It is possible that as these technologies become more commonplace, older adults, with and without cognitive impairment, may utilize them with greater frequency. In addition, this study demonstrated non-significant differences in terms of the number of safety-critical events between the controls and those with pre-MCI; it is possible that with more data, such a trend may be found to be statistically significant, thus serving as a possible “canary in the coal mine” for the early detection of pre-MCI.

## Future Efforts

Biomarkers such as tau/beta-amyloid(Aβ) in cerebrospinal fluid (CSF), phosphorylated tau/ Aβ ratios, Aβ, and *APOE* ε4 status have been correlated with deleterious driving performance in MCI and AD and are a promising avenue towards early detection of pre-MCI in driving behavior (Babulal et al., 2018; Babulal et al., 2017; Bayat et al., 2021; Roe, Babulal, et al., 2017; Roe, Barco, et al., 2017). However, each of these works utilized either an on-road driving assessment (Babulal et al., 2018; Babulal et al., 2017; Roe, Barco, et al., 2017; Roe, Babulal, et al., 2017) or naturalistic data collection without video (Bayat et al. 2021). While the on-road driving assessment utilized a structured road test and an occupational therapist/driving rehabilitation specialist, driving behavior was likely affected by the presence of a professional evaluator. The naturalistic collection noted previously (Bayat et al. 2021) may collect much valid information such as GPS location, speed, and kinematic events, but what it lacks is the context in which the event occurred. For example, during the kinematic event validation process in our current analysis, the overwhelming majority (>90%) of potential events turned out to be non-events (i.e., they were the result of crossing or hitting railroad tracks, potholes, or other roadway anomalies). Unfortunately, the lack of video ostensibly precludes the identification of valid events and likely inflates the count of kinematic errors. Work exploring the use of the biomarkers along with video-based naturalistic data collection, such as that used in the current effort, could further expand on these findings and improve real-world validity.

To better understand the use of ACC and LC systems, road type must be considered as well. As these systems are primarily intended to be used on highway-like roadways, potential misuse may occur from activation on roadways not well suited for these types of driving aids. Improper use of L2 systems was not evaluated in this effort, but it may serve as another avenue for exploration. Finally, in order to more fully-explore any driving behavior differences between those with pre-MCI and those without, a more robust data analysis could be undertaken in which drivers are scored on a number of criteria. Such criteria may include traffic signal and sign attentiveness, situational awareness, following distance, engagement in secondary, non-driving related tasks, and drowsiness. Doing so would allow a more granular approach which may reveal differences not yet uncovered in the current effort.

No statistically significant results arose from the comparison between cases and controls for those driving L2-equipped vehicles. One aspect not explored in the current analyses is level of confidence, stress, and worry while driving. If the L2 system provides additional confidence (even if such systems remain unused), it may therefore also increase safety and/or mobility. For instance, a driver may find that simply having access to such systems provides a level of security knowing they are readily available if needed. Such elements were not explored during this work but may prove beneficial. Future work may include questionnaires or focus groups to further explore this relationship and determine the impact these systems have on a driver's level of confidence.

### Limitations

Because of the pre-MCI criteria applied, the relatively small sample size made it difficult to draw conclusions. With a greater number of participants, more robust analyses could be completed. Additionally, due to the period in which data was collected, nearly half of the study vehicles were not outfitted with an LC system. These vehicles utilized a less-robust, LKA system which was not intended to keep the vehicle centered within the lane. As a result, many of the analyses focused on LC use, suffered from even smaller numbers of participants and thus inferential statistics were not warranted.

The second limitation results from using data from multiple datasets, each collected in different times and spaces. In the currently collected data, group assignment was the result of questions asked during the screening process, in the SHRP 2 data collection, that was not an option. By selecting the clock drawing assessment to sort participants into possible groups, the assumption is that the resulting groups are very similar to the group assignment from the intake questions. However, it is possible that the two methods measure different aspects of the cognitive status.

## REFERENCES

Albert MS, DeKosky ST, Dickson D, et al. (2011) The diagnosis of mild cognitive impairment due to Alzheimer’s disease: recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's disease. Alzheimers Dement ;7(3):270–9.

Allison, S., Babulal, G. M., Stout, S. H., Barco, P. P., Carr, D. B., Fagan, A. M., ... & Head, D. (2018). Alzheimer’s disease biomarkers and driving in clinically normal older adults: Role of spatial navigation abilities. Alzheimer disease and associated disorders, 32(2), 101.

