Investigation of Key Automated Vehicle Human Factors Safety Issues Related to Infrastructure: Comparing Intersection Crossing Behaviors of Human Drivers and Automated Vehicles

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike McLean, VA 22101-2296

Turner-Fairbank
Highway Research Center

FOREWORD

Cooperative driving automation (CDA) applications at signalized intersections have the potential to benefit vehicles equipped with automated driving systems and cooperative-automated driving systems by supporting them during intersection approaches. A few recent proof-of-concept studies showed that this CDA technology leads to smoother transitions within intersection approaches and fewer delays, and as a result, less energy consumption and better traffic patterns overall.

This report documents a field study on the effect of an in-vehicle signal countdown timer on the intersection approaching behavior and decision-making of human drivers and compare human responses to this information with the approaching behavior of automated shuttles. This report may interest personnel at State and local transportation agencies who plan to evaluate the impact of signal countdown timers on intersection crossing behaviors and traffic flow at signalized intersections and the efficacy of CDA as part of roadway infrastructure.

John A. Harding
Director, Office of Safety and Operations,
Research and Development

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16. Abstract
This study examined the degree to which an in-vehicle signal countdown timer influenced human drivers' intersection approaching behaviors and decisionmaking. Secondarily, the study compared intersection approaching behaviors between human drivers and automated shuttles. The research team further simulated predicted behaviors of human drivers at lower speeds and predicted behaviors of shuttles at higher speeds. The results indicated that the presence of the signal countdown timer information regulated human drivers' speed and acceleration within the approach zone. This finding supports the first hypothesis: Information from a signal countdown timer will increase the probability of stopping in response to the onset of the yellow signal phase. The results further suggest that safety benefits occur from providing signal phase information to drivers in realtime. Ratings from the postdrive questionnaires indicated that participants who experienced the countdown timer and participants who only read about this technology had similar response distributions on the safety, trust, usability, and traffic management items, further suggesting the perceived benefits of the technology from all participants. However, given the nature of this field study, only 1 approach (out of 55 applicable approaches) cleared the intersection when the vehicles entered the approach zone while the signal phase was green and changed to yellow during the approach. This amount of data did not allow for a thorough examination of the probability of stopping in response to the onset of the yellow signal phase. Therefore, the second hypothesis, that automated shuttles, both observed and predicted, would respond to the yellow light onset more consistently than human drivers, with and without a signal countdown timer, could not be systematically tested. A comparison between human and shuttle data indicated that human drivers tended to cross the intersection relatively more frequently compared with the shuttle at both lower and higher speeds, although the difference was not statistically significant. Overall, the findings and the analytical methods provide an insight on the feasibility of comparing behaviors at different speeds across modes of driving (human versus automated shuttle) for future studies and suggest the safety benefits of presenting signal phase information at signalized intersections in realtime.

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APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

ADS	automated driving system
BSM	Basic Safety Message
C-ADS	cooperative-automated driving system
CAN	controller area network
CDA	cooperative driving automation
CV	connected vehicle
DSRC	dedicated short-range communication
FHWA	Federal Highway Administration
OBU	onboard unit
RSU	roadside unit
SPaT	signal phase and timing
UI	user interface

CHAPTER 1. INTRODUCTION

Cooperative driving automation (CDA) applications at signalized intersections have the potential to benefit vehicles equipped with automated driving systems (ADS) and cooperative-automated driving systems (C-ADS) by supporting them during intersection approaches (Federal Highway Administration, 2023). A few recent proof-of-concept studies showed that this CDA technology leads to smoother transitions within intersection approaches and fewer delays and, as a result, less energy consumption and better traffic patterns overall (Soleimaniamiri et al., 2021). Infrastructure-based CDA may include a roadside unit (RSU) that receives signal phase and timing (SPaT) information from traffic signals. As vehicles approach an intersection equipped with CDA, they can share their locations and speeds with an RSU as well as receive signal phase information and time remaining at that phase.

Traditionally, traffic signals at signalized intersections control vehicle movement and guide driver behavior. When approaching a signalized intersection, drivers must monitor the signal phase of the traffic signal to determine whether they can proceed (green signal phase) or stop (red signal phase). The yellow signal phase occasionally presents drivers with the dilemma of whether they can safely proceed through the intersection before the red signal phase or they should slow to a stop. This decision has important safety consequences. If drivers incorrectly choose to proceed through the intersection, they risk running the red light and being involved in a right-angle crash. Conversely, abruptly stopping in response to the yellow signal phase may increase the risk of being rear-ended by a following vehicle. Countermeasures that help remove the dilemma that drivers face during the onset of the yellow signal phase can reduce the risk or abruptness of drivers' decisions and increase intersection crossing safety.

The dilemma zone is the area upstream of an intersection in which drivers are indecisive about proceeding or stopping during the yellow signal phase. The dilemma zone can be defined by engineering parameters and signal timing (type I dilemma zone) or by the probability of a driver's stopping (type II dilemma zone). Current research focuses on the type II dilemma zone, in which 10–90 percent of drivers decide to stop in response to the yellow signal phase (Zegeer & Deen, 1978). The dilemma zone equates to a distance measured as about 2.5–5.5 s upstream of the intersection (Bonneson et al., 2002). Approach speed, distance to the intersection stop line, yellow signal phase duration, and driver age and gender are some factors that influence the probability of drivers stopping in response to the yellow signal phase (Zhang et al., 2014). In general, drivers are more likely to stop at the intersection when they are farther from the intersection when the yellow signal phase begins, are approaching at a slower speed, or when the yellow signal phase is shorter.

SPaT information at intersections can help support driver decisionmaking and alleviate the dilemma faced during the yellow signal phase. Countdown timers physically mounted to infrastructure at intersections can display the remaining time in the current signal phase. Countdown timers can reduce uncertainty about the duration of the green signal phase when approaching an intersection and facilitate driver decisionmaking when the green signal phase ends. In a driving simulator study, van Haperen et al. (2015) evaluated a countdown signal timer showing the full time remaining in the green signal phase and red signal phase or a version that only showed the final 3 s of the green and red signal phases. Seventy percent of drivers stopped when presented with the final 3 s of the green signal phase, and 54 percent stopped when the full remaining time was displayed compared with only 28 percent of drivers who did not see a countdown timer. Drivers also decelerated more gradually when they were presented with one of the two countdown timers compared with when a countdown was absent.

Islam et al. (2017) also used a driving simulator to examine whether intersection countdown timers reduced dilemma-zone conflicts and red-light running at signalized intersections. The experimenters presented drivers with a green signal countdown timer that showed the last 10 s of the green signal phase at time distances from the stop line ranging from 1.5 to 6 s. Overall, the probability of stopping increased 13.1 percent when drivers were presented with a green signal countdown timer. Similar to the findings of van Haperen et al. (2015), drivers slowed down more gradually when presented with a green signal countdown timer than when the timer was not present.

Wireless communication and connected vehicle (CV) technology is being used to communicate SPaT information from an intersection directly to road users (Federal Highway Administration, 2023). The information can be used to inform drivers and support their intersection crossing decisions. For example, a major automotive maker developed a system that uses SPaT information from connected intersections and other information to provide speed recommendations so drivers can travel through an upcoming intersection during the green phase. The feature also informs the driver when a red light will change to green to reduce startup time and hasten throughput through an intersection. Krause and Bengler (2012) found that drivers complied with speed recommendations from the traffic light assistant feature during about 60 percent of their simulated driving experiment. As of March 2020, a major automotive maker's Traffic Light Information feature was available at more than 10,000 intersections in more than 30 U.S. cities (Barry, 2020). Beyond improving fuel efficiency and comfort, products like Traffic Light Information that inform drivers of the SPaT at upcoming intersections may help eliminate the uncertainty of stop-or-go decisions faced in the dilemma zone.

