Preventing Crashes in Mixed Traffic with Automated and Human-Driven Vehicles

December 2020 | Final Report

SAFE-D
SAFETY THROUGH DISRUPTION

Texas A&M Transportation Institute

San Diego State University
Leadership Starts Here

VT TRANSPORTATION INSTITUTE
VIRGINIA TECH.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Centers Program. However, the U.S. Government assumes no liability for the contents or use thereof.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. [03-072]	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Preventing Crashes in Mixed Traffic with Automated and Human-Driven Vehicles		5. Report Date November 2020 6. Performing Organization Code:
7. Author(s) Aman Sharma Alireza Talebpour Dominique Lord Sahar Ghanipoor Machiani		8. Performing Organization Report No. Report 03-072
9. Performing Organization Name and Address: Safe-D National UTC Texas A&M Transportation Institute 2935 Research Parkway College Station, TX 77843-3135		10. Work Unit No. 11. Contract or Grant No. 69A3551747115/[03-072]
12. Sponsoring Agency Name and Address Office of the Secretary of Transportation (OST) U.S. Department of Transportation (US DOT) State of Texas		13. Type of Report and Period Final Research Report 14. Sponsoring Agency Code

15. Supplementary Notes

This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program, and, in part, with general revenue funds from the State of Texas.

16. Abstract

Reducing crash counts on saturated road networks is one of the most significant benefits of autonomous vehicle (AV) technology. To date, many researchers have studied how AVs maneuver in different traffic situations, but less attention has been paid to car-following scenarios between AVs and human drivers. Braking and accelerating decision mismatches in this car-following scenario can lead to rear-end near-crashes and therefore warrant further study. This project aims to investigate the behavior of human drivers following an AV leader vehicle in a car-following situation and compare the results with a scenario in which the leader is a vehicle with human-modeled braking behavior. In this study, speed trajectory data was collected from 48 participants using a driving simulator. The results indicated a significant difference between the overall deceleration rates and braking speeds of the participants and the designated AV lead vehicle; however, no such difference was found between the participants and the human-modeled lead vehicle.

17. Key Words Publication, guidelines, report, brochure, communication, marketing		18. Distribution Statement No restrictions. This document is available to the public through the Safe-D National UTC website, as well as the following repositories: VTechWorks, The National Transportation Library, The Transportation Library, Volpe National Transportation Systems Center, Federal Highway Administration Research Library, and the National Technical Reports Library.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 21	22. Price $0

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

Abstract

Reducing crash counts on saturated road networks is one of the most significant benefits of autonomous vehicle (AV) technology. To date, many researchers have studied how AVs maneuver in different traffic situations, but less attention has been paid to car-following scenarios between AVs and human drivers. Braking and accelerating decision mismatches in this car-following scenario can lead to rear-end near-crashes and therefore warrant further study.

This project aims to investigate the behavior of human drivers following an AV leader vehicle in a car-following situation and compare the results with a scenario in which the leader is a vehicle with human-modeled braking behavior. In this study, speed trajectory data was collected from 48 participants using a driving simulator. The results indicated a significant difference between the overall deceleration rates and braking speeds of the participants and the designated AV lead vehicle; however, no such difference was found between the participants and the human-modeled lead vehicle.

Acknowledgements

The authors would like to thank the reviewers for the invaluable comments.

This project was funded by the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.

Table of Contents

List of Figures

List of Tables

Introduction

With a boom in autonomous vehicle (AV) technology over the past few years, predictions have been made about related safety benefits as well as safety risks. The benefits, such as decreasing the human error that accounts for 94% of all total crashes, improved mobility, and fuel savings, support the adoption of AV technology. On the other hand, crashes involving rear-end collisions between non-AVs and AVs developed by Google, Nissan North America, and GM Cruise have recently been reported (*1*). These types of reports have raised doubts about public acceptance of the technology, which in turn has started a chain of AV testing for different scenarios and driving conditions.

Safety studies continue to explore the probability of AV sensor failures that may lead to a complete vehicular failure. Measuring correlations between crashes and the number of AV miles traveled has also been undertaken to investigate the potential risks associated with this technology (*2; 3*). A recent study by Rahmati et al. (*4*) explored the influence of AVs on human drivers' car-following behavior and found a mismatch between AVs' and human drivers' braking decisions at intersections. In response, the authors of this study recognized the potential usefulness of conducting a collision risk analysis of rear-end crashes for a car-following scenario with an AV as the leading vehicle (referred to as the leader or lead vehicle) and a human driver following the AV. Accordingly, this report presents an investigation into the response of human drivers to various AV braking behaviors. The outcome of this study will pave the way towards safer AV braking patterns.

Research Objectives

The objective of this study is to examine participants' braking behavior in a following vehicle behind two different types of lead vehicles (AV vs. human-modeled) while stopping at a stop-controlled intersection.

Background

Almost 90% of fatal crashes in the US involving distracted driving, fatigue, alcohol, or human error. AVs are believed to have the potential to mitigate these problems (14). However, system failure due to faulty hardware or software is often considered a major issue with autonomous or complex electronic systems and the frequency with which these occur these has also been a matter of concern for many researchers (15).

Researchers have also pointed out potential risk compensation or offsetting behavior as a result of AV use, which can be seen in cases where drivers or travelers tend to over-trust the technology, leading to additional risk taking behavior (*16; 17*). The potential threat of crashes due to human drivers joining platoons of AVs has also been identified by a few researchers in the recent past.

An increase in crash exposure due to an increase in total vehicle travel is also thought to be a side effect of greater AV use (*18; 19*).

A recent report by eight companies testing AVs in 2017 for the California Department of Motor Vehicles discussed the issue of disengagements, as humans often had to take over control from the automated driving system (ADS) during critical situations (*20*). Problems such as failure to brake adequately at a stop sign, difficulty in identifying vehicles in opposing lanes, inability to maintain GPS signals, failure to detect items indicating construction zones, and failure to detect a signal saying no right turn on red were identified in the report, as were hardware and software issues (*20*). Designing an AV system that can perform safely in critical situations has also been noted to be a demanding task by several researchers (*21*).

Mixed traffic streams involving human-driven cars and AVs are also seen as a potential safety threat, as AVs often try to merge into traffic with inadequate gaps or space (*20*). These problems have led some researchers to suggest that AVs or ADS-equipped cars might not be safer per mile than an average human driver and might also result in a greater proportion of crashes in mixed traffic streams (*1*). Some researchers also argue that the introduction of AVs would be a benefit for the transport industry if they reduce crash rates by 10%, but would be a concern if total vehicle travel increases (*22*). There are few researchers who support the concept of AVs by calling them "crash-less cars" (*23*).

