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NSTSCE

National Surface Transportation Safety Center for Excellence

Moth Effect

Determining Contributing Factors

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Technology Impairment Mobility Infrastructure

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EXECUTIVE SUMMARY

The “moth effect” theory posits that drivers are attracted to or mesmerized by light much as moths are drawn to a flame. The notion that drivers are susceptible to the moth effect is born from the fact that vehicles stopped on the shoulder of a roadway are often struck by passing motorists, despite being obviously lighted and outside the lane of travel. There is very little practical highway transportation research on the moth effect, largely due to the difficulty of capturing the effect in a controlled setting. In fact, there is very little hard evidence that the effect exists at all. Even when a crash is speculated to be a result of the moth effect, that term is never used in an accident report. Therefore, circumstances surrounding crashes that could be a result of the moth effect are largely unknown.

The goal of this research was to incorporate previous successful attempts at studying the moth effect. Research included tactics such as building fatigue, utilizing flashing versus steady lights, creating tasks with vehicles parked on the shoulder, and utilizing eye-tracking technology to determine gaze fixation and duration.

The experiment carried out in this research effort was essentially a series of pilot studies where variables such as following distance, following duration, behavior of the lead vehicle, and the lead vehicle’s rear lights were varied from participant to participant with the goal of eliciting a moth effect and determining the variables that may have caused it. A moth effect behavior was defined as an instance when the participant driver left the lane of travel and steered toward a lead vehicle that had moved to the shoulder.

There were a number of obstacles to overcome when researching the moth effect. For instance, despite the belief that driver over-fatigue and inebriation are major contributors to the effect, it was not feasible to permit over-fatigued or inebriated subjects to drive a vehicle as part of an experiment. To address fatigue’s contribution to the moth effect, this experiment immediately followed a separate experiment that involved participants driving for over an hour. Following the first experiment, those same participants were fitted with a calibrated eye tracker and asked to drive for another hour with the intent of causing more fatigue.

The moth-effect experiment resulted in 1 of 21 participants exhibiting a moth-effect-like steering behavior. Factors contributing to this behavior included a close following distance to a lead vehicle (~100 feet), flashing hazard lights on the lead vehicle, and the participant not wearing an eye-tracking device. The participant exhibiting the moth-effect behavior, like other participants, experienced fatigue from the driving task, which involved driving for nearly an hour at 35 mph with the absence of radio, conversation, or any other tasks apart from following a lead vehicle. The authors believe that reduced alertness, akin to “highway hypnosis” (in which the driver operates the vehicle in a drowsy, trance-like state), may have also contributed to the driver’s behavior.

General results of the study indicated that flashing hazard lights resulted in longer fixation durations, which could potentially lead to drivers steering toward a vehicle with its flashing lights engaged. The longer participants drove, the longer their average fixations were, perhaps indicating increased fatigue.

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LIST OF ABBREVIATIONS AND SYMBOLS

CAN	Controller Area Network
DAS	data acquisition system
DGPS	differential Global Positioning System
VTTI	Virginia Tech Transportation Institute

CHAPTER 1. INTRODUCTION

The “moth effect” theory posits that drivers are attracted to or mesmerized by light much as moths are drawn to a flame. The notion that drivers are susceptible to the moth effect is born from the fact that vehicles stopped on the shoulder of a roadway are often struck by passing motorists, despite being obviously lighted and outside the lane of travel. This phenomenon has its origins in transportation research literature under the term “highway hypnosis,” a term first coined by Griffith Williams (1963). According to Williams, this type of “hypnosis” occurs when monotony and points of fixation result in a trance-like experience where drivers often cannot remember long segments of their drive. The authors of this report believe the moth effect derives from Williams’ theory and may be augmented by drowsiness, fatigue, or inebriation. The research team believes that the effect occurs primarily at night and in rural areas or sections of roadway with low traffic or low cognitive demand, such as straight, flat areas.

Prior to Williams’s work, Hopkinson and Longmore (1959) discussed “phototropism” and “perceptual tropism,” showing that subjects seated in a room focused on lighted spots when they were presented. The term was derived from tropistic behaviors, where an organism grows or turns in a particular direction in response to a stimulus, and phototropism, which essentially means “to face the sun.” The tendency of organisms to direct their attention toward objects of perceptual significance, even light, is termed “perceptual tropism.” This term was first used in 1977 to apply to vehicles being struck while on the side of the road (Helander, 1978). Phototaxis is another term often linked with phototropic organisms, and is defined as the locomotory movement that occurs when an organism moves toward or away from a light stimulus (Gest, 1995).

There is very little practical highway transportation research on the moth effect, largely due to the difficulty of capturing the effect in a controlled setting. In fact, there is very little hard evidence that the effect exists at all, making any research attempts difficult. Even when a crash is speculated to be a result of the moth effect, that term is never used in an accident report. Therefore, circumstances surrounding crashes that could be a result of the moth effect are largely unknown. However, some research conducted outside the realm of highway transportation does lend credence to the moth effect theory; in a study involving airline pilots, Clark, Nicholson, and Graybiel (1953) investigated “fascination” in regard to light fixation, and found that it resulted in pilot error.

In motorcycle riding, where steering and guidance is particularly sensitive to fixation, the phenomenon is widely discussed. Riders use the term “target fixation,” and the topic is discussed as part of beginner motorcycle training programs, such as those sponsored by the National Highway Traffic Safety Administration (2007), which warn against staring at objects you intend to avoid. Research has shown that when both traveling on foot and driving, people tend to orient or steer where they are looking (Grasso, Glasauer, Tekei, & Berthoz, 1996; Land & Lee, 1994; Wann & Swapp, 2000). While this is notably different than being mesmerized by light in a monotonous setting, it does support research claims that fixating on an object can cause one to steer toward it subconsciously (Martin, 1940; Wann, Swapp, & Rushton, 2000), which is what the moth effect theory posits with regard to drivers and light.