Automated vehicles can also use SPaT information to guide behavior at intersections. For example, Altan et al. (2017) demonstrated the potential of using CDA for enhancing the fuel efficiency of intersection crossings. The researchers implemented an Eco-Approach and Departure at Signalized Intersections application (U.S. Department of Transportation, 2013) that used SPaT information, geometric intersection design messages, and dedicated short-range communications (DSRCs) to determine and execute the most energy-efficient speed profile an automated vehicle should follow when approaching and proceeding through an intersection. The study's research team compared the fuel efficiency and performance of an automated vehicle using the application with intersection crossings completed by a human driver in a conventional vehicle, with and without guidance, on the appropriate speed for fuel-efficient driving. The team observed a 5-percent improvement in fuel economy when they provided human drivers with guidance for fuel-efficient driving during an intersection approach. This outcome was smaller than the 17-percent improvement in fuel efficiency observed for the automated vehicle using the application. The automated vehicle also exhibited more consistent performance and driving patterns when approaching and departing the intersection than human drivers did, including those who received guidance on approach speeds.

New vehicle technologies take decades to fully penetrate the vehicle fleet (Highway Loss Data Institute, 2019), so the technological capabilities of the vehicle fleet will remain mixed for some time. Features like a traffic light assistant or an in-vehicle green signal phase countdown timer that require CV technology will only be available to some drivers approaching an intersection and not others. The effect of countdown timer information on CV driver behavior, such as increasing the probability of stopping in response to the onset of the yellow signal phase, may conflict with the behavior of uninformed conventional drivers. CV drivers who slow when a green signal phase is ending or accelerate to beat the red signal phase may confuse neighboring conventional vehicle drivers. The introduction of automated vehicles into the vehicle fleet may further exacerbate mismatched expectations from surrounding road users, considering that automated vehicle algorithms using the same SPaT information perform differently than human drivers (Altan et al., 2017).

STUDY OBJECTIVES

The objectives of this study were to examine the degree to which an in-vehicle signal countdown timer influenced human drivers' intersection approaching behaviors and decisionmaking and to compare human responses to this information with the approaching behavior of automated shuttles. The participants drove through a connected intersection that had an actuated signal countdown. The research team used SPaT information that was broadcast from this intersection to provide half of the drivers with real-time signal countdown information during the intersection approaches. Four signal phases were possible as drivers approached the intersection: remained green, changed from green to yellow and then red, was yellow or red when drivers entered the approach, and changed from red to green while drivers were in the approach.

For each signal phase, the research team analyzed drivers' speed and acceleration (or deceleration, depending on the signal phases) at the beginning (~500 ft from the intersection stop line) and the end (the stop line) of the intersection approach. In addition, the team examined the abrupt braking rate, which is defined as any vehicle decelerations greater than 8.76 ft/s^2 (Nafakh et al., 2022; Desai et al., 2021), and intersection crossing decisions for incidents of signal phase changes from green to yellow or red, as well as when a signal phase was yellow or red at the beginning of the approach.

The research team used the drivers' eye-tracking behaviors to characterize the degree to which providing signal phase countdown information on an in-vehicle display influenced the distribution of visual attention to different areas of interest (i.e., in-vehicle display with countdown information, forward roadway, instrument cluster, and mirrors) when approaching the intersection. Additionally, the team presented two sets of questionnaires to the participants: safety and trust items and usability and traffic management items. The researchers designed these questionnaires to examine whether participants who experienced the signal phase information would perceive it differently compared with those who did not experience the information.

Hypothesis 1

Consistent with previous research (Islam et al., 2017; van Haperen et al., 2015), the research team hypothesized that information from a signal countdown timer would increase the probability of stopping in response to the onset of the yellow signal phase, reduce deceleration rates, and minimize the number of abrupt braking responses.

The intersection crossing behavior when drivers are operating a conventional vehicle and a CV could then be compared with the real-world crossing behavior of a low-speed automated shuttle and the simulated crossing behavior of an automated shuttle traveling at higher speeds.

Hypothesis 2

The research team hypothesized that automated shuttles, both observed and predicted, would respond to the yellow light onset more consistently than human drivers, with and without a signal countdown timer, and demonstrate a higher probability of stopping.

CHAPTER 2. METHOD

PART 1. HUMAN DRIVER INTERSECTION APPROACHES

Participants

The research team recruited drivers from the Washington, DC, metropolitan area via study flyers. They invited interested individuals to contact the research team by going to a signup intake form.

The research team initially recruited 56 participants; however, data from a few participants were not usable due to data collection technical issues. The team then recruited additional participants, and the final sample size was 57. These 57 participants were licensed U.S. drivers who were at least 18 yr old and had a visual acuity of at least 20/40 (as is required for licensure in most States) based on the Freiburg Visual Acuity test (Bach, 1996). The participant group comprised 29 females and 28 males. Of the 57 participants, 29 were considered to be older drivers (46 yr old or older) and 28 were in the younger age group (45 yr old or younger); 30 were randomized to the countdown group and 27 to the control group. The researchers collected the data during May and June of 2023, and they compensated the participants $80 for the 2-h experimental session ($40/h).

Experimental Design

The researchers used a between-subjects design to evaluate the effect of signal phase countdown information on human drivers' intersection approaching behaviors. The team manipulated a single-factor, signal phase countdown display and presented this information to participants in the countdown group. The participants in the control group read about this technology just before the research assistant administered the postdrive questionnaire.

Test Route Configuration

This study was conducted at the intersection of Lee Highway and Eskridge Road and Merrilee Drive in Merrifield, VA. Eskridge Road changes to Merrilee Drive after crossing Lee Highway, also known as Highway 29 (figure 1). Merrilee Drive is the road segment north of Lee Highway; Merrilee Drive is a single lane road approaching Lee Highway that splits into a left-turn-only lane and a straight and right-turn lane about 130 ft from the Lee Highway intersection. The segment of Eskridge Road that is south of Lee Highway is a two-lane road that splits into two left-turn-only lanes, one through lane, and a right-turn-only lane about 350 ft from the intersection with Lee Highway. The lanes are 12-ft wide on both sides of Lee Highway. The intersection width of Lee Highway, as measured by the distance between the stop line on Merrilee Drive and the stop line on Eskridge Road, is approximately 170 ft. The posted speed limit on both segments is 25 mph. In addition to designated turning lanes, Lee Highway has three lanes eastbound and two lanes westbound. The speed limit is 40 mph.

Figure 1. Photo. Eastbound view of the intersection of Eskridge Road/Merrilee Drive and Lee Highway (from Lee Highway) (Google Maps, 2021).

The test route consisted of a predefined 1.5-mi loop along Eskridge Road/Merrilee Drive. The participants drove an instrumented vehicle while the crossing behavior at the Lee Highway intersection was recorded. This route started at a parking lot off Eskridge Road. Once participants pulled out of the parking lot and joined Eskridge Road, they would head northbound, cross Lee Highway, and continue on Merrilee Drive. At the intersection of Merrilee Drive and Halstead Square Road, they would make a right turn and two more right turns and then turn left to join Merrilee Drive. They would continue southbound, cross Lee Highway, and pull into the same parking lot on the left side of Eskridge Road. Figure 2 depicts the test route (dotted line) as well as the side streets and the parking lot used for turning around. The participants would drive along the test route 2 times (4 approaches) for practice and 8 times (16 approaches) for the experiment. The beginning and end of the intersection approach zone (150 m (492 ft)) from the intersection stop line) on Eskridge Road and Merrilee Drive are also depicted. This test route was chosen to match the route of the shuttle (solid line in figure 2).