Researchers have also stressed the lack of sufficient existing crash data for determining AV safety. Recent studies conducted by University of Michigan Transportation Research Institute in 2015 and Virginia Tech Transportation Institute in 2016 found much lower crash rates for AVs with high levels of automation as compared to conventional vehicles. However, these studies also noted the low significance levels of the obtained results due to the small number of crashes involving ADS (*1; 24*). For more accurate results on AV and ADS safety, miles traveled using these technologies must increase proportionally to accurately illustrate their benefits (based on fatality rate and injuries) (*25*).

Understanding Braking Behavior in Critical Events

Human-drivers' braking behavior at stop-controlled intersections has been a frequent topic of study over the last few decades. However, identifying a particular braking profile that leads to comfortable braking before coming to a complete stop has posed serious challenges to researchers. The driver's initial speed significantly affects deceleration and acceleration at stop signs, whereas time-of-day and driver demographics are not statistically significant (*26*). Modeling braking behavior using the coefficient of friction between pavement and car tires has also been used to identify occupants' comfort level during deceleration events (*27*). In addition, some researchers have carried out mathematical modeling of deceleration patterns that closely resemble those of an expert driver in order to achieve comfortable braking (*28*).

Despite the work in this area, there is still no single agreed upon threshold value accurately depicting a deceleration event. A threshold deceleration rate of 0.3 g (i.e., 2.94 m/s^2) is believed to depict emergency braking, and a rate of 2 m/s^2 depicts comfortable braking (*27; 29; 30*). The American Association of State Highway Transportation Officials sets the threshold deceleration rate at 3.4 m/s^2 for comfortable braking (*31*). To study emergency braking, learning about a vehicle's maximum deceleration is important. Kudarauskas (*32*) studied emergency braking and maximum longitudinal deceleration a_{xn} based on the adhesion of a vehicle's tires to the pavement coating. An emergency braking rate of 0.7 g was assumed by Anderson et al. (*33*) while studying the effectiveness of autonomous emergency braking systems. In a previous study by Glassco and Cohen (*34*), a braking level of 0.75 g was used as a warning trigger during critical events in urban driving scenarios. Recently, De Ceunynch (*35*) considered a maximum deceleration rate of 8 m/s^2 to be a conservative rate that all vehicles could achieve. Cunto (*36*), however, believed that a vehicle could achieve a braking rate of 12.7 m/s^2, which was later considered to be a radical value. As these conflicting studies show, a single maximum deceleration value during critical events and emergency braking is still not agreed upon.

Method

Driving Simulator Setup

Figure 1 shows the equipment and the driving simulator setup used in this study. The simulator was composed of a 49-inch ultra-wide curved monitor display with a resolution of 3,840 x1,080 pixels, gas/brake pedals from Logitech, and a Sony PlayStation steering wheel, which was in full accordance with a real vehicle. The curved monitor displayed a speedometer indicating the driving speed in mph. The experiment setup did not provide participants with any rear-view mirrors or gearbox. No car engine or environmental surroundings sounds were played during the experiment. Additional details of the driving simulator study can be found in the first author's thesis (5).

Experiment Design

Two car-following scenarios were designed using Unity-3D software to test participants' car-following driving behavior. The test road was set up with a straight alignment and a length of 4,000 m (2.48 miles). The test road with two lanes, one for each direction, was separated by two parallel solid yellow lines to restrict participants from overtaking the lead vehicle (see Figure 2). Eight stop-controlled intersections were arranged on the test segment, each of which was uniformly placed at 500 m apart. The speed limit during the entire segment was set at 30 mph. To adequately test the driving behavior of participants on the test segment during car-following, no other traffic was present on the road. Two similar car-following scenarios were designed, with the only difference being the assignment of the lead vehicle's speed profile in each scenario. The design and assignment of speed profiles are discussed below.

Figure 1. Driving simulator setup.

Figure 2. Lead vehicle in car-following scenario.

Designing Speed Profiles

A total of eight different speed profiles for two kinds of leading vehicle (AV leader and human-modeled leader) were tested in this study. Each car-following scenario tested four different leading vehicle speed profiles. The characteristics of the speed profiles used in the two test scenarios are explained below.

AV Leader (AV-HUMAN scenario)

Four-speed profiles with four different types of constant deceleration profiles—1 m/s^2, 2.25 m/s^2, 2.75 m/s^2 and 3.25 m/s^2—were manually designed (see Figure 3). The profiles shared a common acceleration rate of 0.5 m/s^2 to depict a safe driving pattern by the designated AV leader. The speed profiles were split into three periods:

- **Period 1:** The lead car accelerated at 0.5 m/s^2 until reaching 30 mph.
- **Period 2:** The lead car maintained a constant speed of 30 mph.
- **Period 3:** The lead car decelerated at a stop-controlled intersection at an assigned deceleration rate of either 1 m/s^2 or 2.25 m/s^2 or 2.75 m/s^2 or 3.25 m/s^2, respectively.
- **Period 4:** The lead car stopped for 3 seconds after coming to a full stop and then accelerated again.

The speed profiles were assigned names based on their respective deceleration rates; i.e., C-1 means that the designated AV leader would decelerate at a constant deceleration rate of 1 m/s^2 and so on. Periods 1, 2, and 4 were kept the same for these four speed profiles, as shown in Figure 3. The only change was in Period 3, where the designated AV leader decelerated according to the assigned deceleration rate. The designated AV leader's maximum speed was limited to 30 mph, which was equal to the posted speed limit.

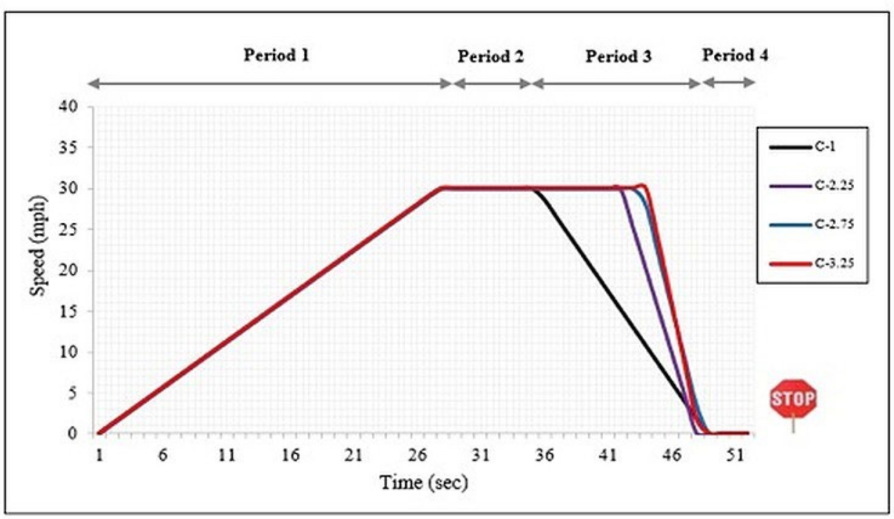

Figure 3. Four speed profiles for designated AV leader.