An early attempt to determine the existence of the moth effect was conducted via accident rate analysis (Charles, Crank, & Falcone, 1990), but as Green (2006) points out, this is a flawed method. The number of crashes mitigated by a marked or lighted vehicle, such as a police car, likely offsets the rare occurrence of such a car being struck due to the increased visibility such vehicles provide. In addition, Green notes that if the aforementioned aviation studies (Clark et al., 1953), where a small percentage of less than 5% of pilot errors were due to the fascination with light, were transferred to road accidents, light-related incident occurrences may not rise above noise in a set of loosely controlled data. The dilemma, of course, is that increasing an experiment's controls also increases a participant's awareness, altering their response, perhaps completely removing the opportunity for a moth-effect event to naturally occur.

In 1994, researchers at Kyushu Sangyo University attempted to determine what effect looking at a vehicle's hazard lights had on steering behavior. Because the study was conducted in Japan, the shoulder on which testing occurred was on the left-hand rather than the right-hand side of the roadway as in the United States. Results of that experiment suggested that when drivers were told to look at the parked vehicle's hazard lights, they tended to travel closer to the car parked on the shoulder at night versus during the day. Drivers also passed closer to the parked car on the shoulder when told to look at the hazard lights versus when no instructions were given about where to look when the hazard lights were not on. The authors suggested these results meant that attention to the hazard lights caused the drivers to steer closer to the light source. While these results are the first to come close to showing a moth effect, the study did have some biases, such as specific instructions to drivers about where to look (Kitamura, Matsunaga, & Nagano, 1994).

The goal of the research effort described in this report was to incorporate previous successful attempts at studying the moth effect. Research included tactics such as building fatigue, utilizing flashing versus steady lights, creating tasks with vehicles parked on the shoulder of the road, as well as utilizing eye-tracking technology to determine gaze fixation and duration.

CHAPTER 2. METHOD

This research effort explored drivers' gaze behavior by using an eye tracker to gather data as drivers approached or passed a vehicle on the shoulder of the road. The shoulder vehicles either had simple rear lights or flashing hazard lights engaged. Lane-keeping behavior was also tracked using built-in vehicle radar systems. The experiment carried out in this research effort was essentially a series of pilot studies where variables such as following distance, following duration, behavior of the lead vehicle, and the lead vehicle's rear lights were varied from participant to participant with the goal of eliciting a moth effect and determining the variables that may have caused it. A moth-effect behavior was defined as an instance when the participant driver left the lane of travel and steered toward a lead vehicle that had moved to the shoulder.

SMART ROAD

All research was conducted on the Virginia Smart Road at the Virginia Tech Transportation Institute (VTTI). The Smart Road is a closed access test track that is 2.2-miles long (3.54-km) from end to end with loops at each end for turning. The track is complete with lane markings, simulating a highway, but lacks any rumble strips to signify the presence of a shoulder. Vehicles traveled between the "top turn" and "bottom turn," which are labeled in Figure 1. The location of the event where the lead vehicle drove onto the shoulder occurred in the slight curve between Turn 3 and Turn 2, as indicated in Figure 1 with a red arrow.

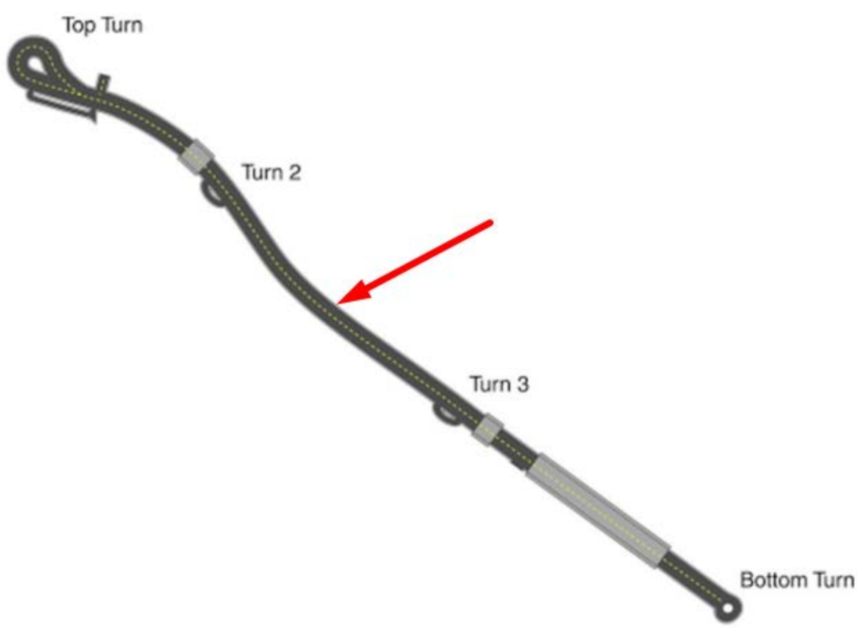

Figure 1. Diagram. Virginia Smart Road.

TEST VEHICLES

The participant vehicle used in the study was a 1999 Ford Explorer instrumented with audio and video collection equipment. Additionally, the vehicle's onboard systems were recorded via a data acquisition system (DAS) connected through the vehicle's Controller Area Network (CAN). The

DAS can collect kinematic data that includes differential Global Positioning System (DGPS) coordinates, speed, lane tracking, and any input from the in-vehicle experimenter.

The vehicle that the participant followed was a gold 2009 Chevy Impala, which was driven by a researcher. There was no recording equipment onboard this vehicle.

EYE-TRACKING APPARATUS

A ViewPoint eye tracker was worn by most participants in the study. The eye tracker is a head-mounted system that uses infrared lights and cameras to detect the pupil (Figure 2). Based on the location of the pupil, the system is able to determine the visual fixation location of the person wearing the device. A forward scene camera records an image of the direction the wearer is facing, and the X-Y coordinates of the fixation point are overlaid on the forward image to represent where the person is looking.