American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders, 5th Edition. 2013.

Antin, J. F., Lee, S. E., Perez, M. A., Dingus, T. A., Hankey, J. M., and Brach, A. (2019). Second strategic highway research program naturalistic driving study methods. Safety Science, 119, 2-10. Doi: https://doi.org/10.1016/j.ssci.2019.01.016

Antin, J. F., Wotring, B., Perez, M. A., & Glaser, D. (2020). Investigating lane change behaviors and difficulties for senior drivers using naturalistic driving data. *Journal of Safety Research*, *74*, 81-87.

Babulal, G. M., Johnson, A., Fagan, A. M., Morris, J. C., & Roe, C. M. (2021). Identifying Preclinical Alzheimer’s Disease Using Everyday Driving Behavior: Proof of Concept. Journal of Alzheimer's Disease, (Preprint), 1-6.

Babulal, G. M., Chen, S., Williams, M. M., Trani, J. F., Bakhshi, P., Chao, G. L., ... & Roe, C. M. (2018). Depression and Alzheimer’s disease biomarkers predict driving decline. Journal of Alzheimer's Disease, 66(3), 1213-1221.

Babulal, G. M., Stout, S. H., Head, D., Holtzman, D. M., Fagan, A. M., Morris, J. C., & Roe, C. M. (2017). Neuropsychiatric symptoms and Alzheimer’s disease biomarkers predict driving decline: brief report. Journal of Alzheimer's disease, 58(3), 675-680.

Bayat, S., Babulal, G. M., Schindler, S. E., Fagan, A. M., Morris, J. C., Mihailidis, A., & Roe, C. M. (2021). GPS driving: a digital biomarker for preclinical Alzheimer disease. Alzheimer's Research & Therapy, 13(1), 1-9.

Blatt, A., Pierowicz, J., Flanigan, M., Lin, P, Kourtellis, A., Jovanis, P., Jenness, J., Wilaby, M., Campbell, J., Richard, C., Good, D., Czar, N., &Hoover, M. (2014). Naturalistic driving study: Field data collection (2014). National Academies of Sciences, Engineering, and Medicine. Washington, D.C., The National Academies Press. https://doi.org/10.17226/22367.

Charlton, J. L., Oxley, J., Fildes, B., Oxley, P., & Newstead, S. (2003). Self-regulatory behaviours of older drivers. In Annual Proceedings/Association for the Advancement of Automotive Medicine (Vol. 47, p. 181). Association for the Advancement of Automotive Medicine.

Chipi, E., Salvadori, N., Farotti, L., & Parnetti, L. (2019). Biomarker-based signature of Alzheimer's disease in pre-MCI individuals. Brain Sciences, 9(9), 213.

Classen, S., Jeghers, M., Morgan-Daniel, J., Winter, S., King, L., & Struckmeyer, L. (2019). Smart in-vehicle technologies and older drivers: A scoping review. OTJR: occupation, participation and health, 39(2), 97-107.

Davis, J. D., Babulal, G. M., Papandonatos, G. D., Burke, E. M., Rosnick, C. B., Ott, B. R., & Roe, C. M. (2020). Evaluation of Naturalistic Driving Behavior Using In-Vehicle Monitoring Technology in Preclinical and Early Alzheimer's Disease. Frontiers in psychology, 11, 2925.

Delmotte, K., Schaeverbeke, J., Poesen, K., & Vandenberghe, R. (2021). Prognostic value of amyloid/tau/neurodegeneration (ATN) classification based on diagnostic cerebrospinal fluid samples for Alzheimer's disease. Alzheimer's research & therapy, 13(1), 1-13.

Dingus, T.A., Hankey, J.M., Anting, J.F., Lee, S.E., Eichelberger, L., Stulce, K., McGraw, D., Perez, M., & Stowe, L. (2014). Naturalistic driving study: Technical coordination and quality control. Transportation Research Board. Washington, D.C. The National Academies Press. https://doi.org/10.17226/22362.

Douthit, N., Kiv, S., Dwolatzky, T., & Biswas, S. (2015). Exposing some important barriers to health care access in the rural USA. Public health, 129(6), 611-620.