Table 1. Key Features of Designated AV Leader Speed Profiles

Features	C-1	C-2.25	C-2.75	C-3.25
Avg. Speed (mph)	15.97	17.67	18.30	18.33
Max. Speed (mph)	30.00	30.00	30.00	30.00`
Min. Speed (mph)	0.00	0.00	0.00	0.00
Avg. Acceleration (m/s2)	0.50	0.50	0.50	0.50
Max. Acceleration (m/s2)	0.50	0.50	0.50	0.50
Min. Acceleration (m/s2)	0	0	0	0
Avg. Deceleration (m/s2)	-0.96	-1.92	-2.24	-2.68
Max. Deceleration (m/s2)	-1.00	-2.25	-2.75	-3.25
Min. Deceleration (m/s2)	-0.60	-0.06	-0.85	-0.77

Note: C-1 refers to speed profile with constant deceleration rate of 1 m/s^2; C-2.25 refers to speed profile with constant deceleration rate of 2.25 m/s^2; C-2.75 refers to speed profile with constant deceleration rate of 2.75 m/s^2; and C-3.25 is the speed profile with constant deceleration rate of 3.25 m/s^2.

HUMAN-modeled Leader (Human-Human scenario)

To create a human-modeled leader in the other car-following situation, four experienced drivers (two males and two females) were asked to drive on the test segment without any other traffic on the road. Their respective driving speeds were used to create four different speed profiles resembling their braking and acceleration behaviors. These drivers had at least 5 years of driving experience and a mean age of 25 years. Figure 4 illustrates the driving speeds of each profile before stopping at the first stop-controlled intersection. The researchers considered gathering human driver behavior from the Safety Pilot data set but found that it did not include information about lead vehicle presence, and so could not be applied to the current study. The accuracy of the GPS used in the Safety Pilot also limited its utility for determining acceleration.

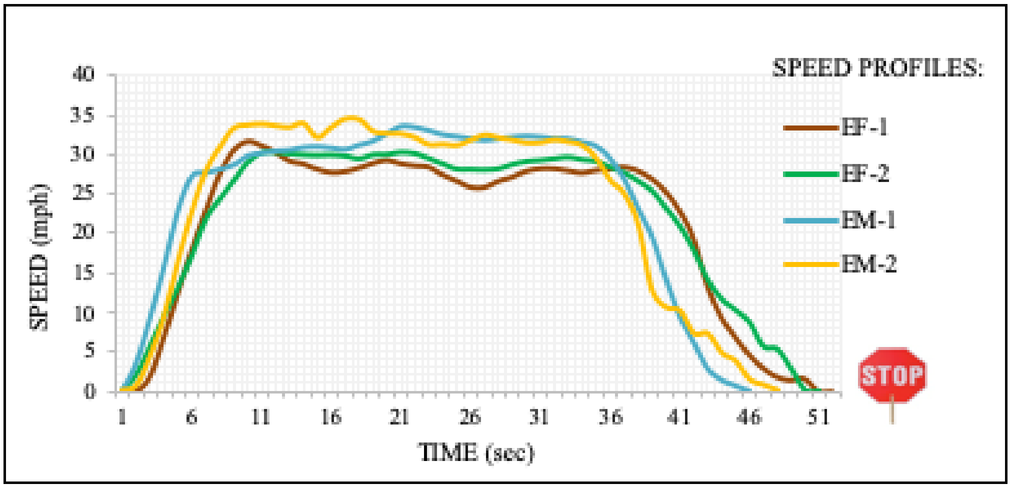

Figure 4. Four speed profiles of human-modeled leader. Note: EF-1 refers to experienced female driver profile 1; EF-2 refers to experienced female driver 2 profile; EM-1 refers to experienced male driver 1 profile, and EM-2 is the experienced male driver 2 speed profile.

Table 2. Key Features of Speed Profiles

Feature	EF-1	EF-2	EM-1	EM-2
Avg. Speed (mph)	20.75	21.91	24.33	23.28
Max. Speed (mph)	31.70	30.40	33.51	34.47
Min. Speed (mph)	0.00	0.00	0.00	0.00
Avg. Acceleration (m/s2)	0.41	0.42	0.50	0.46
Max. Acceleration (m/s2)	2.48	2.07	3.16	3.08
Min. Acceleration (m/s2)	0.03	0.03	0.03	0.03
Avg. Deceleration (m/s2)	-0.63	-0.74	-0.90	-0.89
Max. Deceleration (m/s2)	-2.68	-1.68	-2.38	-3.73
Min. Deceleration (m/s2)	-0.02	-0.02	-0.02	-0.02

Car Following Scenarios

Scenario 1: AV-HUMAN

In this scenario, the AV leader drove in front of the participants' vehicle based on the designed driving speeds in the four profiles (C-1, C-2.25, C-2.75, and C-3.25), as discussed in the previous section. A total of 24 participants (12 males and 12 females) were asked to follow the AV leader on the driving simulator. Each speed profile was assigned to the AV leader for one intersection and was then switched to a different profile for the next intersection. In this manner, the four-speed profiles were tested twice on a total of eight stop-controlled intersections. The complete speed profile of the AV leader during the experiment is shown in Figure 5. The AV leader's assigned speed profile for each intersection is shown in Table 3.

Table 3. AV Leader Speed Profile Assignment at Each Intersection

Intersection	Leader's Assigned Speed Profile
#1	C-1
#2	C-3.25
#3	C-2.25
#4	C-1
#5	C-2.75
#6	C-3.25
#7	C-2.25
#8	C-2.75

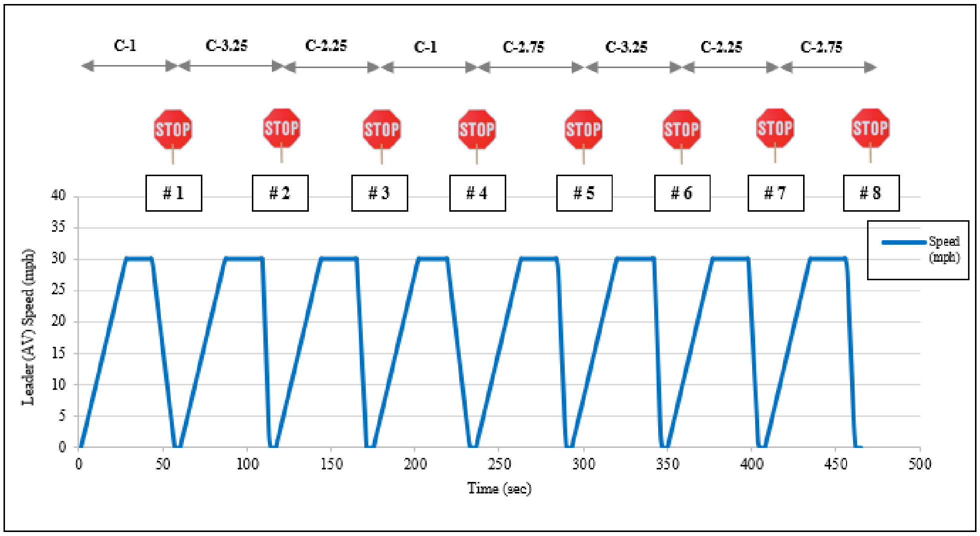

Figure 5. AV leader speed profile in scenario 1.

