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Driver Readiness in Autonomous Vehicle Take-Overs

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***Abstract*—**Level 3 autonomous vehicles are able to take full responsibility over the control of the vehicle unless a system boundary is reached or a system failure occurs, in which case, the driver is expected to take-over the control of the vehicle. While this happens, the driver is often not aware of the traffic situation or is engaged in a secondary task. Factors affecting the duration and quality of take-overs in these situations have included secondary task type and nature, traffic density, take-over request (TOR) time, and TOR warning type and modality. However, to the best of the authors' knowledge, no prior study examined time buffer for TORs when a system failure occurs immediately before intersections. The first objective of this study is to investigate the effect of time buffer (3 and 7 seconds) on the duration and quality of take-overs when a system failure occurs just prior to intersections. In addition, eye-tracking has become one of the most popular methods to report what individuals view, in what order, for how long, and how often, and it has been utilized in driving simulations with various objectives. However, to the extent of authors' knowledge, none has compared drivers' eye gaze behavior in the two different time buffers in order to examine drivers' attention and comprehension of salient information. The second objective is to understand the driver's attentional focus on comprehension of salient traffic-related information presented on different parts of the dashboard and on the roads.

***Keywords*—**Autonomous vehicles, driving simulation, eye gaze, attention, comprehension, take-over duration, take-over quality, time buffer.

I. Introduction

THERE have been numerous research and development efforts in autonomous vehicles. Currently, various versions of autonomous vehicles are being tested in various cities within the US. The range of autonomous vehicles are defined on a five level continuum (from zero; vehicles with no automation, to four; vehicles with full automation) by the National Highway Traffic Safety Administration with different autonomy functionalities implemented at different levels [1]. At level 2, the vehicle takes the responsibility of some main driving functions while sharing authority over some other functions with the driver and the driver is expected to continuously monitor the roadway and take-over control immediately as needed. At level 4, the vehicle takes full control of primary driving functionalities, and the driver is not expected to monitor the roadway under any condition.

At level 3, the vehicle is able to take full responsibility over the control of the vehicle unless a system boundary (under certain traffic and environmental conditions such as high traffic density, accident on the road, roadway construction, ambiguous environment, a stationary obstacle on the road, an animal jumping in front of the vehicle, etc.) is reached or system failure occurs (due to software or hardware issues including sensor or actuator issues), in which case, the driver is expected to take-over the control of the vehicle [2]-[5]. The driver is provided with a certain transition or buffer time following a warning called TOR prompted before he/she must take-over the manual control of the vehicle. The driver is allowed to be free of roadway monitoring and focus on the traffic. Accordingly, unless a TOR is prompted, the driver is free to pay their attention to another task, or occupy him/ herself with unrelated tasks, but expected to be ready to take-over control upon a TOR [1]. Therefore, the driver will not be aware of the traffic situation or will be out of the loop when a TOR is prompted. The driver's out-of-the-loop status coupled with distraction with a secondary task leads to deterioration in his/her performance in take-over quality and timing in case of a system failures or reach of a system boundary [6], [7].

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II. Factors Affecting Take-Over Time and Quality

Factors affecting take-over quality and time as the driver is involved in a secondary task and is out-of-the loop when a TOR is prompted has been studied by researchers. The factors included type and nature of secondary tasks, traffic density, TOR time, visual information prompted for TOR, and TOR modality [6].

Researchers [6] examined the type and nature of secondary tasks affecting time and quality of take-overs, and reported that increased visual attention to secondary tasks (texting and internet search) have resulted in decreased take-over time and quality in terms of larger lane deviations and more frequent steering corrections [6]. In addition, this study found that drivers with maladaptive monitoring behavior reacted more slowly and more often incorrectly in sudden emergency takeover situations. On the other hand, some other studies found that involvement in a secondary task has no effect on driver's take-over quality and time. For example, [8] investigated the effects of non-driving task (20-question task) on the timing and quality of takeover performance, and found no statistically significant effect that the secondary task the drivers were involved in during TOR had on the quality and timing of take-overs.