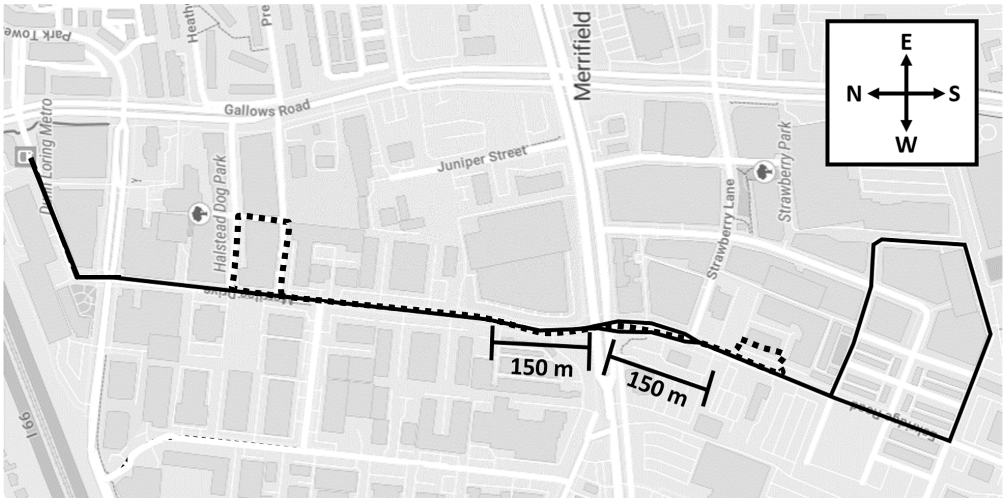

Figure 2. Map. Test route (dotted black line) overlaid with the automated shuttle's route (solid black line) (Google Maps, 2021).

Apparatus and Materials

Instrumented Vehicle

The research team equipped the instrumented test vehicle with CDA features, including collision warning and mitigation features and eye-tracking technologies. The vehicle's local data acquisition system recorded data from the vehicle controller area network (CAN) bus, including speed, steering wheel angle, and brake force. The researchers used cameras mounted within the vehicle cabin to monitor the drivers' interaction with the steering wheel and dashboard and to verify the participants' vehicle speed and status throughout the experiment in realtime. The team mounted a display screen that relied on a preexisting user interface (UI) capable of presenting signal phase countdown information in the center of the dashboard of the vehicle (figure 3). Figure 4 shows the test vehicle approaching the intersection on Eskridge Road.

Source: FHWA.

Figure 3. Photo. UI of the signal phase countdown.

Source: FHWA.

Figure 4. Photo. Test vehicle (circled) approaching the intersection.

Signal Phase Countdown

The signal phase countdown display contained information about the time remaining in the current signal phase (red, yellow, or green) before the transition to the following signal phase would begin (figure 5). The research team generated information by using SPaT information that was broadcast from an RSU at the intersection and received by an onboard unit (OBU) in the test vehicle. Only participants in the countdown group were exposed to this display. The in-vehicle display was blank when the countdown was absent in the control group.

Source: FHWA.

Figure 5. Illustration. Signal phase countdown information display example.

Questionnaires

The postdrive questionnaire included five questions about the participants' background information, including age, years of driving experience, familiarity with the test route area and signal countdown timers, and experience with signal countdown timers (if any). Additionally, eight questions asked about the participants' perceived safety and trust related to signal countdown timers on a Likert scale of 1 to 7 (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree). For example, one question asked participants to rate the degree to which "the presence of the signal countdown timer made me feel safer driving through the intersection." The wording was slightly adjusted for the control group to "the presence of a signal countdown timer would make me feel safer driving through the intersection." Lastly, seven questions were about the usability and traffic management aspects of signal countdown timers on a scale of 1 to 7 (ranging from 1 = strongly disagree to 7 = strongly agree). For example, one question asked the participants to rate their level of agreement with the statement "I felt there was too much inconsistency in the signal countdown timer." The wording was again adjusted for the control group to "I feel there would be too much inconsistency in the signal countdown timers." The two versions of the postdrive questionnaire are in the Appendix.

Procedures

The team instructed each participant to meet the researcher at a designated surface parking lot near the beginning of the test route. The researcher began the experimental session by giving the participant a copy of the informed consent form to review and sign.

Next, the research team asked each participant to show their driver's license to the researcher to verify age and licensure status. The researcher then assessed the participant's visual acuity using the Freiburg Visual Acuity test (Bach, 1996). The researcher then assigned each participant to either the control group or the countdown group according to a randomization table.

Each participant sat in the driver's seat in the test vehicle while the researcher sat in the front passenger seat. The researcher then provided instructions on the study procedure and introduced the test vehicle's features, including the signal phase countdown display, if applicable, and the test route to the participant. The researcher also initiated the calibration process for the eye tracker. The team provided the participants in the countdown group with the following description of the signal phase countdown timer:

> During this study you will be presented with a signal phase countdown timer. This timer is meant to provide you with information about the number of seconds left until the current traffic signal light phase changes. As you can see on the display (*reference the display,* figure 5) a traffic signal head is shown. As the vehicle approaches the intersection, the lights on the display will reflect the current phase of the traffic signal head (*refer to the traffic signal toward the test route intersection*). Additionally, the lights in the display will contain a countdown timer with the number of seconds remaining until the traffic light changes to the next phase.
>
> The intersection you will be driving through is an actuated intersection, meaning the timing of the lights change depending on the number of vehicles present and waiting in the intersection. This actuation will affect the countdown. The signal countdown timer may "skip" from a higher number to a lower number, such as going from 30 to 15 s remaining. However, the countdown should settle and no longer skip once the countdown is at 10 s or less remaining. Additionally, the in-vehicle countdown timer is novel technology, and due to the actuation, the countdown timer display may flicker or lose connection at times. If the signal is lost and the countdown no longer appears on the signal-head display, please continue driving as normal and do not touch the display, and the researcher in the vehicle will reset the display to regain connection with the intersection.

The researchers instructed all the participants in both conditions to observe traffic laws, signs, and signals when driving. The team also asked the participants to observe and follow the posted speed limit. If any participant's speed exceeded the posted speed limit by 10 mph, the researcher asked the participant to slow down and reminded them to observe the speed limit.

After the instruction, the participants completed two practice laps along the study route for a total of four approaches. The researchers provided turn-by-turn directions to guide participants from the surface parking lot to the beginning of the study route and then along the route. Signal countdown information was displayed during the practice for participants in the countdown condition. The participants in the control group were not exposed to the signal countdown timer. The researchers directed the participants back to the surface parking lot after they completed the practice laps, and then the researchers addressed any questions or concerns the participants raised.

Once the team answered all the participants' questions, the participants began the experimental laps along the test route. The researchers informed the participants about which group they were in before they began the first lap. The participants crossed the Lee Highway intersection twice during each lap, once heading north on Eskridge Road and once heading south on Merrilee Drive. As with the practice laps, the researchers provided turn-by-turn directions and monitored the test vehicle's speed. The team presented the signal phase countdown information on the in-vehicle display for participants in the countdown condition. The participants drove eight laps along the test route continuously. At the end of the eighth lap, the participants returned to the surface parking lot and parked the test vehicle.

The participants in the countdown group then responded to questions regarding their opinions of the signal countdown information and the perceived impact it had on their behavior. The team gave the participants in the control group the description of the signal countdown timer (the same description used in the countdown group) and then asked them to share their opinions on how the signal countdown timer might impact their driving. The participants answered the questionnaire items displayed on a separate laptop computer. The research team debriefed and compensated the participants after they completed the poststudy questionnaire and saved their responses. All the participants completed the study within 2 h.