Scenario 2: HUMAN-HUMAN

In this scenario, the lead car was assigned with four-speed profiles modeled from four experienced human drivers (EF-1, EF-2, EM-1, and EM-2), as discussed in the previous section. A new set of participants (12 males and 12 females) were asked to follow the lead car (human-modeled) on the driving simulator. Except for the lead car's (human-modeled) speed profiles at each intersection, all other conditions were unchanged in this scenario. The speed profile of the human-modeled lead car during the experiment can be seen in Figure 6. The lead car's assigned speed profile for each intersection is shown in Table 4.

Table 4. Human-modeled Leader Speed Profile Assignment at Each Intersection

Intersection	Leader's Assigned Speed Profile
#1	EF-1
#2	EM-1
#3	EM-2
#4	EF-2
#5	EM-1
#6	EF-1
#7	EF-2
#8	EM-2

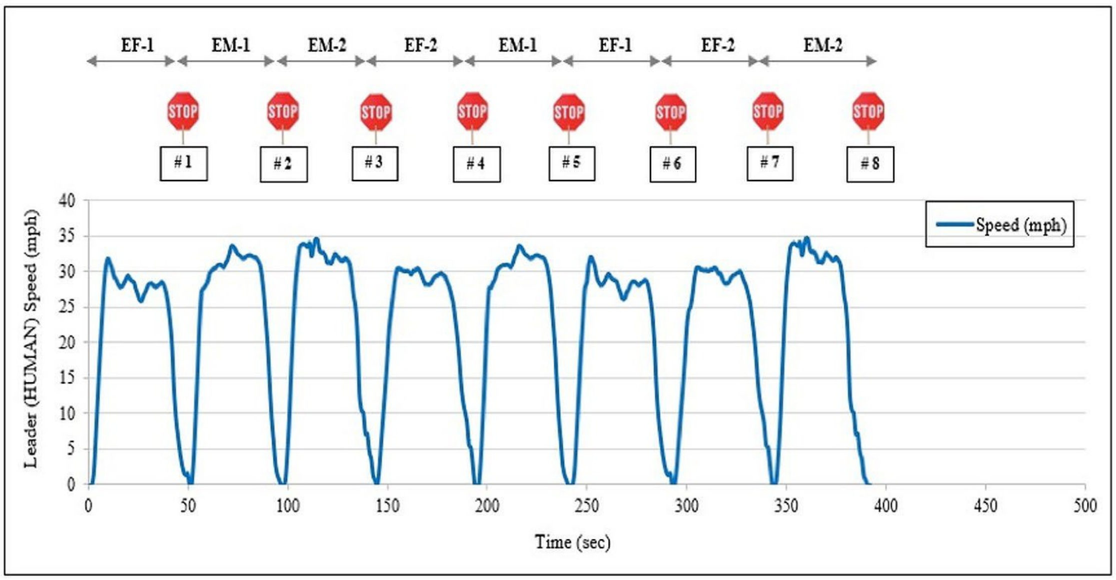

Figure 6. Human-modeled leader's speed profile in scenario 2.

Data Collection

In this experiment, a total of 48 participants (24 males and 24 females) were recruited through a recruitment email per Institutional Review Board guidelines. Each participant had to be between 18 and 30 years of age, was required to hold a valid US driver's license, and have at least 1 year of driving experience. The participants were compensated $25 USD for their participation after completing the experiment. For the first scenario, the average age of the participants was 24.8 years, and the standard deviation was 2.43 years. For the second scenario, the average age of the participants was 25.3 years, and the standard deviation was 2.12 years.

Experiment Procedure

Upon arrival, each participant signed an informed consent form and completed a pre-test questionnaire. The pre-test questionnaire asked participants about their age, gender, years of driving experience, and any visual impairments. Participants were also checked to ensure they had valid permanent US driving license. Participants were then given a short introduction to the controls and functions of the driving simulator. All participants were given at least a 5-minute trial run on the driving simulator to gain familiarity with the setup and learn about the driving environment. After being familiarized with the simulator, participants were given no strict instructions which could potentially influence their driving behavior during the experiment. They were instructed only to "always be behind the lead vehicle." Participants were not given any information about the purpose of the experiment. Each participant was randomly assigned to one of the two car-following scenarios—AV-HUMAN or HUMAN-HUMAN. No participant took part in both test scenarios to minimize the risk of bias in driving behavior. In each scenario, the subject's vehicle (i.e., following vehicle) was initially kept at 6 m from the lead car to allow safe speeding. A speed limit sign with a posted speed limit of 30 mph was also visible to participants before starting the experiment. Once the simulation began, participants could watch their driving speeds on the on-screen speedometer and were allowed to choose their speed.

Variables Recorded

The simulator allowed researchers to record the time taken by each participant to complete the experiment, the following vehicle's lateral and longitudinal position, following and lead vehicle speeds, and the input of accelerator/brake pedals. The clearance between vehicles—the distance from the front bumper of the following vehicle to the rear bumper of the lead vehicle—was also recorded in the output file. The simulator captured the driving data every 1 second.

The applied pressure on the accelerator and brake pedal ranged between -1 to +1 where -1 meant maximum possible brake application and +1 meant maximum possible acceleration input. The maximum deceleration rate was set to 0.81 g or -8 m/s^2 and the maximum achievable acceleration was set to +3 m/s^2.

Results and Discussion: AV-Human

Descriptive Analysis

Table 5 presents the descriptive statistics of the measured variables. Table 5 shows a high standard deviation in the average speed of the participants and the AV leader. During the experiment, participants were slightly slower than the AV leader. The AV leader reached a maximum speed of 30 mph; the maximum speed recorded from a participant was 47.65 mph. The analysis revealed a considerable average clearance of 24.64 m between participants in the following vehicle and the AV leader. On some occasions, participants did achieve the maximum acceleration rate of +3 m/s^2 as compared to the +1 m/s^2 acceleration of the AV leader. Similarly, participants occasionally applied emergency brakes (deceleration rate of -8 m/s^2) while performing braking maneuvers at the intersections.