Scholars [4], [7] explored the influence of traffic density on drivers' take-over performance, and reported that higher traffic density was shown to negatively affect take over performance. Reference [4] reported poorer takeover performance with a high traffic density of approximately 30 vehicles per kilometer in the neighboring lane. Reference [7] examined the effect of different traffic densities on the take-over process, and reported that drivers' behaviors are negatively affected by high traffic density during a TOR in terms of mean take-over times, time to collision, longitudinal accelerations, and number of collisions occurred.

Scholars [8] explored the effect of the TOR time on take-over performance, and reported that with shorter TOR-time (5 compared to 7 seconds), the subjects come to a decision more quickly, reacting faster, but the quality is generally worse, gazes in mirrors and shoulder checks decrease, the accelerations increase, and the brake is used excessively with a high collision risk. Reference [9] studied whether a short TOR time of four seconds is sufficient for drivers to recognize subtle cues that may indicate a potentially hazardous situation after they have been out of the loop while not driving. The study found that drivers need at least 7 seconds to locate other vehicles properly in a novel traffic scene.

Researchers [10] looked into the effect of the amount of visual information given to the drivers at the time of TOR on how quickly they were able to resumed manual control, and found that less information lead to slower take-over times, however, there was no statistically significant effect on drivers' timing of collision avoidance maneuver. The results suggested that take-over time and quality of avoidance response appear to be largely independent of visual information provided for TOR, and while long take-over time did not predict collision outcome, kinematically late TOR did.

Researchers [5] investigated the effects of TOR modality (auditory, vibrotactile, and auditory-vibrotactile) on drivers' responses (i.e., steering, braking, and lane change). The study reported that auditory-vibrotactile led to significantly faster steer-touch times than the other two TOR modalities. Results also showed that there was no statistically significant difference between TOR modalities on brake times and lane change times.

III. Eye Gaze to Measure Take-Over Quality

Eye-tracking has become one of the most popular methods to investigate what individuals view, in what order, for how long, and how often [11], and it has been used in many studies to examine viewers' eye movements and gaze patterns to understand their cognitive processes and behaviors during various tasks [11]–[14]. Specifically, the use of eye-tracking technology has been studied as an instrument to analyze cognitive process to determine comprehension, learning, and performance. Based on eye-tracking data, for example, a clear hierarchy of areas of higher and lower interests are identified [12], a) aspects of attentional focus, b) salient parts of display, c) information, the extent and processing order of information, and d) how several pieces of information are integrated or compared are identified, revealed, and reported [13], and the fact that people use a variety of scanning patterns to understand (single scan, multiple scan, focus on text, focus on numbers, etc.) are determined [14].

Many prior research studies have utilized eye-tracking technology in driving simulations. In [15], eye-tracking technology was used to assess the effects of a game-based, multi-player, online driving simulation on the extent of young drivers' horizontal eye scanning (HS) abilities before, during, and after hazardous situations. However, to the best of the authors knowledge, no prior study investigated the use of eye-tracking technology in exploring drivers' gaze behavior before, during, and after TORs in level-3 autonomous vehicles with two different time buffers (3 and 7 seconds). The purpose is to understand the driver's attentional focus on salient parts of the dashboard and traffic as well as their comprehension of the traffic situation surrounding them when the autonomous vehicle's system fails at three different time buffers (3 and 7 seconds). The study aims to compare driver's attention and comprehension of different traffic symbols and situations on two different time buffers (3 and 7 seconds) prior to intersections.

IV. Problem Significance and the Purpose

Various factors affecting the quality and duration of take-over have been studied including type and nature of secondary tasks [8], traffic density [4], [7], TOR time [8], visual information prompted for the TOR [10], and TOR modality [5]. However, to the extent of authors' knowledge, there is no prior study looking into the effect of time buffer when TOR occurred on certain road sections. In addition, autonomous vehicle failures in prior studies were generally limited to system boundaries exhibited by some type of blockage (crash, constructions, obstacle, etc.) on the roadway [4]–[8]; but, to the best of authors' knowledge, no prior study examined take-over quality and duration when a system failure instead of a system boundary occurs. Furthermore, none of the previous studies examined driver's eye gazes in an attempt to understand their attention and comprehension before, during, and after TORs when level 3 autonomous vehicle system fails prompting users to takeover control.