Analytic Plans

The researchers processed and analyzed the following data from three main sources collected from each participant to study how the in-vehicle signal countdown timer influenced the intersection approaching and crossing behavior of human drivers:

1. Vehicle dynamics measurements, including speed and acceleration recorded by the CAN bus on the test vehicle.

2. Eye-tracking data on visual attention to different areas of interests, including in-vehicle center display, forward roadway, instrument cluster, and mirrors recorded by a third-party camera-based eye-tracking system installed in the test vehicle.

3. Responses to the postdrive questionnaire, including safety and trust and usability and traffic management items.

For the vehicle dynamic measurements and eye-tracking data, the team based the analysis on the four possible scenarios that drivers would encounter in the intersection approach zone (150 m (492 ft)): The signal phase remained green, the signal phase was green at the beginning and then changed to yellow and then to red, the signal phase was yellow or red at the beginning, and the signal phase changed from red to green while the test vehicle was stopped within the approach zone. The researchers derived dependent variables based on these scenarios and used linear mixed modeling or generalized linear mixed modeling, as applicable. In addition to analyzing speed and acceleration, the team compared the frequency of abrupt braking, defined as any vehicle decelerations greater than 8.76 ft/s^2, between the two groups, when applicable. For the eye-tracking data, the researchers focused the analysis on the in-vehicle display area because it was the main interest of the study. In addition to the primary independent variable (the presence of signal countdown timer), the team included gender and age in the initial model as control variables. For the questionnaire data, the researchers analyzed the items separately and used a nonparametric method to conduct hypothesis testing. For all the analyses, the researchers adopted a significance level of 0.05.

Predicting Human Driver Crossing Decisions at Lower Speeds

The research team predicted the human driver crossings at lower speeds from a logistic regression model using the observed battery-powered autonomous electric shuttle data as described in the next part. The independent variables used in the model included the speed, the acceleration, and the time remaining in the green signal phase at the start of the target zone. First, the team estimated the model parameters using only the human driver data from those participants who received the signal phase information since the information was always available to the battery-powered autonomous electric shuttle. Next, the researchers entered the selected data from the battery-powered autonomous electric shuttle into the model to predict an analogous human driver crossing decision at a lower speed.

PART 2. SHUTTLE INTERSECTION APPROACHES

Autonomous Shuttle Description

The research team observed the battery-powered autonomous electric shuttle, which was operating as part of a pilot program supported by the Virginia Department of Transportation, during the study. The shuttle traveled a fixed route between the Dunn Loring–Merrifield Metrorail Station and a commercial area in Merrifield, VA, called the Mosaic District, at speeds less than 10 mph. The shuttle traveled along Eskridge Road and Merrilee Drive and crossed Lee Highway, using the same intersection that the human participants drove through with the signal phase countdown timer. The shuttle's scheduled hours of operation were 10 a.m. to 2 p.m., Monday through Thursday.

The battery-powered autonomous electric shuttles include a localization algorithm that calculates the vehicle's position in realtime by fusing data obtained from light detection and ranging (known as LiDAR) sensors, a differential Global Positioning System and real-time kinematic positioning data, an inertial measurement unit, and odometry. The shuttles also have a range of sensors that can detect and avoid potential obstacles on the road. The shuttle's software supports its navigation capabilities, vehicle-to-everything communication, and intersection crossing decisions. The research team used the existing operational capability of the battery-powered autonomous electric shuttle without access to the proprietary data of the shuttle operation algorithm.

Shuttle Data Collection

The research assistants observed and recorded the intersection crossing behavior of the battery-powered autonomous electric shuttles. The automated shuttle transmits a Basic Safety

Message (BSM) every second (1 Hz) using a 5.9-GHz DSRC. The BSM includes position (e.g., latitude, longitude) and motion state (e.g., speed, heading, acceleration) information about the shuttle. These data can be received by other equipment in the DSRC service, such as RSUs and OBUs. The research assistants positioned themselves on the top level of a parking garage about 250 ft from the center of the intersection field site to capture wireless communications from the shuttle and the intersection field site using an OBU.

The research assistants collected the battery-powered autonomous electric shuttle data for 37 d between August 9, 2021, and November 29, 2021. The team kept 30 d of shuttle data for the downstream analysis because the shuttle BSMs from 7 d were not transmitted and received accurately.

Shuttle Data Processing

The researchers processed the shuttle's trajectory data within the approach zone along with the intersection traffic signal phase information. However, due to the nature of the field study and technical constraints, the researchers were able to process information about the traffic signal phase only at the exact moments when the shuttle was situated within the range of data collection at the approach zone. Thus, the data lacked any information about the start of the current signal phase. This limitation made it difficult for the team to determine the duration of red or green signal phases before the initial recorded time stamp, which was critical for analyzing shuttle behavior at various speeds near signalized intersections. Without knowing when the current traffic signal phase began, predicting whether a high-speed shuttle would encounter a red or green light was challenging. Additionally, no data were available on the duration of the traffic signal phases given the actuation setup.

To overcome these limitations and improve trajectory prediction, especially for high-speed conditions, acquiring more comprehensive signal timing data was essential. Consequently, the research team looked into storing PCAP (packet capture) files to obtain more detailed signal timing information. Initially, the signal phase data included all time points, whereas the trajectory data only noted instances when shuttles were close to the intersection. To synchronize and streamline the analysis, the team adjusted the signal phase data to match the time stamps in the shuttle trajectory data precisely.

Despite these improvements, several challenges with both signal phase and trajectory data persisted:

- Many trajectories had an insufficient number of data points.
- The data predominantly showed that the shuttles stopped at the intersection stop line, with few instances of shuttles passing through intersections without stopping.
- Some signal data might be unreliable, particularly for instances where traffic signals transitioned directly from red to yellow, skipping the green phase and deviating from standard traffic signal sequences.

Consequently, the research team identified 77 valid intersection approaches by the shuttle from the 30 d of collection. Among the valid approaches, the research team further selected 11 approaches that had sufficient information to be used for predicting shuttle behaviors as shuttles approached the intersection at higher speeds.

High-Speed Shuttle Trajectory Computation

This section outlines the steps the researchers took to generate high-speed trajectories from the original shuttle data. First, the team processed the original shuttle data in the following way:

- Shuttle and signal phase data were separated by date for the purpose of matching the corresponding signal phase data for each trajectory.
- Time stamps in the original shuttle data files were synchronized with the time stamps in signal phase data.
- Speeds, accelerations, and distances to the intersection stop line in the original trajectories were recalculated using the shuttle's latitude and longitude positioning and assuming piecewise constant acceleration rates.
- Missing data points in the original shuttle trajectories were filled in, assuming constant acceleration rates between existing data points.
- If an original shuttle trajectory stopped behind the intersection stop line, this stopping location was recorded.

Next, the research team mapped the original shuttle trajectories to higher speed trajectories with the following assumptions:

- The road's speed limit was 25 mph for original trajectories and would remain 25 mph for high-speed trajectories. The speed limit defined the maximum speed that the shuttle could have. If, at any point along the trajectory, the calculated shuttle speed exceeded the speed limit, it would be reset to the speed limit.
- The maximum emergency deceleration rate was set to -8.0 m/s^2, and the maximum comfortable deceleration rate was the lesser of -3.0 m/s^2 or the minimum deceleration rate from the original trajectory (American Association of State Highway and Transportation Officials, 2011).
- The stopping location from the original trajectory was considered the desired stopping location for the high-speed trajectory, accounting for potential preceding vehicles.