Duara, R., Loewenstein, D. A., Potter, E., Barker, W., Raj, A., Schoenberg, M., ... & Borenstein, A. (2011). Pre-MCI and MCI: neuropsychological, clinical, and imaging features and progression rates. The American Journal of Geriatric Psychiatry, 19(11), 951-960.

Duchek, J. M., Carr, D. B., Hunt, L., Roe, C. M., Xiong, C., Shah, K., & Morris, J. C. (2003). Longitudinal driving performance in early-stage dementia of the Alzheimer type. Journal of the American Geriatrics Society, 51(10), 1342-1347.

Evans, J. (1999). Elderly mobility & safety focus group research report, SEMCOG the Southeast Michigan Council of Governments, Detroit, Michigan.

Federal Highway Administration, U.S. Department of Transportation. (2017). National Household Travel Survey. https://nhts.ornl.gov/

Feng, Y. R., Meuleners, L., Stevenson, M., Heyworth, J., Murray, K., Fraser, M., & Maher, S. (2021). Driving exposure, patterns and safety critical events for older drivers with and without mild cognitive impairment: findings from a naturalistic driving study. Accident Analysis & Prevention, 151, 105965.

Frittelli, C., Borghetti, D., Iudice, G., Bonanni, E., Maestri, M., Tongnoni, G., Pasquali, L., Iudice, A. (2008). Effects of Alzheimer’s disease and mild cognitive impairment on driving ability: a controlled clinical study by simulated driving test. International Journal of Geriatric Psychiatry. 24(3), 232-238.

Jessen, F. (2014). Subjective and objective cognitive decline at the pre-dementia stage of Alzheimer’s disease. European archives of psychiatry and clinical neuroscience, 264(1), 3-7.

Gwyther, H., & Holland, C. (2012). The effect of age, gender and attitudes on self-regulation in driving. Accident Analysis & Prevention, 45, 19-28.

Hendrix, S. B. (2012). Measuring clinical progression in MCI and pre-MCI populations: enrichment and optimizing clinical outcomes over time. Alzheimer's Research & Therapy, 4(4), 1-7.

Knopman, D. S., Gottesman, R. F., Sharrett, A. R., Wruck, L. M., Windham, B. G., Coker, L., ... & Mosley Jr, T. H. (2016). Mild cognitive impairment and dementia prevalence: the atherosclerosis risk in communities neurocognitive study. Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring, 2, 1-11.

Lam, O., Broderick, B., & Toor, S. (2018). How far Americans live from the closest hospital differs by community type. https://www.pewresearch.org/fact-tank/2018/12/12/how-far-americans-live-from-the-closest-hospital-differs-by-community-type/

Liang, D., Antin, J. F., Lau, N. K., & Stulce, K. E. (2021). Examining Seniors' Adaptation to Mixed Function Automated Vehicles: Analysis of Naturalistic Driving Data.

Liang, D., Antin, J., Lau, N., Stukce, K. F Baker, S., and Wotring, B (2018). Examining senior drivers adaption to mixed level automated vehicles: A Naturalistic Study. National Surface Transportation Safety Center for Excellence Final Report #. 03-040 (https://www.vtti.vt.edu/utc/safe-d/wp-content/uploads/2019/10/Project_03-040%20FinalResearchReport_Final.pdf)

Mattson, J. (2017). Rural transit fact book 2017 (No. SURLC 17-007). Western Transportation Institute.

Meara, A., Davidson, N., Steigelman, H., Zhao, S., Brock, G., Jarjour, W. N., ... & Ardoin, S. P. (2018). Screening for cognitive impairment in SLE using the Self-Administered Gerocognitive Exam. Lupus, 27(8), 1363-1367.

Nelson, A. P., & O'Connor, M. G. (2008). Mild cognitive impairment: a neuropsychological perspective. CNS spectrums, 13(1), 56-64.

Neuhuber, N., Lechner, G., Kalayci, T. E., Stocker, A., & Kubicek, B. (2020, July). Age-Related Differences in the Interaction with Advanced Driver Assistance Systems-A Field Study. In International Conference on Human-Computer Interaction (pp. 363-378). Springer, Cham.