Table 6 shows the correlation matrix of the five measured variables. The correlation test on measured variables showed a serious (uphill) positive correlation of +0.85 between participants' and the AV leader's average speed. In other words, an increase in the AV leader's speed resulted in a higher following vehicle speed in this car-following scenario. Due to this serious correlation, the AV leader speed variable was omitted from the analysis and the relative speed variable was introduced. Table 7 shows that the serious correlation among measured variables was eliminated, as no variable shared a significant correlation.

Table 5. Descriptive Statistics of Measured Variables

Variables	Units	N (number of observed instances)	Mean	Std. Dev.	Min.	Max.
Ego Speed	mph	10934	18.48	11.21	0	47.65
Leader Speed	mph	10934	19.20	10.88	0	30.00
Clearance	m	10934	24.64	23.36	-6.77	135.53
Ego Acc./Dec.	m/s2	10934	-0.17	1.04	-8.00	3.00
Leader Acc./Dec.	m/s2	10934	0.02	0.79	-3.25	1.00

Table 6. Correlation Matrix of Measured Variables

Variables	Ego Speed	Leader Speed	Ego Acc./Dec.	Leader Acc./Dec.	Clearance
Ego Speed	1.00	0.85	0.18	-0.30	0.32
Leader Speed	0.85	1.00	0.28	-0.10	0.33
Ego Acc./Dec.	0.18	0.28	1.00	0.29	0.15
Leader Acc./Dec.	-0.30	-0.10	0.29	1.00	-0.17
Clearance	0.32	0.33	0.15	-0.17	1.00

Table 7. Correlation Matrix of Measured Variables

Variables	Ego Speed	Relative Speed	Ego Acc./Dec.	Leader Acc./Dec.	Clearance
Ego Speed	1.00	0.32	0.18	-0.30	0.32
Relative Speed	0.32	1.00	-0.16	-0.38	0.00
Ego Acc./Dec.	0.18	-0.16	1.00	0.29	0.15
Leader Acc./Dec.	-0.30	-0.38	0.29	1.00	-0.17
Clearance	0.32	0.00	0.15	-0.17	1.00

Participants' Braking Behavior

Analysis of 192 average speed profiles from 24 participants (12 males and 12 females) depicted how participants began to decelerate or brake before coming to a stop at 8 stop-controlled intersections. Table 7 illustrates a mismatch in the braking patterns of 24 participants and the lead AV as participants decelerated to slow speeds of approximately 5 mph and then slowly stopped at the stop-sign. Two-sample t-test also indicated a significant difference in the overall deceleration rates of participants and the AV leader with a two-tailed p-value of 0.04 ($t = 2.10$, std. error = 0.286) at the significance level of 5%.

Figure 8 presents a comparison between the average deceleration behavior of 24 participants behind the AV leader at 8 stop-controlled intersections. Participants demonstrated very similar late braking characteristics when following the AV leader with C-2.25, C-2.75, and C-3.25 profiles. However, participants made more gradual and smooth braking maneuvers when the AV leader decelerated at 1 m/s^2 (at C-1 profile).

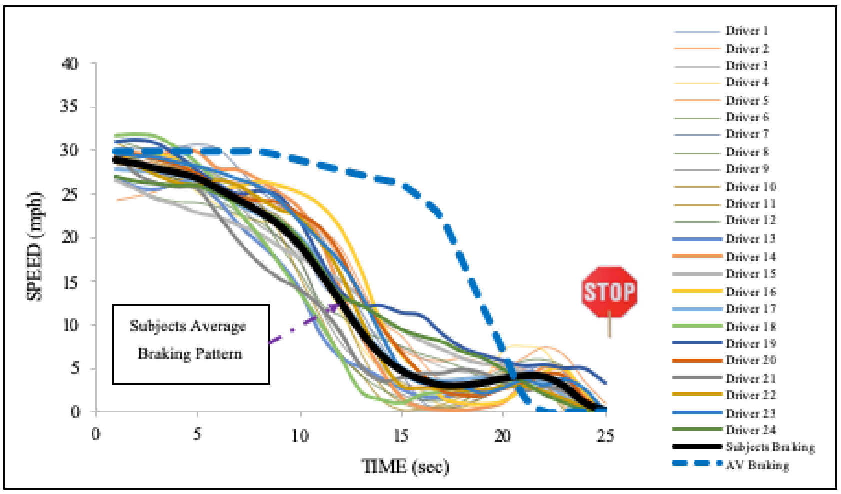

Figure 7. Participants average braking speeds behind AV leader.

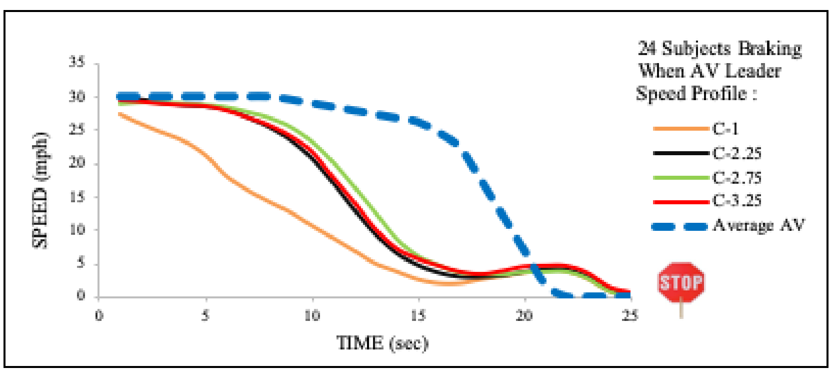

Figure 8. Participants average braking speeds vs AV leader speed profiles.

Figure 9 shows participants' braking speeds based on the speed profile of the AV leader. The figure shows that participants were likely to brake in a similar way as the AV leader. Table 8 summarizes the results from the two-sample t-test comparing the participants' means and AV deceleration rates based on each profile. This table indicates that there was no significant difference in the braking rates between the human follower and the corresponding AV (significant difference was found among the human followers' behavior in different scenarios). Therefore, the t-tests revealed a mismatch during the braking maneuvers only, as based on participant and AV leader approach speeds.

Figure 10 shows that the participants started decelerating from 30 m (approx.) to 8 m (approx.) in ~15 s behind the AV leader at the stop sign. The average clearance maintained by the participants during the braking maneuvers was nearly identical.