The research team then generated the high-speed trajectories with the following assumptions:

- The initial distance to the intersection stop line was the same as in the original trajectory.
- The initial speed was doubled from that of the original trajectory.
- The research team first used the shuttle's latitude and longitude information to calculate the distance traveled between each pair of consecutive trajectory points. Then, starting from the first trajectory point, the research team used the distance values and the doubled initial speed, assuming a constant acceleration rate, to calculate the shuttle's speed, acceleration, and distance to the stop line for the next trajectory point. The team used a kinematic formula for these calculations: ($x\_1 = ½ \times a \times (t^2) + v\_0 \times t + x\_0$), where x_1 is the vehicle location at the next time point, x_0 is the vehicle location at the current time point, a is the vehicle acceleration between the current and the next time points, v_0 is the vehicle speed at the current time point, and t is the time interval between the current and the next time points (Knight, 2016).
- If the distance to stop was sufficient at the desired location with a deceleration rate lower than the maximum comfortable rate, the trajectory used the acceleration rate from the original trajectory for subsequent speed and distance calculations.
- Once the shuttle reached the point where it must decelerate at its maximum comfortable deceleration rate or higher to stop at the desired stopping location, the algorithm would check the signal phase data as the shuttle approached the intersection at a constant speed:
  - If the signal phase was green, the high-speed trajectory would continue moving until it crossed the stop line.
  - If the signal phase was not green, the high-speed trajectory would stop at the predetermined location, mirroring the original shuttle trajectory.
- If a high-speed trajectory came to a stop at any point, it used the acceleration rate from the original shuttle trajectory to accelerate again.

CHAPTER 3. RESULTS

PART 1. HUMAN DRIVER INTERSECTION APPROACHES

This section presents the results from studying participants' driving and approaching behaviors, distributions of fixations from eye tracking, and responses to the postdrive questionnaires. The research team further broke down the driving and approaching behaviors by the signal phase scenarios. The team individually analyzed four possible signal phase scenarios that drivers might encounter while approaching the intersection.

The researchers identified 829 valid intersection approaches by participants. The team excluded 83 intersection approaches because their associated signal phase data were either missing or not reliable. Table 1 lists the signal phase change sequences and their frequencies during these intersection approaches. In the analysis, the researchers would further select appropriate approaches to be analyzed, depending on the signal phase scenario.

Table 1. Number of each signal phase change sequence.

Signal Phase Change Sequence	Frequency
Green	70
Green–yellow	1
Green–yellow–red–green	59
Red–green	672
Red–green–yellow–red–green	12
Yellow–red–green	15

Signal Phase Remained Green During the Approach

Difference in Speed

The researchers identified 58 applicable approaches to be analyzed for the scenario during which the signal phase remained green. The team excluded 22 approaches due to insufficient data points. Table 2 lists the average differences in vehicle speeds between the end and the start of the approach. These data indicate that the participants in the control group decreased speed relatively more than the countdown group as they approached the intersection. The difference between the two groups was statistically significant (t = 3.182, p < 0.01). The researchers did not observe significant differences in gender and age.

Table 2. Difference in speed when signal phase remained green during the approach.

Group	Number of Approaches	Mean of Speed Difference (mph)	Standard Deviation of Speed Difference (mph)
Control	35	−4.830	4.329
Countdown	23	−0.461	6.197

Difference in Acceleration

Table 3 shows the average difference in vehicle accelerations between the end and the start of the approach. Although, on average, the countdown group participants' vehicles accelerated more than the control group participants' vehicles as they approached the intersection, the difference between the two groups was not statistically significant ($t = 1.648$, $p = 0.105$). The researchers also did not observe significant differences in gender and age.

Table 3. Difference in acceleration when signal phase remained green during the approach.

Group	Number of Approaches	Mean of Acceleration Difference (m/s^2)	Standard Deviation of Acceleration Difference (m/s^2)
Control	35	0.020	0.664
Countdown	23	0.309	0.639

Eye Tracking

Table 4 shows the proportions of eye fixations in the six areas of interest. The difference between the in-vehicle display fixations from the two groups was statistically significant ($t = 3.125$, $p < 0.01$), indicating that participants in the countdown group had more fixations on the in-vehicle display area than the control group as they approached the intersection. For the other areas of interest, the researchers did not observe significant difference between the two groups. The team also did not observe significant differences in gender and age.

Table 4. Mean proportion of recorded eye fixations when signal phase remained green during the approach.

Group	In-Vehicle Display	Instrument Panel	Rearview Mirror	Left Mirror	Right Mirror	Outside
Control	0.045	0.122	0.096	0.072	0.011	0.683
Countdown	0.116	0.148	0.039	0.068	0.002	0.659

Signal Phase Changed From Green to Yellow and Then Red During the Approach

Differences in Speed

The researchers identified 55 applicable approaches to be analyzed for the scenario during which the signal phase changed from green to yellow or red. The team excluded five approaches due to insufficient data points. Table 5 shows the average differences in vehicle speeds between the start of the approach and after the green signal phase changed. The difference between the two groups was not statistically significant ($t = -1.010$, $p = 0.322$). The researchers also did not observe significant differences in gender and age.

Table 5. Difference in speed between the start of the approach and after the green signal phase changed.

Group	Number of Approaches	Mean of Speed Difference (mph)	Standard Deviation of Speed Difference (mph)
Control	39	−11.027	9.935
Countdown	16	−14.321	8.550

Difference in Acceleration

Table 6 shows the average difference in vehicle accelerations between the start of the approach and after the green signal phase changed. The difference between the two groups was not statistically significant ($t = 0.554$, $p = .582$). The researchers also did not observe significant differences in gender and age.

Table 6. Difference in acceleration between the start of the approach and after the green signal phase changed.

Group	Number of Approaches	Mean of Acceleration Difference (m/s^2)	Standard Deviation of Acceleration Difference (m/s^2)
Control	39	−0.874	0.816
Countdown	16	−0.749	0.597

Abrupt Braking

Table 7 shows the average frequency of abrupt braking between the start of the approach and after the green signal phase changed. In general, the participants did not press the brake abruptly during the intersection approach. The difference between the two groups was not statistically significant ($t = 1.632$, $p = 0.103$). The researchers also did not observe significant differences in gender and age.

Table 7. Abrupt braking between the start of the approach and after the green signal phase changed.

Group	Number of Approaches	Mean Frequency of Abrupt Braking (per second)	Standard Deviation of Abrupt Braking
Control	39	0.026	0.160
Countdown	16	0.188	0.544

Eye Tracking

Table 8 shows the proportion of eye fixations in the six areas of interest. The difference in the in-vehicle display fixations between the two groups was statistically significant ($t = 3.298$, $p = 0.001$), indicating that the participants in the countdown group had more fixations on the in-vehicle display area than the control group. In addition, younger participants had fewer fixations on the in-vehicle display area than older participants ($t = -3.274$, $p < 0.001$). The researchers did not observe significant differences in gender.

For the instrument panel fixations, the team observed a significant interaction between the control and countdown groups and the age groups ($t = 2.52$, $p < 0.05$), suggesting that compared with the control group, the younger participants from the countdown group were more likely to have more fixations on the instrument panel area than the older participants from the countdown group. The researchers did not observe significant differences in gender. For the other areas of interest, the researchers did not observe significant differences between the two groups. The team also did not observe any significant differences in gender and age in the other areas of interest.

Table 8. Mean proportion of recorded eye fixations between the start of the approach and after the green signal phase changed.

Group	In-Vehicle Display	Instrument Panel	Rearview Mirror	Left Mirror	Right Mirror	Outside
Control	0.066	0.122	0.093	0.092	0.010	0.624
Countdown	0.116	0.154	0.078	0.080	0.002	0.574

Signal Phase Was Yellow or Red in the Beginning of the Approach

Speed

The researchers identified 480 applicable approaches to be analyzed for the scenario during which the signal phase was yellow or red at the beginning of the approach. The team excluded approaches that had insufficient data points. The researchers also dropped approaches that had unusually low speeds (10 mph or less) at the beginning of the intersection approach zone, as this scenario implied the presence of unusual traffic that could introduce bias to the analysis. Table 9 shows the average speeds of vehicles entering the approach zone, indicating that vehicle speeds in the countdown group tended to be lower than those of the control group when entering the approach zone. The difference between the two groups was statistically significant ($t = -6.566$, $p < 0.001$). The researchers did not observe significant differences in gender and age.