Specifically, to the extent of authors' knowledge, no prior study examined time buffer when TOR is prompted immediately before intersections as a result of a system failure, which are likely to occur in Level 3 vehicles [9]. In prior studies [4], [5], [7], [10]. TORs occurred in road sections where there was no need to communicate and/or interact with other drivers in order to avoid accidents. Intersections are dangerous road sections representing a traffic situation and complexity that have not been studied to see how TOR time affects the quality and duration of take-overs when TOR is prompted 3 and 7 seconds prior to intersections.

There are several indications that the location and position of the autonomous vehicle in the traffic, when TOR occurs, may affect the quality and duration of take-overs. When TOR occurs right before an intersection, the situation would be hazardous and life threatening and the possibility of a fatal crash would be at a maximum. Intersections require multi-tasking (vehicle control and interactions with other drivers), are dynamic traffic situations [16], are common traffic zones for accidents [17], and require higher attention of drivers to several areas. Approaching an intersection, drivers need to both manage and anticipate interactions with other road users, and keep control of the vehicle [16].

Eye gaze patterns, including the number of fixations (a relatively stable eye gaze on a location) and duration of fixations (the extent of the fixations), can be used as a proxy for cognition and can reveal important aspects of students' cognitive processes [18]. Eye fixation is a relatively stable eye gaze on a location, and fixation duration is the time the eye gaze dwells continuously within an AOI [6]. High fixation duration corresponds to difficulty in comprehension, higher number of fixations show more attention and higher level of focus to the most useful parts of the view or to specified areas of interests [19]–[22]; higher attention and focus indicate expertise and are associated with performance [23], [24]. These eye-gaze measures, i.e., number of fixations and fixation duration (FD), are invaluable data to understand driver's state of cognition before, during, and after TORs in a level 3 autonomous vehicle. Therefore, this study investigates the effect of time buffer (3 and 7 seconds) on the duration and quality of take-overs in order to safely take control of level 3 vehicles when a system failure occurs just prior to intersections while the driver is involved in a secondary task and is out-of-the loop. In addition, this study examines driver's eye gaze data in order to understand their attention and comprehension before, during, and after TORs comparing eye gaze data for 3 and 7 seconds time buffers.

V. Research Methods

A. Participants and Materials

The participants of the study consist of 15 young drivers aged 18–25 years. All participants were 'drivers' in the level 3 autonomous vehicle in GMOST. The autonomous vehicles had random system failures occurring at 7, 5, or 3 seconds before intersections. The participants' driving behaviors and eye gaze data were categorized into 3 and 7 seconds, and no system failure groups are identified as TSG, SSG, and NSG, respectively.

B. Procedures

The study took place over two days, with 25 minutes a session (10 minutes training & preparation plus 15 minutes experiment). Each participant drove across approximately 16 intersections in a session. During these trips, autonomous vehicles had random system failures occurring randomly at 3 or 7 seconds prior to intersections with a TOR prompt (auditor and visual).

During the initial 10 minutes training period, participants were given instructions regarding the purpose of the experiment, and provided with a brief training about GMOST including the autonomous vehicle with its dashboard, speedometer, and text-messaging system, the traffic, TORs, and intersection manager indicating the right of way for the autonomous vehicle. The participants were trained about how they would respond to the text messages, which were presented to them every 4 seconds. Participants were also given instructions about how to control the steering wheel, accelerator and brake pedals when the autonomous system fails. Then, they were seated in the simulator, where they were able adjust the seat and steering wheels, and asked to drive around for a while to get familiar with the driving environment and the simulator. During the second half of the sessions, participants were asked to ride in the autonomous vehicle for about 15 minutes to, which were designed to take the participants from point A to point B. Participants were told that the autonomous vehicle functions perfectly, they do not need to monitor the roadways, and are encouraged to engage in the secondary task, reading and responding to text-messages.