Figure 2. Photograph. ViewPoint EyeTracker goggles.

The eye tracker requires calibration for each individual participant. This consists of aiming the infrared light and camera at the pupil and tasking the participant with acknowledging the location of a laser pointer presented to them on a flat surface. Once the points on the surface have all been adequately identified, the system is calibrated. A screenshot of the eye tracker in use is shown in Figure 3.

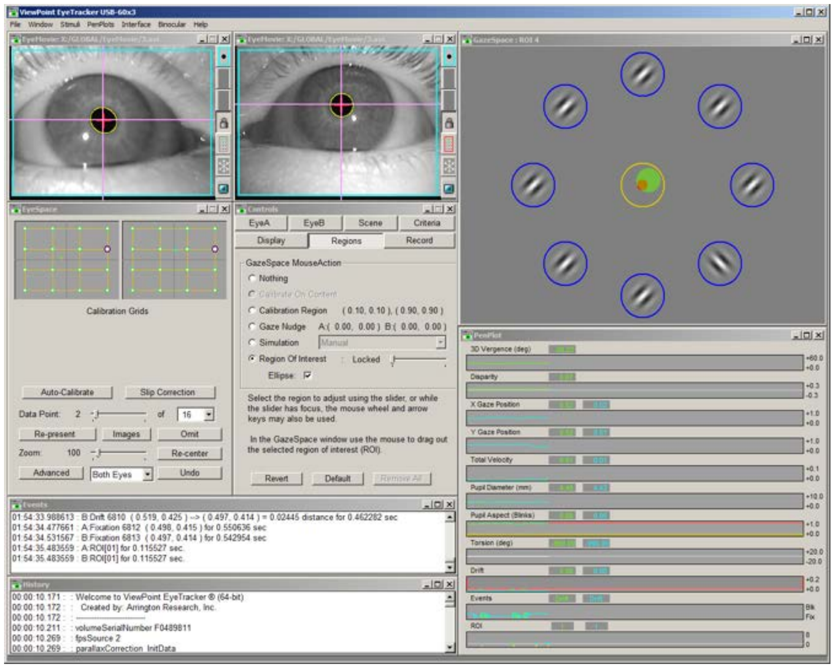

Figure 3. Screenshot. ViewPoint EyeTracker.

LIMITATIONS

There were a number of obstacles to overcome when researching the moth effect. For instance, despite the belief that driver over-fatigue and inebriation are major contributors to the effect, it was not feasible to permit over-fatigued or inebriated subjects to drive a vehicle as part of an experiment. To address fatigue's contribution to the moth effect, this experiment immediately followed a separate experiment that involved participants driving for over an hour. Following the first experiment, those same participants were fitted with a calibrated eye tracker and asked to drive for another hour with the intent of causing more fatigue.

In general, the study was looking for participants to deviate from the path of travel when they became fixated on following the lead vehicle. However, the Hawthorne effect (i.e., the observer effect, where individuals modify their behavior in response to awareness of being observed; Monahan & Fisher, 2010) may have caused participants to drive more vigilantly and be more aware. This same effect was believed to be especially applicable when participants were wearing the eye-tracking device.

PARTICIPANTS

The subject pool was limited to participants who participated in another study in the same night. Participants who agreed to participate in both studies were given the option to decline the second study if they felt too tired after the first. The study could also not be performed in inclement weather, and due to the already restricted subject pool, it was not possible to control for gender, age, or any other demographic. There were 21 total participants who took part in the study. In total, 10 females and 11 males participated. The subject pool consisted only of participants age

55 and over. The average age of females in the study was 60 years with a range of 55 to 70. The average age of males in the study was 60.27 years with a range of 56 to 68.

RESEARCH PROTOCOL

This study was treated as an extended pilot, and therefore each participant was subjected to a slightly altered protocol. The following study protocol elements were altered:

- distance to the lead vehicle
- hazard lights on vs. off
- eye tracker worn vs. not worn
- number of laps participant followed the lead vehicle
- how close lead vehicle was to the right white edge line

The alterations to the study protocol for each participant are described in more detail in the Results section and Appendix B.

In addition to building participant fatigue by having drivers participate in another study immediately preceding this one, drivers completed four uneventful laps on the Smart Road to acclimate them to the monotonous task of driving on a rural road at night with no other traffic. On the fourth lap, a lead vehicle was introduced for the participants to follow for another three laps. The lead vehicle was approximately 600 feet in front of the subject vehicle, with both vehicles traveling at the same speed in order to maintain that general distance. This distance was chosen as it was far enough away that the subject vehicle would not need to react to the lead vehicle by braking, but also near enough so that drivers could see the lead vehicle’s taillights and perhaps orient their own vehicle to following that vehicle. This arrangement allowed the taillights to serve as a lighted stimulus upon which drivers could fixate. At 35 mph, each lap took approximately 8–10 minutes to complete. Altogether, the drive took approximately one hour. The details of this experimental plan were slightly adjusted for each participant in order to build toward a combination of factors that might contribute to a moth effect.

On the seventh and final complete lap, the lead vehicle slowly merged over to the shoulder without any indication to the following participant driver. The merge was not indicated with a turn signal, and because the direction of travel involved an uphill climb, the lead vehicle did not need to apply the brakes. This event took place in a slight curve to offset the lead vehicle from view so that the following participant driver would be less sure about whether the lead vehicle was still in the lane of travel or not. As the participant’s vehicle continued to approach the now stopped lead vehicle, the participant driver’s gaze direction and lane-keeping behavior in response to this event were of interest.

After this event, the participant drove past the lead vehicle, and the lead vehicle then turned around and parked on the shoulder of the roadway in the opposite direction with the hazard lights engaged. Once again, the lead-vehicle was parked on the shoulder in a slight curve to cause the participant some uncertainty about whether that vehicle was in the direct lane of travel. As the subject approached and passed the vehicle on the shoulder, their gaze and lane-keeping behavior were once again of interest. Table 1 details the protocol for the initial participants.