Table 9. Speed when entering the approach zone while signal phase was yellow or red.

Group	Number of Approaches	Mean of Speed (mph)	Standard Deviation of Speed (mph)
Control	325	25.454	3.743
Countdown	155	21.510	4.366

Acceleration

Table 10 shows the average accelerations among vehicles entering the approach zone, indicating that participants in the countdown group tended to decelerate more than the control group when entering the approach zone. The difference between the two groups was statistically significant ($t = -3.754$, $p < 0.001$). The researchers did not observe significant differences in gender and age.

Table 10. Acceleration when entering the approach zone while signal phase was yellow or red.

Group	Number of Approaches	Mean of Acceleration (m/s^2)	Standard Deviation of Acceleration (m/s^2)
Control	325	−0.062	0.360
Countdown	155	−0.258	0.530

Eye Tracking

Table 11 shows the proportion of eye fixations in the six areas of interest recorded between the start of the approach while the signal phase was yellow or red and after the red signal phase changed. The difference between the in-vehicle display fixations from the two groups was statistically significant, and the team observed a significant interaction between the control and countdown groups and the age groups ($t = 2.361$, $p < 0.05$), suggesting that compared with the control group, younger participants from the countdown group were more likely to have more fixations on the in-vehicle display area than older participants from the countdown group. The researchers did not observe significant differences in gender.

For the instrument panel fixations, the team observed a significant interaction between the control and countdown groups and the age groups ($t = 2.066$, $p < 0.05$), suggesting that compared with the control group, the younger participants from the countdown group were more likely to have more fixations on the instrument panel area than the older participants from the countdown group. The researchers did not observe significant differences in gender. For the other areas of interest, the research team did not observe significant differences between the two groups. The team did not observe any significant differences in gender and age in the other areas of interest, except for the outside fixations. The younger participants were more likely to have more fixations on the outside area than the older participants ($t = 2.473$, $p < 0.05$).

Table 11. Mean proportion of recorded eye fixations between the start of the approach while signal phase was yellow or red and after the red signal phase changed.

Group	In-Vehicle Display	Instrument Panel	Rearview Mirror	Left Mirror	Right Mirror	Outside
Control	0.071	0.132	0.089	0.110	0.016	0.618
Countdown	0.119	0.149	0.058	0.091	0.014	0.588

Signal Phase Changed From Red to Green While Test Vehicle Was Stopped Within the Approach Zone

Acceleration

The researchers identified 634 applicable approaches to be analyzed for the scenario during which participants encountered the red signal phase and brought the vehicle to a full stop. The team excluded approaches that had insufficient data points or did not bring the vehicle to a full stop. Table 12 shows the average vehicle accelerations at the moment when the signal phase changed from red to green, indicating that participants in the countdown group tended to accelerate more than those who were in the control group. The difference between the two groups was statistically significant ($t = 4.929$, $p < 0.001$). The researchers did not observe significant differences in gender and age.

Table 12. Acceleration at the time when the signal phase changed from red to green while the vehicle was fully stopped within the target zone.

Group	Number of Approaches	Mean Acceleration (m/s^2)	Standard Deviation of Acceleration (m/s^2)
Control	310	0.994	0.819
Countdown	324	1.422	0.664

Eye Tracking

Table 13 shows the proportion of eye fixations in the six areas of interest recorded during the time when the vehicle was stopped within the target zone. The difference between the in-vehicle display fixations from the two groups was statistically significant, and the team observed a significant interaction between the control and countdown groups and the age groups ($t = 2.558$, $p < 0.05$), suggesting that compared with the control group, the younger participants from the countdown group were more likely to have more fixations on the in-vehicle display area than the older participants from the countdown group. The researchers did not observe significant differences in gender.

For the instrument panel fixations, the team observed a significant interaction between the control and countdown groups and the age groups ($t = 2.263$, $p < 0.05$), suggesting that compared with the control group, the younger participants from the countdown group were more likely to have more fixations on the instrument panel area than the older participants from the countdown group. The researchers did not observe significant differences in gender. For the other areas of interest, the researchers did not observe significant difference between the two groups. The research team did not observe any significant differences in gender and age in the other areas of interest, except for the outside fixations. The younger participants were more likely to have more fixations on the outside area than the older participants ($t = 2.539$, $p < 0.05$).

Table 13. Mean proportion of recorded eye fixations while the vehicle was stopped within the target zone.

Group	In-Vehicle Display	Instrument Panel	Rearview Mirror	Left Mirror	Right Mirror	Outside
Control	0.075	0.130	0.087	0.123	0.018	0.606
Countdown	0.134	0.153	0.062	0.101	0.016	0.568

Postdrive Questionnaires

Table 14 and table 15 show the number of responses by group for questionnaire items related to familiarity with both the area and signal countdown timers, respectively.

Table 14. Frequency of responses by group and by the familiarity with the area.

Response Choice	Control	Countdown
Extremely familiar	4	5
Moderately familiar	8	11
Somewhat familiar	4	6
Slightly familiar	5	1
Not at all familiar	6	7

Table 15. Frequency of responses by group and by the familiarity with signal countdown timers.

Response Choice	Control	Countdown
Extremely familiar	0	0
Moderately familiar	0	2
Somewhat familiar	5	1
Slightly familiar	6	3
Not at all familiar	16	24

When asked about any knowledge or experience with signal countdown timers, most participants did not have prior knowledge of this technology, nor did they have experience using it (table 16 and table 17, respectively).

Table 16. Frequency of responses by group and by the experience of having knowledge of signal countdown timers.

Response Choice	Control	Countdown
No	23	23
Yes	4	7

Table 17. Frequency of responses by group and by the experience of using signal countdown timers.

Response Choice	Control	Countdown
No	25	29
Yes	2	1

The participants had similar mean years of driving experience, with 32 yr for the control group and 31 yr for the countdown group.

The researchers administered a questionnaire for safety and trust and usability and traffic management to the participants at the end of their drives. The questionnaire consisted of eight safety and trust items (four positively phrased and four negatively phrased) and seven usability and traffic management items (four positively phrased and three negatively phrased). The research team asked the participants to rate how much they agreed with each item on a scale of 1 to 7 (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree). Table 18 and table 19 show the response summaries of the safety and trust items for the control and countdown groups, respectively; whereas table 20 and table 21 show the response summaries of the usability and traffic management items for the control and countdown groups, respectively.

For the safety and trust items, a Wilcoxon rank-sum test showed that the distributions of ratings in the two groups did not differ significantly ($p > .05$). For the usability and traffic management items, the Wilcoxon rank-sum test also showed that the distributions of ratings in the two groups did not differ significantly ($p > .05$).

Table 18. Summary of safety and trust item responses for the control group.

Item	Median	Interquartile Range
safety_trust_1	5	2.5
safety_trust_2	5	2
safety_trust_3	5	2
safety_trust_4	2	2.5
safety_trust_5	4	3
safety_trust_6	5	2
safety_trust_7	4	2.5
safety_trust_8	4	3

Table 19. Summary of safety and trust item responses for the countdown group.

Item	Median	Interquartile Range
safety_trust_1	4	2.5
safety_trust_2	5	1
safety_trust_3	5	2
safety_trust_4	2	2.75
safety_trust_5	5	3.75
safety_trust_6	5	4
safety_trust_7	4	2
safety_trust_8	2	3.75

Table 20. Summary of usability and traffic management item response for the control group.