Ng, L. S., Guralnik, J. M., Man, C., DiGuiseppi, C., Strogatz, D., Eby, D. W., Ryan, L. H., Molnar, L. J., Betz, M. E., Hill, L., Li, G., Crowe, C. L., & Mielenz, T. J. (2020). Association of physical function with driving space and crashes among older adults. The Gerontologist, 60(1), 69–79. https://doi.org/10.1093/geront/gny178

Nunes, T., Fragata, I., Ribeiro, F., Palma, T., Maroco, J., Cannas, J., ... & de Mendonça, A. (2010). The outcome of elderly patients with cognitive complaints but normal neuropsychological tests. Journal of Alzheimer's Disease, 19(1), 137-145.

Ott, B. R., Jones, R. N., Noto, R. B., Yoo, D. C., Snyder, P. J., Bernier, J. N., ... & Roe, C. M. (2017). Brain amyloid in preclinical Alzheimer's disease is associated with increased driving risk. Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring, 6, 136-142.

Oxley, J., Fildes, B., Corben, B., Langford, J. (2006). Intersection design for older drivers, Transportation Research Part F, 9, 335-346.

Payyanadan, R. P., Lee, J. D., & Grepo, L. C. (2018). Challenges for older drivers in urban, suburban, and rural settings. Geriatrics, 3(2), 14.

Perez, M. A., Sudweeks, J. D., Sears, E., Antin, J., Lee, S., Hankey, J. M., & Dingus, T. A. (2017). Performance of basic kinematic thresholds in the identification of crash and near-crash events within naturalistic driving data. Accident Analysis & Prevention, 103, 10-19.

Petersen, R. C. (2004). Mild cognitive impairment as a diagnostic entity. Journal of internal medicine, 256(3), 183-194.

Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. G., & Kokmen, E. (1999). Mild cognitive impairment: clinical characterization and outcome. Archives of neurology, 56(3), 303-308.

Portet, F., Ousset, P. J., Visser, P. J., Frisoni, G. B., Nobili, F., Scheltens, P., Vellas, B., Touchon, J., & MCI Working Group of the European Consortium on Alzheimer's Disease (EADC) (2006). Mild cognitive impairment (MCI) in medical practice: a critical review of the concept and new diagnostic procedure. Report of the MCI Working Group of the European Consortium on Alzheimer's Disease. Journal of neurology, neurosurgery, and psychiatry, 77(6), 714–718. https://doi.org/10.1136/jnnp.2005.085332

Roe, C. M., Babulal, G. M., Stout, S. H., Carr, D. B., Williams, M. M., Benzinger, T. L., ... & Morris, J. C. (2018). Using the A/T/N framework to examine driving in preclinical Alzheimer’s disease. Geriatrics, 3(2), 23.

Roe, C. M., Babulal, G. M., Head, D. M., Stout, S. H., Vernon, E. K., Ghoshal, N., ... & Morris, J. C. (2017). Preclinical Alzheimer's disease and longitudinal driving decline.

Alzheimer's & Dementia: Translational Research & Clinical Interventions, 3(1), 74-82.

Roe, C. M., Barco, P. P., Head, D. M., Ghoshal, N., Selsor, N., Babulal, G. M., ... & Morris, J. C. (2017). Amyloid imaging, cerebrospinal fluid biomarkers predict driving performance among cognitively normal individuals. Alzheimer disease and associated disorders, 31(1), 69.

Roe, Catherine M., Sarah H. Stout, Ganesh Rajasekar, Beau M. Ances, Jessica M. Jones, Denise Head, Tammie LS Benzinger et al. (2019) "A 2.5-year longitudinal assessment of naturalistic driving in preclinical Alzheimer's disease." Journal of Alzheimer's Disease 68, no. 4: 1625-1633.

Sachdev, P. S., Lipnicki, D. M., Kochan, N. A., Crawford, J. D., Thalamuthu, A., Andrews, G., ... & Cohort Studies of Memory in an International Consortium. (2015). The prevalence of mild cognitive impairment in diverse geographical and ethnocultural regions: the COSMIC collaboration. PloS one, 10(11), e0142388.

SAE On-road Automated Vehicles Standards Committee. (2021). SAE J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems. Retrieved from: https://www.sae.org/standards/content/j3016_202104/

Scharre, D.W. (2007). Self Administered Gerocognitive Exam. www.sagetest.osu.edu

Scharre, D. W., Chang, S. I., Murden, R. A., Lamb, J., Beversdorf, D. Q., Kataki, M., ... & Bornstein, R. A. (2010). Self-administered Gerocognitive Examination (SAGE): a brief cognitive assessment Instrument for mild cognitive impairment (MCI) and early dementia. Alzheimer Disease & Associated Disorders, 24(1), 64-71.