To manually disengage the automation, the participants were told that they could either press a button on the steering wheel to turn the system on and off, or that steering or braking would disengage the automation. Participants were instructed that when a TOR was provided, they had to take the steering with both hands and make a decision as to what they were supposed to do based on the signal given by the intersection manager, which would be either pass or stop. If they were not given the right of the way, participants were asked to press the brake to stop at the intersection, and wait for the provision of a green light on the dashboard indicating that they were given the right of the way. If they were given the right of the way after the TOR occurred as they got closer to the intersection, they were asked to take control of the wheel as well as the gas pedal so as to continue driving the autonomous vehicle and pass the intersection at or closer to the speed prior to the TORs. They were asked to drive the vehicle as if they are in real traffic.

C. GMOST

The study was conducted in a multi-player driving simulator. The front and side views of the environment were presented through three mounted LCD screens. The middle LCD screen represented the front windshield and dashboard. The dashboard presents a directional arrow, the text messaging window, traffic light for the right of way, speedometer, and a visual warning for the system failure. With three LCD screens, the 'driver' has 180-degree field of view. A rearview mirror was placed to provide rear visibility, and side mirrors were implemented to show side views. Road and engine noise were played back via speakers. Autonomy of the vehicles is turned off when the 'driver' either presses the brake pedal with more than 10% depression or steers to deviate by 2°. The traffic density was set to be high with vehicles spaced an average 100 m from each other, representing a 4 s time gap [16] in all directions. Right of ways at intersections were managed by an intersection manager, designed and implemented on GMOST.

Text Messaging as a Secondary Task: A text messaging system was designed and implemented into GMOST. Texting was chosen as the secondary task because texting while driving has been reported to have the most negative impact on driving performance because it involves all three type of distractions: cognitive, manual, and visual [25], [26]. With more frequent and longer glances off-the-road as well as at least one-hand off the wheel, texting while driving has the greatest probability of leading to an accident [27]. National Highway Traffic Safety Administration reported that 14% of all fatal distraction-affected crashes involved cell phone use and texting [28]. This is a specially greater concern for young and inexperienced drivers (generally defined in this context as novices) because texting while driving is widespread among high school and college students ranging between 15-24 year-olds in age, over 70% of whom text while driving [26], [29], [30]. Text messages as secondary tasks in the form of questions were sent to the participating drivers and presented in a 200 X 400 pixels screen on the far right of the dashboard on the bottom right corner of the front-view, below the windshield. A total of 60 distractive messages (DM) inquiring responses were developed, and digitally stored. The system is designed to send one of these randomly selected messages with a 4 second time gap in between the messages responded and received. The driver is expected to select one of the four predefined choices to each DM. Both to read and answer these DMs, the driver has to take his/her eyes off the road to be able to respond to messages. Then, 4 seconds after a message is sent, another random message is received by the driver for another response.

System Failure and TOR Time: Participants were instructed that they would need to take control of the vehicle if a sudden system failure occurs. For each participant, approximately 15 (six 7 and nine 3 seconds) system failures occurred, and these system failures occurred when the autonomous vehicle is 3 and 7 seconds away from an intersection depending on the speed of the autonomous vehicle when the TOR occurs. 3 and 7 second time buffers were chosen to compare drivers' readiness because these two time buffers were found to be average late and early, respectively, time buffers in prior literature although there is no agreed-upon time buffer in prior literature. For example, a 7-second time buffer was found to be needed by drivers to locate other vehicles properly in a novel traffic scene [31], 4 seconds was found to be too short and 6 seconds was sufficient [9]; novice drivers were found to need at least 8 seconds to become fully situationally aware and take control of an autonomous vehicle after being out of the loop [32], and older and more experienced drivers were reported to be in need of 6 seconds to become fully situationally aware and take control of an autonomous vehicle [33].

TOR: Two types of TOR modality were given; auditory and visual: TOR through double high-pitched beeps (240 ms beeps of 2800 Hz with a 100 ms interval in between), according to guidelines of NHTSA for crash warnings [5], [34], and an icon change in the instrument panel. The sounds were produced from left and right speakers located on both sides of the simulators.

D.Data

Two types of data recorded throughout the experimental sessions were driving behavior in terms of take-over time and take-over quality, and eye-gaze consisting of visual attention and cognitive effort.