Item	Median	Interquartile Range
usability_traffic_09	5	1.5
usability_traffic_10	3	2
usability_traffic_11	6	1
usability_traffic_12	4	2
usability_traffic_13	4	2
usability_traffic_14	4	2.5
usability_traffic_15	4	1.5

Table 21. Summary of usability and traffic management item response for the countdown group.

Item	Median	Interquartile range
usability_traffic_09	5	3.75
usability_traffic_10	3	3
usability_traffic_11	5	1.75
usability_traffic_12	2	3
usability_traffic_13	4	3
usability_traffic_14	4	2
usability_traffic_15	3.5	2

PART 2. SHUTTLE INTERSECTION APPROACHES

Observed Shuttle Approaches

The research team noted 77 valid intersection approaches were by the shuttle. Among the first recorded data when the shuttle was within the approach zone, 16 approaches occurred during the green signal phase, and 61 approaches occurred during the red signal phase. Table 22 shows the distances between the shuttle and the intersection stop line as well as the shuttle speed at the first recorded location. The mean shuttle speed was 3.40 m/s for the green signal phase and 2.70 m/s for the red signal phase.

Table 22. Summary of distance between the shuttle and the intersection stop line and shuttle speed at the first recorded location.

Measurement	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
Distance (m)	3.10	10.17	60.60	50.79	82.72	107.94
Speed (m/s)	0.020	1.700	3.320	2.844	4.160	4.400

Among the 77 intersection approaches, 68 approaches experienced a signal phase change, and 9 approaches did not experience a signal phase change. Table 23 shows the breakdown of the approaches by signal phase change.

Table 23. Frequency of approaches by signal phase.

Signal Phase Change	Number of Approaches
Green	9
Green–yellow	2
Green–yellow–red–green	5
Red–green	61

Comparing Intersection Crossing Behavior Between Human Drivers and Shuttles

The combination of observed and modeled intersection crossing decisions allowed the research team to make comparisons between the human driver and automated shuttle crossing decisions at lower and higher speeds (table 24).

Table 24. Proposed comparisons at lower and higher speeds.

Approach Speed	Human Driver	Shuttle
Lower speed (<10 mph)	Predicted	Observed
Higher speed (>10 mph)	Observed	Predicted

For the predicted crossing decisions by human drivers at lower speeds, the researchers used data from the human drivers from the countdown group that had the green phase when entering the approach zone (resulting in 54 approaches) and data from the shuttle that had the green phase when entering the approach zone (resulting in 16 approaches). First, the team built a logistic regression model using data from the 54 approaches by the human drivers. Then, they supplied the data from the 16 approaches by the shuttle to the model to predict crossing decisions by human drivers at lower speeds. The model initially included distance to the intersection stop line, vehicle speed, vehicle acceleration, and signal phase as independent variables and intersection crossing behavior as the binary dependent variable. This initial model showed that acceleration was not significant; thus, the team used a reduced model without vehicle acceleration to predict human driver crossings at lower speeds. Table 25 displays the crossing decisions by the observed shuttle versus predicted human drivers at lower speeds based on the modeling results. The table shows that human drivers are predicted to be more likely to cross the intersection at lower speeds as compared with the shuttle.

Table 25. Observed shuttle data versus predicted human driver behaviors at a lower speed from the modeling.

Shuttle Versus Human Drivers	Number of Observations
Shuttle no–human no	5
Shuttle yes–human no	1
Shuttle yes–human yes	6
Shuttle no–human yes	4

For predicting shuttle behaviors, the research team first identified 11 applicable approaches as the shuttles approached the intersection at higher speeds, and later, the team selected 6 approaches that had the green phase after entering the approach zone. Table 26 displays the crossing decisions by the observed shuttle at lower speeds and the predicted shuttle at higher speeds, based on the high-speed shuttle trajectory.

Table 26. Shuttle crossing behaviors under lower (observed) and higher (predicted) speeds.

Speed Level	No Crossing	Crossing
Lower (no. observed)	1	5
Higher (no. predicted)	0	6

Table 27 shows the overall human and shuttle crossing behaviors from the observation and prediction. Table 28 and table 29 further display the human and shuttle crossing behaviors at lower speeds and higher speeds, respectively. Although human drivers tended to cross the intersection more compared with the shuttle, Pearson's chi-squared test and Fisher's exact test showed that the difference was not statistically significant ($p > .05$).

Table 27. Crossing behaviors from human drivers and shuttle.

Vehicle	No Crossing	Crossing
Human driver (total no. predicted and observed)	26	44
Shuttle (total no. predicted and observed)	11	11

Table 28. Crossing behaviors from human drivers and shuttle at lower speeds.

Vehicle	No Crossing	Crossing
Human driver (no. predicted)	6	10
Shuttle (no. observed)	11	5

Table 29. Crossing behaviors from human drivers and shuttle at higher speeds.

Vehicle	No Crossing	Crossing
Human driver (no. observed)	20	34
Shuttle (no. predicted)	0	6

CHAPTER 4. DISCUSSION

This study examined the degree to which an in-vehicle signal countdown timer influenced human drivers' intersection approaching behaviors and decisionmaking and compared human responses to this information with the approaching behavior of automated shuttles. The research team analyzed observed human driver data and shuttle data as well as simulated predicted behaviors of human drivers at lower speeds and predicted behaviors of shuttles at higher speeds.

The presence of the signal countdown timer information appeared to have regulated drivers' speed and acceleration within the approach zone. The participants in the countdown group maintained a relatively higher speed when the signal phase remained green, and they reduced their speed when the signal phase was yellow or red when they entered the approach zone. The participants in the countdown group also tended to decelerate more when entering the approach zone while the signal phase was yellow or red.

The countdown group also had more instances of acceleration right before the signal phase changed from red to green. Data from the eye tracker confirmed that participants in the countdown group had more fixations in the in-vehicle display area compared with that of the control group, indicating that participants in the countdown group looked toward the signal phase countdown timer and spent more time on the display regardless of the signal phases. The rate of abrupt braking was similar between the groups. Significant interactions occurred between the presence of the in-vehicle display and age on the fixations on the in-vehicle display. Specifically, during the green to yellow to red approaches, the younger drivers (45 yr old and younger) had fewer fixations on the in-vehicle display compared with older drivers (46 yr old and older), and younger drivers had a greater number of fixations on the instrument cluster than older drivers during this same approach. This outcome could possibly suggest that older drivers were attempting to use the assistive technology more than younger drivers and that younger drivers were more cognizant of the vehicle's status and less reliant on the assistive technology on this kind of approach.

During yellow to red approaches and red to green approaches, while stopped at the red light waiting for the green light, younger drivers in the countdown group had a greater number of fixations on the in-vehicle display, the instrument cluster, and on the outside of the vehicle. This outcome would suggest that younger drivers may have been more distracted by the in-vehicle display, and thus, the distraction caused them to have more eye glances and fixations than older drivers who may not have been using the in-vehicle display as much under those conditions.

Overall, these findings are consistent with previous studies conducted in the simulator (Islam et al., 2017; van Haperen et al., 2015) that found drivers use the countdown timer information to regulate their driving, especially when seeing a yellow or red signal during the approach. This finding supports hypothesis 1 and further suggests the safety benefits of providing signal phase information to drivers in realtime. The ratings from the postdrive questionnaires indicated that participants who experienced the countdown timer and participants who only read about this technology had similar response distributions on the safety, trust, usability, and traffic management items, further suggesting the perceived benefits of the technology from all participants.

However, given the nature of this field study, only 1 out of 55 applicable approaches cleared the intersection upon entering the approach zone while the signal phase was green and changed to yellow during the approach. A participant who had no access to the countdown display made the approach. This finding did not allow for a thorough examination of the probability of stopping in response to the onset of the yellow signal phase. Therefore, hypothesis 2 could not be systematically tested.