Table 1. Initial protocol.

Laps	Event	Lead Light Condition	Effect
Laps 1–3	Eventless drive	NA	Free drive, monotony
Lap 4–6	Follow lead vehicle	Taillights	Fixation, monotony
Lap 7 down	Follow lead vehicle	Taillights	Fixation, monotony
Lap 7 up	Lead vehicle merge	Taillights	Fixation, lane deviation
Lap 8 down	Lead vehicle park	Hazards	Fixation, lane deviation

The following section will detail each participant's experience, including any protocol changes and the participant's reaction to the lead vehicle.

CHAPTER 3. RESULTS

The four sections of this chapter detail results from the different data collection methods. The first section provides a description of the protocol for each participant as well as their observed reaction to the lap 7 event. The responses to the questionnaire administered to a set of the participants are detailed in the next section. The third section provides information about participants' visual fixation as a rough measure of fatigue. Lastly, participants' lane-keeping behavior is detailed in the final section. The lap 8 event detailed in Table 1 above was removed from analysis, as there were no notable reactions, which was likely due to the arousal caused by the previous merge event on lap 7.

PARTICIPANT PROTOCOL AND EVENT REACTION

Summaries of the reaction for individual participants numbered 1 through 17 are detailed in Appendix B. That section details the protocol for each participant, the reasoning for any protocol change from a previous participant, as well as that participant's speed, lane behavior, and questionnaire responses regarding the event. This section highlights the final four participants (18 through 21) in the study, leading up to the final participant who exhibited the closest behavior to that associated with a moth effect.

The participants were run in order consecutively from 1 to 21. All of the changes experienced for each participant are detailed in Table 2. Over the course of the study prior to participant 18, the protocol for each participant was slightly altered. The following distance of the lead vehicle experimentally decreased from 600 feet, to 500 feet, to 400 feet. Ultimately researchers allowed participants to follow at a distance they were most comfortable as this allowed them to rely less on their speedometer to maintain the study's speed limit of 35 mph and focus their attention forward. Each participant followed a lead vehicle that either had flashing or steady taillights engaged, and this was alternated for roughly every other participant. Most participants wore the eye tracker; however, starting at Participant 15, some participants were not outfitted with the eye tracker as the mounting discomfort caused by the device was believed to prevent drivers from becoming completely relaxed. Lastly, the laps the participant would follow the lead vehicle changed from the final three laps to every lap after the first four participants were run. It was believed the addition of a new stimulus halfway through increased the attention of the driver.

A summary of the protocol changes instituted for each participant is provided in Table 2. Participant 21 is highlighted as the participant who exhibited the closest moth effect behavior.

Table 2. Protocol changes per participant.

Participant No.	Avg. Follow Distance (ft)	Lead Vehicle Light Condition	Eye Tracker	Following Laps
1	600	Steady	Yes	4–7
2	600	Flashing Hazards	Yes	4–7
3	500	Steady	Yes	4–7
4	500	Flashing Hazards	Yes	4–7
5	400	Steady	Yes	1–7
6	400	Steady	Yes	1–7
7	400	Steady	Yes	1–7
8	400	Flashing Hazards	Yes	1–7
9	400	Flashing Hazards	Yes	1–7
10	400	Steady	Yes	1–7
11	400	Flashing Hazards	Yes	1–7
12	400	Steady	Yes	1–7
13	400	Flashing Hazards	Yes	1–7
14	400	Steady	Yes	1–7
15	300	Steady	No	1–7
16	130	Flashing Hazards	No	1–7
17	130	Steady	Yes	1–7
18	200	Flashing Hazards	Yes	1–7
19	180	Steady	Yes	1–7
20	100	Flashing Hazards	Yes	1–7
21	100	Flashing Hazards	No	1–7

PARTICIPANT 18

Following distance: 200 feet
Following laps: 7 total
Lead vehicle light condition: Flashing hazard lights

The protocol for Participant 18 included the participant wearing the eye tracker and flashing hazard lights on the lead vehicle. The desired following distance was approximately 200 feet and the participant was able to maintain roughly that distance throughout.

Just before the merge, the lead vehicle was instructed to ride near and occasionally on the white edge line so that the maneuver toward the shoulder of the roadway would not be as dramatic as before, potentially reducing the possibility of jarring the participant's attention. Compared to the earlier participants, where the following distance was much further away, the distance of 200 feet or less allowed the participant to clearly see when the lead vehicle had crossed over the white edge line.

As the lead vehicle neared the white edge line prior to the merge, the participant began lowering their speed cautiously. Their speed decreased from 33.9 to 31.36 mph before the merge, to 27.3 mph as the lead vehicle completely merged, and then increased again to approximately 35 mph as they passed the merged vehicle. The participant only slightly adjusted their steering to provide a buffer to the merged vehicle as they passed (Figure 4). These actions did not indicate any lack of attention or moth effect.

Figure 4 and all lane behavior figures to follow in this section detail participants' steering behavior as they approached the event area. Each line represents the center position of the vehicle. The blue line represents the average position of laps 1–3, which often differed from the average position in laps 4–6, indicated by the red line, for early participants in terms of protocol. Protocol differences are described for each participant. The black line represents the final lap, which is the lap where the lead vehicle merged to the shoulder. Many participants, like Participant 18 shown here, moved toward the left lane to give the merged vehicle space as they passed. A moth effect would presumably result in the black line moving toward the "Merged Vehicle Zone" indicated in the bottom of the figure. The yellow line in the figure signifies the center of the roadway and the white line represents the edge of the roadway.