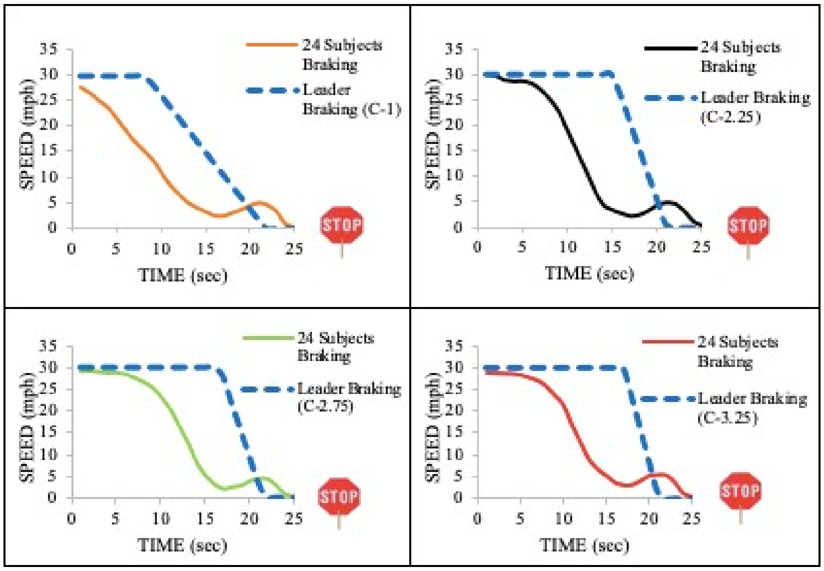

Figure 9. Participant braking vs AV leader profile.

Table 8. Two-Sample T-Tests Results of Participants and AV Leader Deceleration Rates (measured in m/s^2)

Comparison Pairs	Mean	Std. Dev.	t-value	p-value	Different (p < 0.05)
Participants	-0.49	0.46	0.32	0.74	No
Leader (C-1)	-0.53	0.49	0.32	0.74	No
Participants	-0.54	0.68	0.02	0.98	No
Leader (C-2.25)	-0.53	0.94	0.02	0.98	No
Participants	-0.52	0.68	0.05	0.95	No
Leader (C-2.75)	-0.54	1.04	0.05	0.95	No
Participants	-0.51	0.67	0.06	0.94	No
Leader (C-3.25)	0.54	1.18	0.06	0.94	No

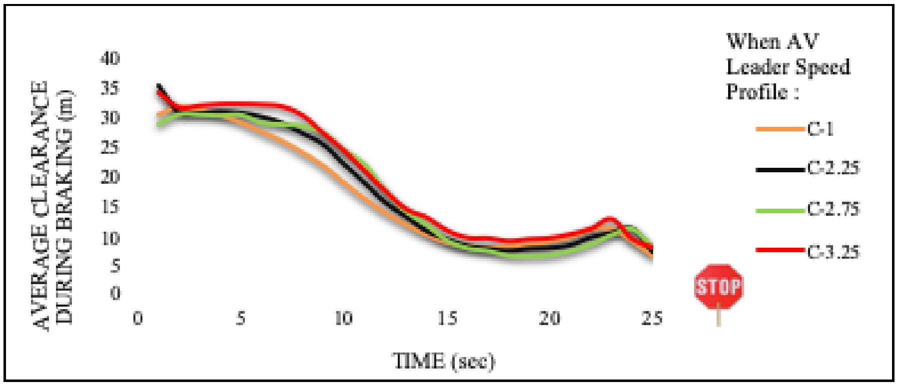

Figure 10**. Average clearance between participants and AV leader during braking based on speed profiles.**

Results and Discussion: Human-Human

The section presents results based on the driving behavior of 24 participants using the methodology discussed in the previous section.

Descriptive Analysis

Table 9 shows that the participants' and human-modeled leader's average speeds—21.36 mph and 22.11 mph, respectively—were not significantly different from each other. The following vehicle rarely traveled more than 45 mph, with a maximum speed of 63.45 mph. In this car-following situation, participants maintained an average clearance of 46.06 m with the human-modeled leader. The clearance histogram illustrates a decreasing trend (towards the right) as the clearance increases from 20 m to 140 m. In contrast to the previous scenario, the average speed of participants and that of the human-modeled leader share a moderate upward relationship with a correlation coefficient of 0.50. Table 10 shows that no other variable pair shared a high correlation.

Table 9. Descriptive Statistics of Measured Variables.

Variables	Units	N (Number of observed instances)	Mean	Std. Dev.	Min.	Max.
Ego Speed	mph	8093	21.36	13.23	0.00	63.45
Leader Speed	mph	8093	22.11	11.31	0.00	34.58
Clearance	m	8093	46.06	37.35	-1.70	139.94
Ego Acc./Dec.	m/s2	8093	-0.31	1.49	-8.00	3.00
Leader Acc./Dec.	m/s2	8093	0.00	1.23	-8.00	3.00

Table 10. Correlation Matrix of Measured Variables.

Variables	Ego Speed	Leader Speed	Clearance	Ego Acc./Dec.	Leader Acc./Dec.
Ego Speed	1.00	0.50	0.37	0.14	-0.31
Leader Speed	0.50	1.00	0.42	0.24	-0.13
Clearance	0.37	0.42	1.00	0.27	-0.23
Ego Acc./Dec.	0.14	0.24	0.27	1.00	0.09
Leader Acc./Dec.	-0.31	-0.13	-0.23	0.09	1.00

Participants' Braking Behavior

Participants' braking behavior behind the human-modeled leader, as shown in Figure 11, does not reveal any potential mismatch while stopping at the intersection. Also, the results from two-sample t-tests on participants' braking speed and the human-modeled leader in Table 11 show no significant difference at the significance level of 5% ($t = 0.19$; p-value = 0.85). This finding seems realistic in general, as the human-modeled leader in this scenario was designed with speed profiles extracted from actual human drivers. Thus, a similarity in the braking behavior of the human-modeled leader and the participants would be expected. Participants' braking behind the human-modeled leader with the assigned EM-1 profile (green curve) were driving at a high speed before making the braking maneuver. This high speed might be the reason behind participants' high average deceleration rate (-1.76 m/s^2) in the last 18 seconds of approaching the stop-sign.

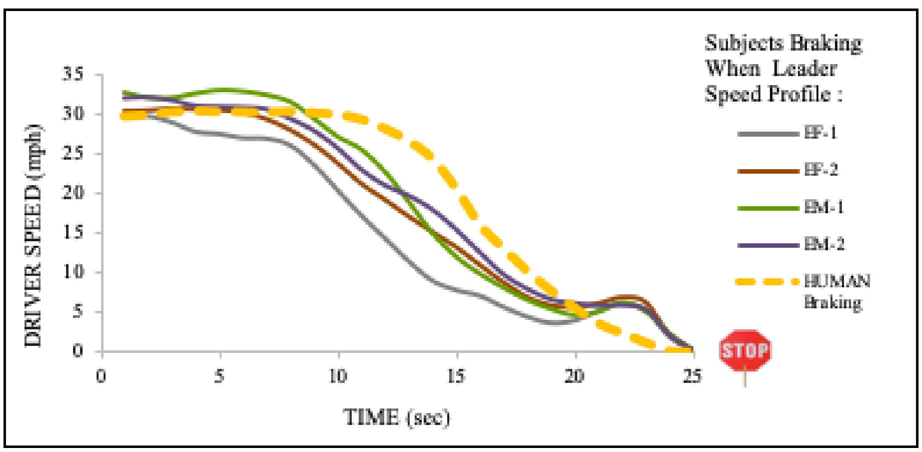

Figure 11. Participants' braking speeds based on human-modeled leader speed profiles.