Scharre, D. W., Nagaraja, H. N., Wheeler, N. C., & Kataki, M. (2021). Self-Administered Gerocognitive Examination: longitudinal cohort testing for the early detection of dementia conversion. Alzheimer's research & therapy, 13(1), 1-11.

Seo, E. H., Kim, H., Lee, K. H., & Choo, I. L. (2016). Altered executive function in pre-mild cognitive impairment. Journal of Alzheimer's Disease, 54(3), 933-940.

Staplin, L., Lococo, K. H., Mastromatto, T., Gish, K. W., Golembiewski, G., Sifrit, K. J., & TransAnalytics, L. L. C. (2019). Mild Cognitive Impairment and Driving

Performance (No. DOT HS 812 577). United States. Department of Transportation. National Highway Traffic Safety Administration.

Stout, S. H., Babulal, G. M., Ma, C., Carr, D. B., Head, D. M., Grant, E. A., ... & Roe, C. M. (2018). Driving cessation over a 24-year period: Dementia severity and cerebrospinal fluid biomarkers. Alzheimer's & Dementia, 14(5), 610-616.

Strogatz, D., Mielenz, T. J., Johnson, A. K., Baker, I. R., Robinson, M., Mebust, S. P., Andrews, H. F., Betz, M. E., Eby, D. W., Johnson, R. M., Jones, V. C., Leu, C. S., Molnar, L. J., Rebok, G. W., & Li, G. (2020). Importance of driving and potential impact of driving cessation for rural and urban older adults. The Journal of Rural Health : Official Journal of the American Rural Health Association and the National Rural Health Care Association, 36(1), 88–93. https://doi.org/10.1111/jrh.12369

Verghese, J., De Sanctis, P., & Ayers, E. (2022). Everyday function profiles in prodromal stages of MCI: Prospective cohort study. Alzheimer's & Dementia.

Vespa, J., Armstrong, D. M., & Medina, L. (2018). Demographic turning points for the United States: Population projections for 2020 to 2060. Washington, DC: US Department of Commerce, Economics and Statistics Administration, US Census Bureau.

Vrkljan, B. H. and Polgar, J. M. (2007). Driving, navigation, and vehicular technology: experiences of older drivers and their co-pilots, Traffic Injury Prevention, (8), 403-410.

Winblad, B., Palmer, K., Kivipelto, M., Jelic, V., Fratiglioni, L., Wahlund, L. O., ... & Petersen, R. C. (2004). Mild cognitive impairment–beyond controversies, towards a consensus: report of the International Working Group on Mild Cognitive Impairment. Journal of internal medicine, 256(3), 240-246.

Wood, J. M., Lacherez, P. F., & Anstey, K. J. (2013). Not all older adults have insight into their driving abilities: evidence from an on-road assessment and implications for policy. The Journals of Gerontology. Series a, Biological Sciences and Medical Sciences, 68(5), 559–66. https://doi.org/10.1093/gerona/gls150

Zahabi, M., Razak, A. M. A., Mehta, R. K., & Manser, M. (2021). Effect of advanced driver-assistance system trainings on driver workload, knowledge, and trust. Transportation research part F: traffic psychology and behaviour, 76, 309-320.

Zhou, J., Benoit, M., & Sharoar, M. G. (2021). Recent advances in pre-clinical diagnosis of Alzheimer's disease. Metabolic Brain Disease, 1-23.

# APPENDIX

## APPENDIX A - Intake Assessment

### Demographic Questions and Background

1) Please specify your gender.
    a. Male
    b. Female
    c. Other: __________________
    d. Prefer Not to Disclose

2) What is your current age? __________

3) What is the year, make and model of your primary vehicle?
    a. Year:___________
    b. Make: ___________
    c. Model:_____________

4) With what ethnicity do you most closely relate yourself?

    a) American Indian/Native American
    b) Asian
    c) Black/African American
    d) Hispanic/Latino
    e) White/Caucasian
    f) Pacific Islander
    g) Other

5) What is your current level of employment?