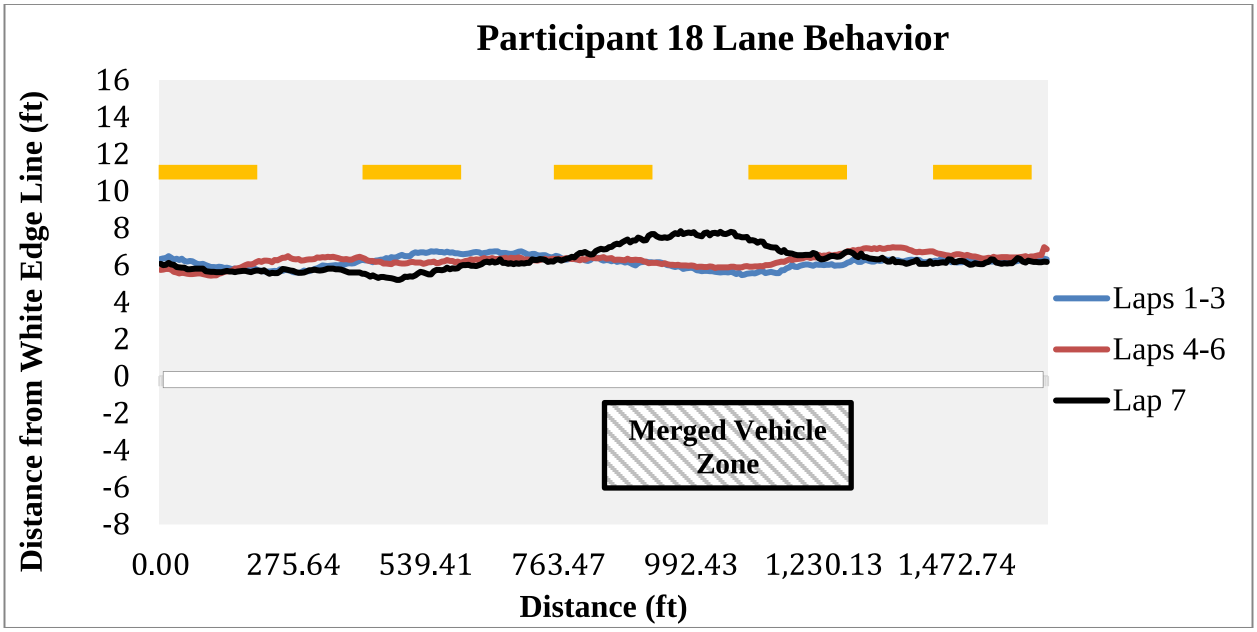

Figure 4. Diagram. Participant 18 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
There was a definite decline to the point I began yawning near the end.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
I notice the lead vehicle veer to the shoulder on several occasions.

Other comments.
The goggles gave me a headache.

PARTICIPANT 19

Following distance: 180 feet
Following laps: 7 total
Lead vehicle light condition: Steady (no hazards)

The protocol for Participant 19 was the same as that for Participant 18, with the exception that the lead vehicle had steady taillights in place of flashing hazard lights. The desired following distance was once again approximately 200 feet, with the participant maintaining a distance of approximately 180 feet.

The lead vehicle was instructed to perform a more gradual merge maneuver for the event lap. For participants who had a longer following distance as part of their protocol, a more drastic and quick maneuver to the shoulder was desired, as researchers wanted the merge to take place without the participant seeing or realizing it. This was possible due to the lead vehicle's distance being beyond the participant's headlamps and the curvature of the roadway at the location where the event took place. For shorter following distances, it was believed a more gradual merge to the shoulder would be less jarring. In addition, the lead vehicle was also instructed to occasionally be nearer to the white edge line throughout the laps, as well as to sometimes cross the white edge line by a few inches. This was added to the protocol so that when the merge event occurred, the eclipse of the white line would not be as surprising, having been seen before by the participant. The lead vehicle neared the white edge line at least once per lap at different locations so that the action appeared random to the participant.

Much like the previous participant, Participant 19 lowered their speed slightly by easing off the accelerator when the lead vehicle neared the edge line (from 35.3 to 32.4 mph). The participant continued to let the vehicle coast uphill to 27.7 mph when passing the merged vehicle. The participant slightly veered toward the center line to allow for a buffer for the pass (Figure 5). There were no indications from their speed adjustment and steering behavior that a moth effect had occurred.