Table 11. Two-Sample T-Tests Results of Participants and AV Leader Deceleration Rates (measured in m/s^2)

Comparison Pairs	Mean	Std. Dev.	t-value	p-value	Different ($p < 0.05$)
Participants	-0.53	0.53	0.31	0.75	No
Leader (EF-1)	-0.47	0.73	0.31	0.75	No

Comparison Pairs	Mean	Std. Dev.	t-value	p-value	Different (p < 0.05)
Participants	-0.54	0.56	0.22	0.82	No
Leader (EF-2)	-0.50	0.57	0.22	0.82	No
Participants	-0.59	0.64	0.03	0.97	No
Leader (EM-1)	-0.59	0.76	0.13	0.89	No
Participants	-0.58	0.49	0.13	0.89	No
Leader (EM-2)	-0.56	0.85	0.13	0.89	No

Figure 12 illustrates the average clearance maintained by participants during the braking maneuver based on the speed profile of the human-modeled leader. Participants maintained a greater clearance from the human-modeled leader with EM-1 and EM-2 assigned speed profiles. However, the figure depicts relatively close clearance measurements for EF-1 and EF-2 leader profiles. A gradual application of brakes leading to a more gradual decline in the clearance values was also observed.

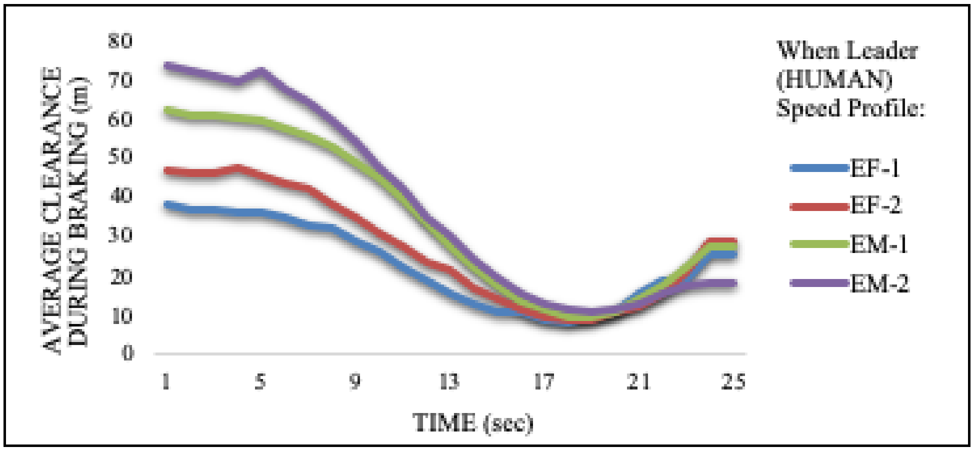

Figure 12. Average clearance between participants and human-modeled leader based on test speed profiles.

Conclusions and Recommendations

This section provides the key summary conclusions of this research and provides further recommendations. Note that the conclusions and recommendations are based on all the findings of this study and not only the contents of this report.

Summary of Key Results

This research provides valuable insights into different aspects of human driving behavior in two different car-following scenarios using a Unity-based driving simulator. Understanding how participants decelerate behind two different types of leading vehicle (AV and human-modeled) at stop-controlled intersections and how quickly they accelerate after stopping were the key objectives of this study. Performing risk analysis by detecting near-crashes in car-following scenarios using six popular Surrogate Safety Measures was another vital aspect of this study.

The results from braking behavior analysis indicated a mismatch in the overall braking pattern of the 24 participants and the AV leader. Conversely, two-sample t-tests did not yield any significant difference in the braking behavior of 24 participants and the human-modeled leader.

After stopping at the stop-controlled intersection, participants accelerated at faster rates while following the human-modeled leader due to a greater available clearance. Results from two-sample t-tests indicated a mismatch in the acceleration rates of 24 participants (1.25 m/s2) and that of the AV leader (0.5 m/s2) at the significance level of 5%. However, there was no such mismatch in the scenario when the participants accelerated behind the human-modeled leader.

Recommendations

This study recommends that researchers test different types of car-following behaviors between an AV and a human driver. This study involved the participation of 48 human participants; research with a larger sample size could further validate the findings from this study. The research demonstrates the changes in driver behavior when following an AV; designers of forward-collision warning systems might take the results found here into account to achieve safer near-crash avoidance systems. To further assess this, designing more car-following scenarios on driving simulators and in real-world environments will provide validation of this study's findings.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project are described below and are listed on the Safe-D website here. The final project dataset is unavailable for upload to Safe-D Dataverse due to the departure of the PI and student in December 2019.

Education and Workforce Development Products

A total of three PhD students and one MS student were involved in this project. The project resulted in three submitted papers (under review in *Transportation Research Part C* and *Accident Analysis and Prevention*) and one presentation at the 98th Annual Meeting of the Transportation Research Board (TRB) in January 2019. One MS thesis was also generated as part of this study.

Technology Transfer Products

The Principal Investigators (PIs) presented the findings of this study to General Motors, NIO, and the Army Research Lab (ARL). Moreover, the PIs will present the findings from the project at the IEEE ITSC 2019 Conference and TRB 2020 workshops.

Data Products

Driving simulator data from 48 participants was collected as part of this project. This dataset contains the time taken by each participant to complete the experiment, the ego vehicle's lateral and longitudinal position, ego and lead vehicle speeds, and finally the input of accelerator/brake pedals. The clearance between vehicles—i.e., the distance from the front bumper of the following vehicle to the rear bumper of the leading vehicle—was also recorded in the output file. The simulator captured the driving data every 1 second.

The applied pressure on the accelerator and brake pedal ranged between -1 to +1 where -1 meant maximum possible brake application and +1 meant maximum possible acceleration input. The maximum deceleration rate was set to 0.81g or -8 m/s^2 and the maximum achievable acceleration to +3 m/s^2.

References

[1] Schoettle, B., and M. Sivak. A preliminary analysis of real-world crashes involving self-driving vehicles. University of Michigan Transportation Research Institute, 2015.

[2] Das, P. Risk analysis of autonomous vehicle and its safety impact on mixed traffic stream. 2018.