Take-over Time: *First-contact-time (FCT)* is the time in milliseconds between TOR and hands on steering wheel, press on brake pedal, or press on gas pedal. First contact with steering wheel or brake/gas pedal was considered a measure of motor readiness [6]. This is the time between the TOR and moment when the hands steered the wheel by greater than 1° [5] or pressed on the brake/gas pedal greater than 0% [5] or whichever comes first, which indicates how long it takes the driver to return to a driving position. During automated driving, the steering wheel does not move, and an absolute steering velocity of 1° was the minimum value which could be reliably attributed to human input [5]. Similar to the steer touch reaction time, brake/gas pedal depression greater than 0% represents the initial movement of the brake/gas pedal [5]. If the autonomous vehicle is given the right of the way through a green light on the dashboard, then pressing on the gas pedal would be reasonable to keep the vehicle at a steady speed until it is time to slow down for a smooth transition from its current lane to the intended lane at the intersection towards its destination. *Take-control-time (TCT)* is the time in milliseconds between TOR and the first measurable brake/gas pedal or steering wheel response to the situation [8], which is defined by 10% for brake/gas pedal position or 2° for steering wheel angle [4], [6]. Whether press on brake or gas pedal is taken for the TCT depends on if the autonomous vehicle was directed to stop at the intersection by the intersection manager or given the right of way to transition into to the designated lane towards its destination at the intersection. TCT is calculated as the time in milliseconds between TOR and first measurable press (10% or greater) on gas pedal if the vehicle is given the right of way, or TCT is calculated as the time in milliseconds between TOR and first measurable press (10% or greater) on the brake pedal if the vehicle was directed to stop at the intersection. As soon as the driver's input exceeded one of these thresholds, it was considered to be an overt maneuver and counted as the take-control-time [4].

Take-over Quality: *Maximum longitudinal braking (MLB)* in m/s^2 (time to stabilize the vehicle) [4], as the braking velocity behavior starting with TCT leading to the stop at the intersection. Drivers with smoother velocities are considered to exhibit better take-over quality. These were indicators for safely controlling the vehicle. *Standard Deviation of Lateral Position (SDLP):* SDLP, keeping the vehicle within the allocated lane, is considered to be a sensitive parameter for vehicle control and traffic safety [30]; and therefore, SDLP in this study is used as another indicator of a good driving behavior.

Eye Gaze Patterns: To examine the driver's eye gaze pattern, five areas of interests (AOIs) are defined in this study. These are 1) text messaging window on the dashboard (TM), which represents the secondary task and gives information about the driver's focus and attention on the secondary task, 2) visual signal by the intersection manager indicating whether the autonomous vehicle is given the right of way to proceed to the intersecting lane towards its destination or directed to stop at the intersection (SG), which gives information about the driver's focus and comprehension of the signal by the intersection manager, 3) driver's lane (DL), the road in front of the driver that would give information about driver's vehicle control, 4) intersecting road to transition to if the autonomous vehicle is given the right of way (IR), which gives information about the driver's focus on interactions with other drivers/objects/road lines/etc. in the intersecting road, 5) intersection stop line if the vehicle is directed to stop (SL), which gives information about the driver's attention and focus on where to stop. Eye-gaze data are collected within a specified amount of time on each intersection, which means NF on TM, SG, DL, IR, and SL are collected starting from 2 seconds prior to TORs until the vehicle leaves the intersection. This normalizes the NFs across participants. To normalize NFs across the two groups (3 and 7 seconds), the NFs are divided by their corresponding buffer-times (3 or 7 seconds). Five NFs for five AOIs are calculated at each intersection.

Participants' mean number of gaze fixations on the aforementioned AOIs during these specific time frames reveals information regarding their focus and attention on the information presented by the AOIs. Their mean duration of gaze fixations on the aforementioned AOIs during these specific time frames provide information about their comprehension of information presented by the corresponding AOIs. Therefore, the mean number of eye fixations and the mean duration of eye fixations would indicate participant's attention, focus, and comprehension of the most useful parts of the view and surrounding traffic situation. They would indicate driver's readiness to take-over the control of the autonomous vehicles when the system fails with a comparison between two different time buffers (3 and 7 seconds).