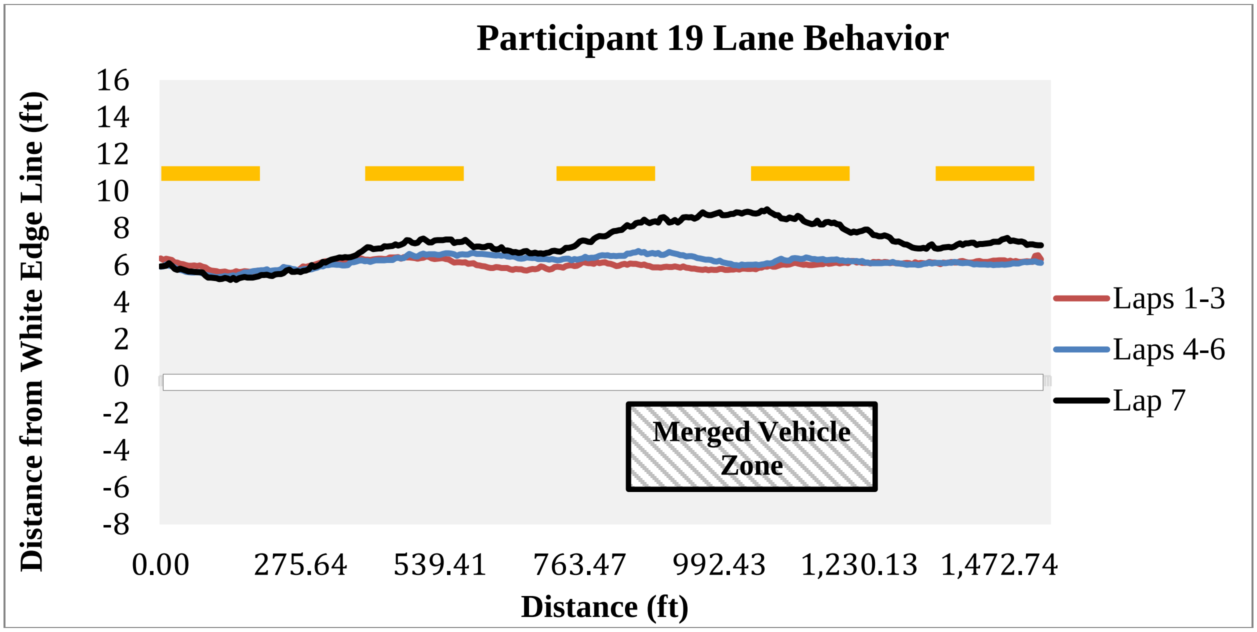

Figure 5. Diagram. Participant 19 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
Two-thirds to three-quarters of the way through, I was starting to get tired and distracted.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
Sharpened my focus and was more alert.

Other comments.
I was interested then bored and was looking for passing of the car. The tail lights were starting to be a distraction three quarters of the way through, and I looked for a way to keep alert by not using brakes to moderate the speed.

PARTICIPANT 20

Following distance: 100 feet
Following laps: 7 total
Lead vehicle light condition: Flashing hazard lights

The following distance was reduced to approximately 100 feet, half of the previous participant's distance. The participant wore the eye tracker and the lead vehicle's hazard lights were engaged for the entire drive. Once again, the lead vehicle was instructed to be near the white edge line and occasionally ride upon it throughout the course of the drive.

Throughout the laps, the participant appeared to emulate the lead vehicle by maintaining a similar lane position. When the lead vehicle neared the white edge line, the participant did as well. Their speed was consistently greater than 35 mph and the following distance was often closer than 100 feet, but not enough to warrant concern or warnings from the researcher.

When the merge event took place, the participant slowed considerably to 21.6 mph. Unsure of what the newly merged vehicle might do next, the participant asked the researcher what they should do, and the researcher advised them they could pass the merged vehicle (Figure 6). Despite emulating the lane position of the lead vehicle several times throughout the drive, the participant did not follow the lead vehicle off the roadway.

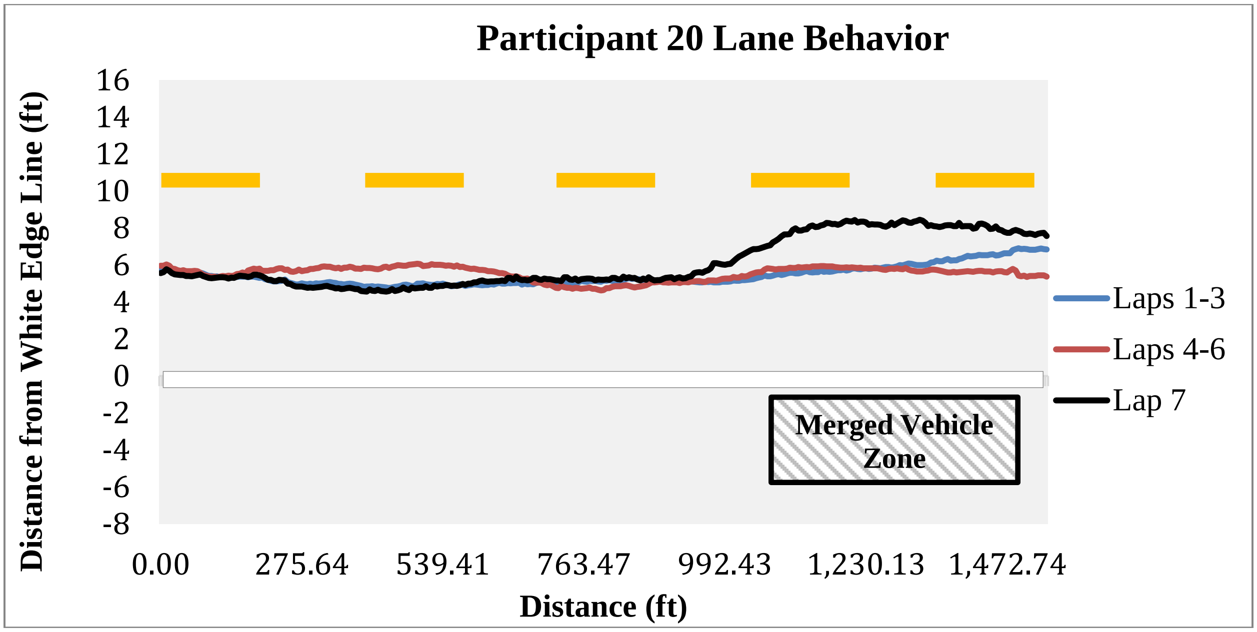

Figure 6. Diagram. Participant 20 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
I started out awake but became very sleepy.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
I asked the passenger what the vehicle was doing and he advised me to go around.

Other comments.
Thank you for allowing me to participate in the study.

PARTICIPANT 21

> *<u>Following distance</u>: 100 feet*
> *<u>Following laps</u>: 7 total*
> *<u>Lead vehicle light condition</u>: Flashing hazard lights*

The protocol for Participant 21 was the same as that for Participant 20 except the eye tracker was not used for this participant. Throughout the drive, the participant steered across the white edge line when the lead vehicle drifted near it, indicating a strong connection to the lead vehicle. The participant also showed many signs of fatigue, including yawning, sighing, and touching their face. All participants were told prior to the drive that if they became too sleepy, drowsy, or too fatigued to continue, they should let the researcher know and the study would stop. The in-vehicle researcher deemed this participant to be simply tired rather than a danger.

During the lap 7 event, the driver drifted across the white edge line and followed the lead vehicle almost off the roadway before realizing the lead vehicle was stopping. The participant then jerked the wheel back onto the roadway and continued driving past the merged vehicle (Figure 7). The in-vehicle researcher did not need to use the auxiliary emergency brake, but was ready to do so. The research team believes that this participant did exhibit a moth effect, and by fixating on the lead vehicle while in a fatigued state, followed it to the shoulder. The broken-black line on the figure below indicates the right tire position of the participant's vehicle.