[3] Favarò, F. M., N. Nader, S. O. Eurich, M. Tripp, and N. Varadaraju. Examining accident reports involving autonomous vehicles in California. PLoS one, Vol. 12, No. 9, 2017, p. e0184952.

[4] Rahmati, Y., A. S. Abianeh, A. Talebpour, and F. Sharifi. Driving to Safety: Who Is at Fault in CAVs Rear-End Collisions?In 98th Annual Meeting of the Transprotation Research Board, Washington D.C., 2019.

[5] Sharma, A. Analyzing Crash Potential in Mixed Traffic With Autonomous and Human-Driven Vehicles.In Civil and Environmental Engineering, No. Master of Science, Texas A&M University 2019.

[6] Dickmanns, E. D., and A. Zapp. Autonomous high speed road vehicle guidance by computer vision. IFAC Proceedings Volumes, Vol. 20, No. 5, 1987, pp. 221-226.

[7] Dickmanns, E. D., R. Behringer, D. Dickmanns, T. Hildebrandt, M. Maurer, F. Thomanek, and J. Schiehlen. The seeing passenger car'VaMoRs-P'.In Proceedings of the Intelligent Vehicles' 94 Symposium, IEEE, 1994. pp. 68-73.

[8] Pomerleau, D. A. Alvinn: An autonomous land vehicle in a neural network.In Advances in neural information processing systems, 1989. pp. 305-313.

[9] Thrun, S., M. Montemerlo, H. Dahlkamp, D. Stavens, A. Aron, J. Diebel, P. Fong, J. Gale, M. Halpenny, and G. Hoffmann. Stanley: The robot that won the DARPA Grand Challenge. Journal of field Robotics, Vol. 23, No. 9, 2006, pp. 661-692.

[10] The DARPA Grand Challenge: Ten Years Later, Defense Advanced Research Projects Agency (DARPA). https://www.darpa.mil/news-events/2014-03-13 Accessed 2/17/2019.

[11] Burns, L. D. Sustainable mobility: a vision of our transport future. Nature, Vol. 497, No. 7448, 2013, p. 181.

[12] Marks, P. Autonomous cars ready to hit our roads. New Scientist, Vol. 213, No. 2858, 2012, pp. 19-20.

[13] Faisal, A., T. Yigitcanlar, M. Kamruzzaman, and G. Currie. Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy. Journal of Transport and Land Use, Vol. 12, No. 1, 2019, pp. 45-72.

[14] Fagnant, D. J., and K. Kockelman. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, Vol. 77, 2015, pp. 167-181.

[15] Litman, T. Autonomous vehicle implementation predictions. Victoria Transport Policy Institute Victoria, Canada, 2017.

[16] Ackerman, E. Toyota's Gill Pratt on self-driving cars and the reality of full autonomy. IEEE Spectrum, Vol. 23, 2017.

[17] Millard-Ball, A. Pedestrians, autonomous vehicles, and cities. Journal of Planning Education and Research, Vol. 38, No. 1, 2018, pp. 6-12.

[18] Dawson, C. Your Next Car May Be a Living Room on Wheels. Wall Str. J.

[19] Trommer, S., V. Kolarova, E. Fraedrich, L. Kröger, B. Kickhöfer, T. Kuhnimhof, B. Lenz, and P. Phleps. Autonomous driving-the impact of vehicle automation on mobility behaviour. 2016.

[20] Edelstein, S. California Reports Highlight Issues With Self-Driving Cars The Drive. http://thedrive.com/tech/20561/california-reports-highlight-autonomous-cars-shortcomings. Accessed 2/26/2019.

[21] Campbell, M., M. Egerstedt, J. P. How, and R. M. Murray. Autonomous driving in urban environments: approaches, lessons and challenges. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, Vol. 368, No. 1928, 2010, pp. 4649-4672.

[22] Kalra, N., and D. G. Groves. The enemy of good: Estimating the cost of waiting for nearly perfect automated vehicles. Rand Corporation, 2017.

[23] KPMG and CAR (2012) Self-Driving Cars: The Next Revolution. Ann Arbor, MI.

[24] Blanco, M., J. Atwood, S. Russell, T. Trimble, J. McClafferty, and M. Perez. Automated vehicle crash rate comparison using naturalistic data.In, Virginia Tech Transportation Institute, 2016.

[25] Kalra, N., and S. M. Paddock. Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability? Transportation Research Part A: Policy and Practice, Vol. 94, 2016, pp. 182-193.

[26] Haas, R., V. Inman, A. Dixson, and D. Warren. Use of intelligent transportation system data to determine driver deceleration and acceleration behavior. Transportation research record, Vol. 1899, No. 1, 2004, pp. 3-10.

[27] Wu, Z., Y. Liu, and G. Pan. A smart car control model for brake comfort based on car following. IEEE transactions on intelligent transportation systems, Vol. 10, No. 1, 2008, pp. 42-46.

[28] Wada, T., S. i. Doi, N. Tsuru, K. Isaji, and H. Kaneko. Formulation of braking behaviors of expert driver toward automatic braking system.In 2008 IEEE International Conference on Mechatronics and Automation, IEEE, 2008. pp. 89-94.

[29] Miyajima, C., H. Ukai, A. Naito, H. Amata, N. Kitaoka, and K. Takeda. Driver risk evaluation based on acceleration, deceleration, and steering behavior.In 2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), IEEE, 2011. pp. 1829-1832.

[30] Naito, A., C. Miyajima, T. Nishino, N. Kitaoka, and K. Takeda. Driver evaluation based on classification of rapid decelerating patterns.In 2009 IEEE International Conference on Vehicular Electronics and Safety (ICVES), IEEE, 2009. pp. 108-112.

[31] Maurya, A. K., and P. S. Bokare. STUDY OF DECELERATION BEHAVIOUR OF DIFFERENT VEHICLE TYPES. International Journal for Traffic & Transport Engineering, Vol. 2, No. 3, 2012.

[32] Kudarauskas, N. Analysis of emergency braking of a vehicle. Transport, Vol. 22, No. 3, 2007, pp. 154-159.

[33] Anderson, R., S. Doecke, J. Mackenzie, and G. Ponte. Potential benefits of autonomous emergency braking based on in-depth crash reconstruction and simulation.In Proceedings of the 23rd International Conference on Enhanced Safety of Vehicles, US National Highway Traffic Safety Administration, Washington DC, 2013.

[34] Glassco, R., and D. Cohen. Collision avoidance warnings approaching stopped or stopping vehicles.In 8th World Congress on Intelligent Transport SystemsITS America, ITS Australia, ERTICO (Intelligent Transport Systems and Services-Europe), 2001.

[35] De Ceunynck, T. Defining and applying surrogate safety measures and behavioural indicators through site-based observations. Hasselt University, 2017.

[36] Cunto, F. Assessing safety performance of transportation systems using microscopic simulation. 2008.