In response to this limitation, the research team then focused on the observed approaches when the signal phase was green. Even though only 54 and 16 applicable approaches from the human driver and shuttle data, respectively, were available, the research team was able to use these approaches to simulate human drivers' crossing behaviors at lower speeds and the shuttles' crossing behaviors at higher speeds. The findings, based on limited data, suggest that human drivers are more likely than shuttles to cross the intersections at lower and higher speeds.

Overall, this study supports the concept of providing real-time traffic signal phase information to drivers, as drivers used this information to regulate their speed and deceleration accordingly. Participants from both groups rated the technology and perceived benefits similarly, suggesting that even participants who did not experience the technology during the study felt that they could benefit from it.

Additionally, the team learned many high-level lessons during the course of this study. The research team acknowledges that the study had several study limitations. Unlike lab-based studies where study parameters can be carefully managed, the research team observed human drivers and shuttles naturalistically, without any intervention to ambient traffic, the presence of other road users, and the signal phases. Thus, the researchers collected an uneven number of signal phase change sequences; furthermore, not enough data were available for the dilemma zone analysis.

Using only a subset of the approaches in the comparison analysis was possible. Furthermore, due to the novel nature of the CV technology, the research team encountered several technical issues when trying to implement the in-vehicle signal countdown timer display. The in-vehicle display relied on a preexisting UI as part of the OBU, which has only been used for research purposes to date. The team did not have access to the proprietary RSU software because it was owned and controlled by an organization outside of the research team's control. The team was only permitted to connect the OBU to the RSU and use the broadcasted SPaT information.

Multiple iterations were necessary to properly connect the research vehicle OBU to the RSU for accurately mapping the respective live intersection and display relevant information in the vehicle UI. The actuated traffic signal at the signalized intersection posed additional issues as the experimental countdown timer had always been used with a pretimed traffic signal. Issues included unexpected range in the signal countdown and occasional jitters in the countdown display. To overcome these issues, the research team installed a cap and filter to limit the highest value displayed to the driver and to prevent the display from jumping between two or more values. However, the in-vehicle display still had some issues. The countdown display cap was set to 60 s and would count down, jumping 5–15 units per s until the actuated signal settled on the actual amount of time remaining on a green or red signal. The countdown timer would usually return to a normal 1 s countdown around the 14–10 s range.

These types of limitations and issues are examples of real-world complications that have to be addressed before these kinds of assistive technologies are widely implemented on real-world roadways. The findings and methods of the current study provide insight into the feasibility of comparing behaviors at different speeds across modes of driving (human versus automated shuttle) for future studies as well as a roadmap for testing these advanced connected assistive technologies in a real-world setup.

APPENDIX. POSTDRIVE QUESTIONNAIRES

POSTDRIVE QUESTIONNAIRE (FOR COUNTDOWN CONDITION)

Participant Beliefs About the Signal Countdown Timer

Based on your experience today driving a vehicle equipped with a signal phase countdown timer, how would you rate your belief in the following statements on a scale of 1 to 7 (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree)?

Safety/Trust Items

1. The presence of the signal countdown timer made me feel safer driving through the intersection.
2. The presence of the signal countdown timer increased my likelihood of speeding up through a green or yellow light at intersections.
3. I felt confident about the information provided by a signal countdown timer.
4. Having the signal countdown timer in the vehicle made me feel stressed.
5. If every vehicle had a signal countdown display, there would be fewer traffic violations at intersections.
6. The signal countdown timer in the vehicle made me pay more attention to the intersection signals.
7. I would feel safer driving through intersections if all other traffic had a signal countdown timer display.
8. I felt the signal countdown timer distracted me.

Usability/Traffic Management Items

1. When stopped at a red light, the presence of the signal countdown timer helped me react more quickly when the light turned green.
2. I ignored the signal countdown timer while waiting for the signal to turn green.
3. I used the signal countdown timer when approaching the intersection to help determine if I would make it through on green or need to stop.
4. I felt the presence of the signal countdown timer forced me to drive slower.
5. Having a signal countdown timer in my vehicle would help me save time on my commutes.
6. If more vehicles were equipped with signal countdown timers, there would be less traffic congestion.
7. I felt there was too much inconsistency in the signal countdown timer.

Background Information

1. Prior to today's drive, how familiar were you with the area?

    a. Not at all familiar.
    b. Slightly familiar.
    c. Somewhat familiar.
    d. Moderately familiar.
    e. Extremely familiar.

2. Prior to today's drive, how familiar were you with signal countdown timers?

    a. Not at all familiar.
    b. Slightly familiar.
    c. Somewhat familiar.
    d. Moderately familiar.
    e. Extremely familiar.

3. Prior to today's drive, do you have any knowledge or experience with technology that informs drivers of when traffic signals go from red to green?

    a. Yes.
    b. No.

4. Prior to today's drive, have you had experience of using a signal countdown timer?

    a. Yes.

        ➢ If yes, approximately how many times have you used it? Or how often do you use it? _________________

    b. No.

5. What is your age? _________________
6. How many years of driving experience do you have? _________________

POSTDRIVE QUESTIONNAIRE (FOR CONTROL GROUP)

Participant Beliefs About the Signal Countdown Timer

Based on what you just read about signal phase countdown timers, how would you rate your belief in the following statements on a scale of 1 to 7 (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree).

Safety/Trust Items

1. The presence of a signal countdown timer would make me feel safer driving through the intersection.
2. The presence of a signal countdown timer would increase my likelihood of speeding up through a green or yellow light at intersections.
3. I feel confident about the information provided by a signal countdown timer.
4. Having a signal countdown timer in the vehicle would make me feel stressed.
5. If every vehicle had a signal countdown display, there would be fewer traffic violations at intersections.
6. The signal countdown timer in the vehicle would make me pay more attention to the intersection signals.
7. I would feel safer driving through intersections if all other traffic had a signal countdown timer display.
8. I feel a signal countdown timer would distract me.

Usability/Traffic Management Items

1. While stopped at a red light, the presence of a signal countdown timer would help me react more quickly when the light turns green.
2. I would ignore the signal countdown timer while waiting for the signal to turn green.
3. I would use the signal countdown timer when approaching the intersection to help determine if I would make it through on green or need to stop.
4. I feel the presence of a signal countdown timer would force me to drive slower.
5. Having a signal countdown timer in my vehicle would help me save time on my commutes.
6. If more vehicles were equipped with signal countdown timers, there would be less traffic congestion.
7. I feel there would be too much inconsistency in the signal countdown timers.

Background Information

1. Prior to today's drive, how familiar were you with the area?

   a. Not at all familiar.
   b. Slightly familiar.
   c. Somewhat familiar.
   d. Moderately familiar.
   e. Extremely familiar.

2. Prior to today's drive, how familiar were you with signal countdown timers?

    a. Not at all familiar.
    b. Slightly familiar.
    c. Somewhat familiar.
    d. Moderately familiar.
    e. Extremely familiar.

3. Prior to today's drive, do you have any knowledge or experience with technology that informs drivers of when traffic signals go from red to green?

    a. Yes.
    b. No.

4. Prior to today's drive, have you had experience of using a signal countdown timer?

    a. Yes.

        - If yes, approximately how many times have you used it? Or how often do you use it? _________________

    b. No.

5. What is your age? _________________
6. How many years of driving experience do you have? _________________

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The researchers blurred the business names on the map in figure 1. The team modified figure 2 to show the routes of the research vehicle (dotted black line) and the automated shuttle (solid black line). The original maps are the copyrighted property of Google Maps (2021) and can be accessed at https://www.google.com/streetview/.

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