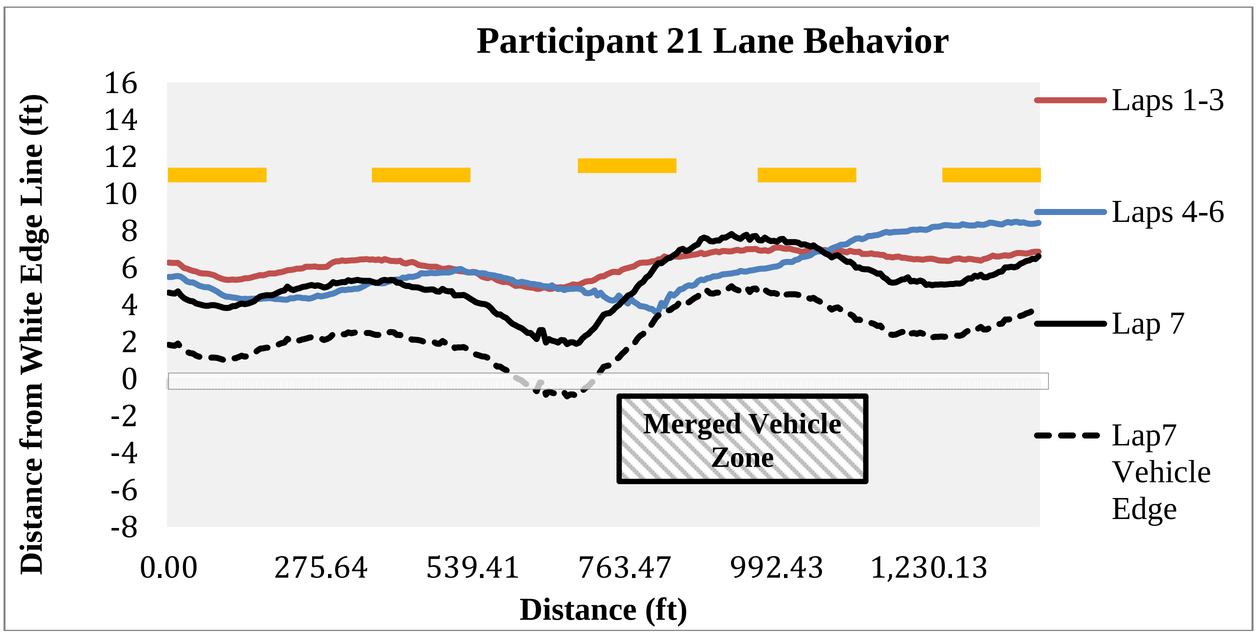

Figure 7. Diagram. Participant 21 lane behavior.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *My alertness/drowsiness was not consistent at start, went downhill about halfway through and at end.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *Caught me by surprise but I stayed on track.*
>
> ***Other comments.***
> *None.*

This was the final participant evaluated, as the study from which the participants were being recruited was ending.

POST-DRIVE SURVEY RESULTS

Starting with Participant 9, a post-drive survey was administered to participants asking them to self-rate their level of fatigue and to explain their mental process when they encountered the lap 7 event. The results from the survey are detailed in this section.

The first question tasked participants with rating their level of alertness before they began driving in the moth effect study (not the previous study they were recruited from). Participants were instructed to place an "x" closest to the term that best described their alertness at the beginning of the study. To view the questionnaire, refer to Appendix A of this report. Figure 8 shows that, on average, participants generally rated themselves as being refreshed, active, alert, and awake and not sleepy, fatigued, tired, or drowsy at the beginning of the test. It is worth noting that they took the survey rating their beginning-of-study alertness after the study was completed.

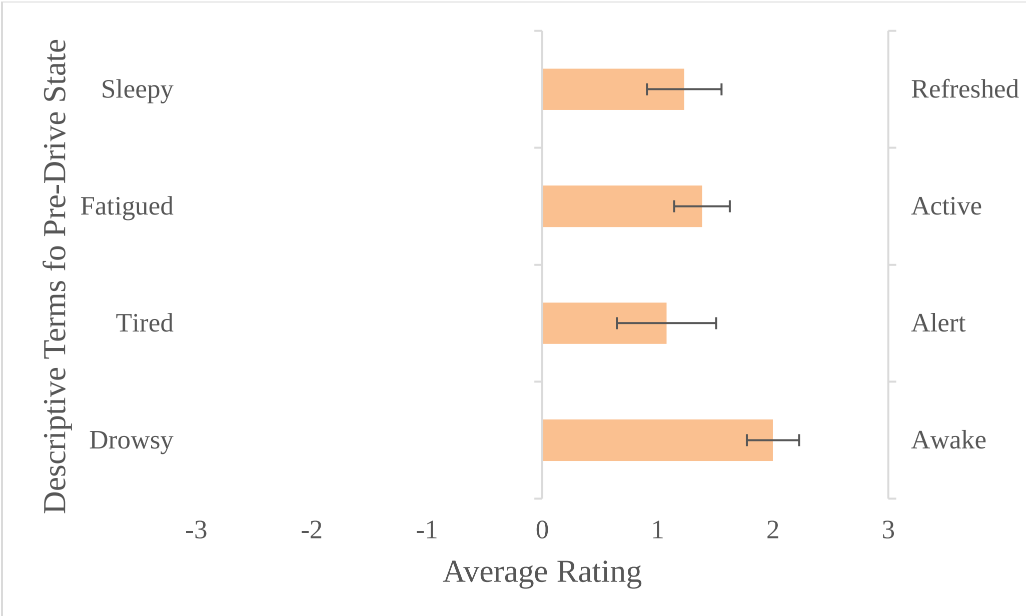

Figure 8. Bar graph. Question 1: Self-rate level of alertness at beginning of test.