    a) Employed full time
    b) Employed part time
    c) Self employed
    d) Unemployed/ Looking for work
    e) Homemaker
    f) Student
    g) Retired

6) What is the highest level of education you have completed?

    a) Less Than Middle School/No Education
    b) Middle School
    c) High School/GED
    d) Associate’s Degree

- e) Bachelor's Degree
- f) Master's Degree
- g) Doctoral Degree
- h) Professional Degree

## 2. Memory

**Instructions:** For the next several questions, please compare yourself to 5 years ago.
**Response options: a) Yes b) No.**

7) Are other people telling you that you are more forgetful?
8) Is concentration and focusing more difficult than it was 5 years ago?
9) Are you being told that you are repeating yourself?
10) Do you forget names, where you have left things, or appointments more than 5 years ago?
11) Do you more frequently forget something you have just read compared to 5 years ago?
12) Do you lose your train of thought more frequently in conversation than 5 years ago?
13) Do you feel that you are not as sharp as you were 5 years ago?
14) Are simple everyday tasks like playing cards and balancing a checkbook more difficult than they were 5 years ago?
15) Do you have more trouble recalling words than you did 5 years ago?

## 3. Medical conditions

16) Have you been diagnosed by a doctor or medical professional as having any of the following (please check all that apply)?
    - a) Alzheimer's disease or any other memory disorder
    - b) Arthritis
    - c) Diabetes
    - d) Osteoporosis
    - e) Hearing impairment? (If yes, do you use a hearing aid?)
    - f) Stroke
    - g) Heart attack
    - h) Other serious medical condition

## 4. Current driving

17) How many hours do you estimate you spend driving each week?

a) 0 hrs b)1-5 hrs c) 6-10 hrs d)11-15 hrs e)16-20 hrs f)More than 20 hrs

18) How enjoyable do you find driving?

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|

**Not Enjoyable** **Very Enjoyable**

19) How old were you when you got your first license?

________year/_______age

20) Have any restrictions been placed on your current license? If yes, please specify______________________

21) Do you wear glasses or contact lenses when you drive? a) Yes b) No

22) Do you wear a seatbelt when you drive?

a) Always
b) Sometimes
c) Never

23) Which way do you prefer to get around?

a) Drive yourself
b) Have someone drive you
c) Use public transportation
d) Take a taxi
e) Use a rideshare service (e.g., Uber or Lyft)
f) Walking or Biking
g) Other________________________________

24) How fast do you usually drive compared with the general flow of traffic?

a) Much faster
b) Somewhat slower
c) Somewhat faster
d) Much slower
e) About the same

25) Has anyone suggested over the past year that you limit your driving or stop driving?

a) Yes b) No

26) If yes, who made that suggestion to you? (check all that apply)

a) spouse
b) son/daughter
c) friend
d) physician
e) other health care provider (e.g., physical or occupational therapist)
f) other

27) How would you rate the quality of your driving?

- a) Excellent
- b) Good
- c) Average
- d) Fair
- e) Poor

28) If you had to go somewhere and didn’t want to drive yourself, what would you do?
- a) Ask a friend or relative to drive you
- b) Call a taxi or take the bus
- c) Drive yourself regardless of how you feel
- d) Cancel or postpone your plans and stay at home
- e) Other (specify): ___________________________

## 5. Accidents and Citations

29. How many accidents have you been involved in over the past year when you were the driver? Please list the number of all accidents, whether or not you were at fault.

____ accidents

30. How many accidents have you been involved in over the past year when you were the driver where the police were called to the scene?

____ accidents

31. How many times over the past year have you been pulled over by the police, regardless of whether you received a ticket?

32. ____ times

33. How many times in the past year have you received a moving violation (other than a parking ticket) where you were found to be guilty, regardless of whether or not you think you were at fault?

____ times

## 6. Driving Avoidance

43– 53 How Often Do You Avoid Driving in the following scenarios or conditions?
Response options coded as: always or often avoid it, rarely or never avoid it.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| **Always** | | **Often avoid it** | | **Rarely avoid it** | | **Never avoid it** |

34. At night

35. Alone

36. On interstates or freeways

37. At rush hour or other peak traffic times for safety reasons

38. On busy roads for safety reasons

39. At complex intersections
40. Making unprotected left turns
41. In the rain
42. To places you haven’t been before
43. In the snow
44. In icy conditions
45. Parallel parking