E. Data Analysis

This study compared two groups (independent variables); 3 seconds (3SG) and 7 seconds (7SG) on six dependent variables representing four constructs; take-over time measured by FCT and TCT, take-over quality measured by MLB and SDLP, eye-gaze consisting of visual attention measured by mean number of gaze fixations (NF), and fixation duration (FD) for cognitive effort on 5 AOIs: TM, SG, DL, IR, and SL. Eye-gaze scores were calculated based on the data recorded during the driving sessions. The scoring of these eye-gaze measures was done by the same raters using the same rubric. MANOVA statistics were ran to compare the two groups (3 and 7 seconds) in order to find out the best time buffer in terms of driving behavior, visual attention, and cognitive effort over salient traffic-related information before, during, and after TORs.

VI. Results & Discussions

The first purpose of this study is to examine the effects of buffer-time on driving behavior in terms of take-over time and take-over quality in a level-3 autonomous vehicle when a system failure occurs before and intersection while the driver is involved in a secondary task and out of loop. The second purpose is to investigate the effects of the buffer-time on the driver's visual attention as measured by the number of fixations and cognitive effort as measured by the duration of gaze fixations on the information presented by the salient parts of the traffic environment.

Table I shows the MLB and SDLP scores for participants in the two groups (3SG and 7SG). Based on the presented data, mean MLB scores were calculated as 2.65 and 2.5 for the 3SG and 7SG groups, respectively. The lower the MLB value is the smoother the braking pattern. Therefore, participants in 3SG had harder breaking pattern indicating lower deceleration quality. Mean SDLP scores were calculated as 1.49 and 1.50 for participants in the 3SG and 7SG groups, respectively. Lower the value is the straighter the driving pattern. As a result, participants in 3SG had a slightly straighter driving pattern

Participants' ATT and COM scores were also reported on Table I. According to these data, participants in 3SG, 5SG, and 7SG groups had 189, 216, and 208 mean number of fixations, respectively, on the 5 AOIs (TM, SG, DL, IR, and SL). Their Com scores were 211.14, 194.51, and 204.07 in 3SG, 5SG, and 7SG groups, respectively. Therefore, participants in 5SG had more focus and attention on salient parts of the display related to the traffic situations as compared to the participants in the other two groups. Also, participants in 5SG had lower mean duration of fixation indicating better comprehension of information presented on salient parts of the display.

TABLE I
DESCRIPTIVE STATISTICS

			Mean	Std. Dev.	N
Take-over Time	FCT (milliseconds)	3SG	2572.69	1250.67	13
		7SG	2314.81	1308.3	13
	TCT (milliseconds)	3SG	6115.97	4608.08	13
		7SG	8775.93	7662.19	13
Take-over Quality	MLB (Braking Score)	3SG	2.65	2.48	13
		7SG	2.5	1.67	13
	SDLP (Lateral Position)	3SG	1.49	2.13	13
		7SG	1.50	1.94	13
Eye-Gaze	NF (Number of fixations)	3SG	7.97	1.77	13
		7SG	10.74	2.29	13
	FD (Fixation durations)	3SG	0.96	0.22	13
		7SG	1.19	0.27	13

Looking at Multiple Analysis of Variance (MANOVA) test results (see Table II), we can conclude that time buffer (3 and 7 seconds) did make a statistically significant difference on participants' driving behavior in terms of take-over time and quality combined ($F = 2.6$, $p = .037$; Pillai's $T = .051$, partial eta squared = 0.51). Therefore, we can safely report that time buffer has a statistically significant effect on driving behavior. The multivariate analysis for eye-gaze data showed a statistically significant difference between the two groups when NF and FD variables considered together (Pillai's $T = .098$, $F = 2.02$, $p = .033$, multivariate eta squared = .877). This result suggests that participants in the two groups were statistically significantly different when attention and cognitive efforts considered together as a single construct over all five AOIs.

TABLE II
MULTIVARIATE TEST

	Value	F	Hypothesis df	Error df	Sig.	Part. Eta Sq.
Wilks' lambda	0.69	7.37	2.0	43	0.05	0.26

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