The second question tasked participants with rating their level of fatigue, using the same descriptors, on the final lap of the study when the event took place. Figure 9 shows that participants rated themselves as less refreshed, active, alert, and awake than when they began the study. No participants rated themselves as being strongly sleepy, fatigued, tired, or drowsy. On the scale, which ranged from −3 to 3, the lowest mark given to any of the descriptors below zero was −1.

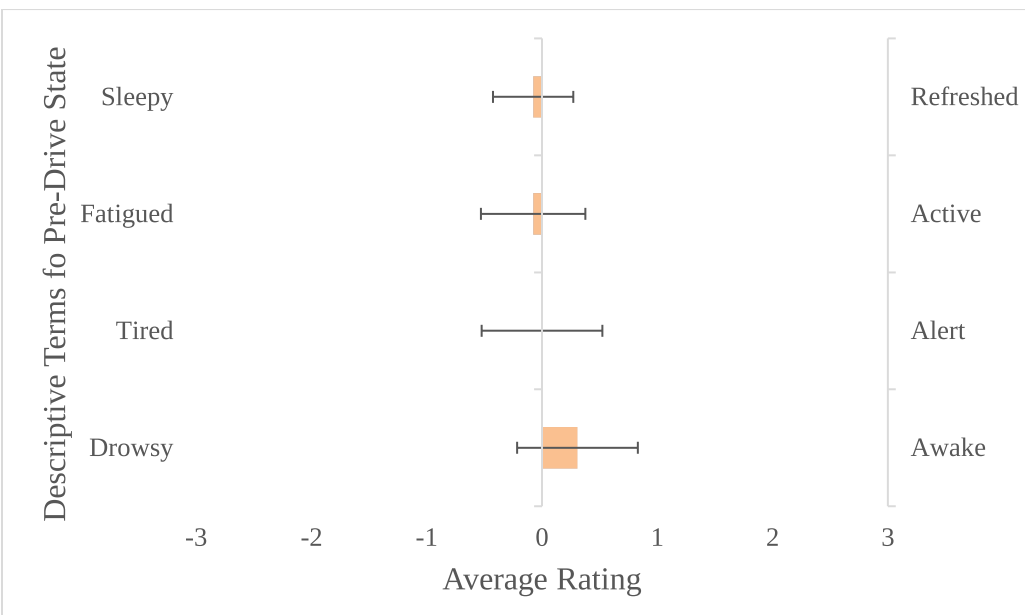

Figure 9. Bar graph. Question 2: Self-rate level of alertness on the final lap.

The third part of the survey inquired specifically about the last laps of the study. The researchers wanted to know what effect the lead vehicle had on the participant, especially steady versus hazard lighting. Participants answered questions related to the laps using a Likert-type rating scale that included Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree. In the following graphs the *x*-axis values are as follows: Strongly Disagree = −2, Disagree = −1, Neutral = 0, Agree = 1, and Strongly Agree = 2.

Question 3-A proposed the statement, “I was distracted by the taillights of the lead vehicle.” For participants who followed hazard lights, the answers averaged to be neutral, indicating they neither agreed nor disagreed with the statement overall. Participants who followed steady taillights tended to disagree with the statement, indicating they did not feel distracted by the lead vehicle’s ordinary taillights. Results are shown in Figure 10.

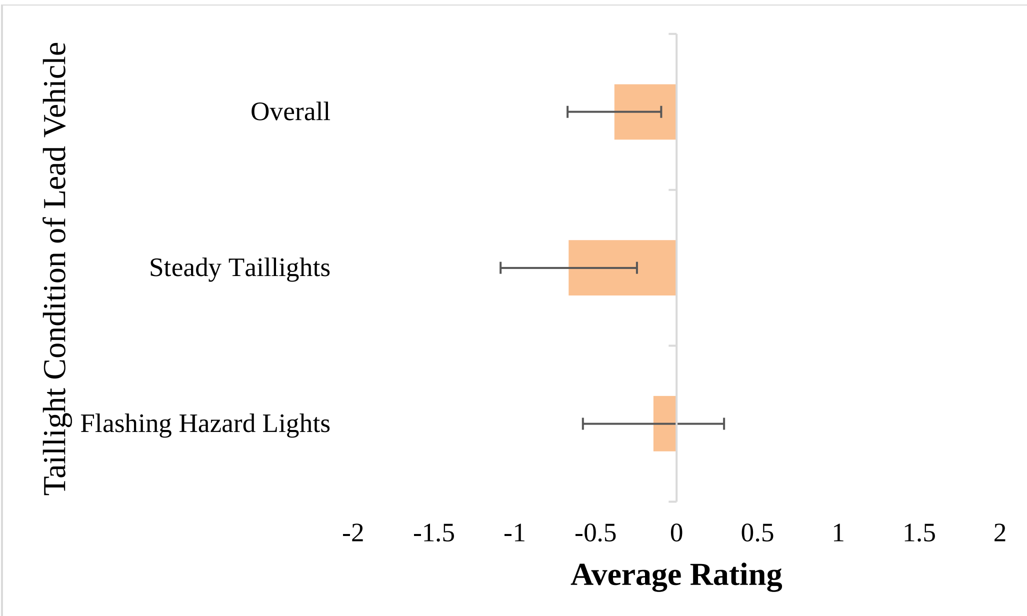

Figure 10. Bar graph. Question 3-A results: Regarding taillight distraction.

In Question 3-B, the statement, “I was transfixed on the taillights of the lead vehicle,” was proposed. The results in Figure 11 illustrate a similar response for followers of both taillights and hazard lights. In general, the average answer slightly disagreed with the statement, indicating that, overall, drivers did not feel as though they had transfixed on the lead vehicle’s taillights. The results for latter participants with a nearer following distance to the lead vehicle did not indicate a different average response than the overall response shown here.

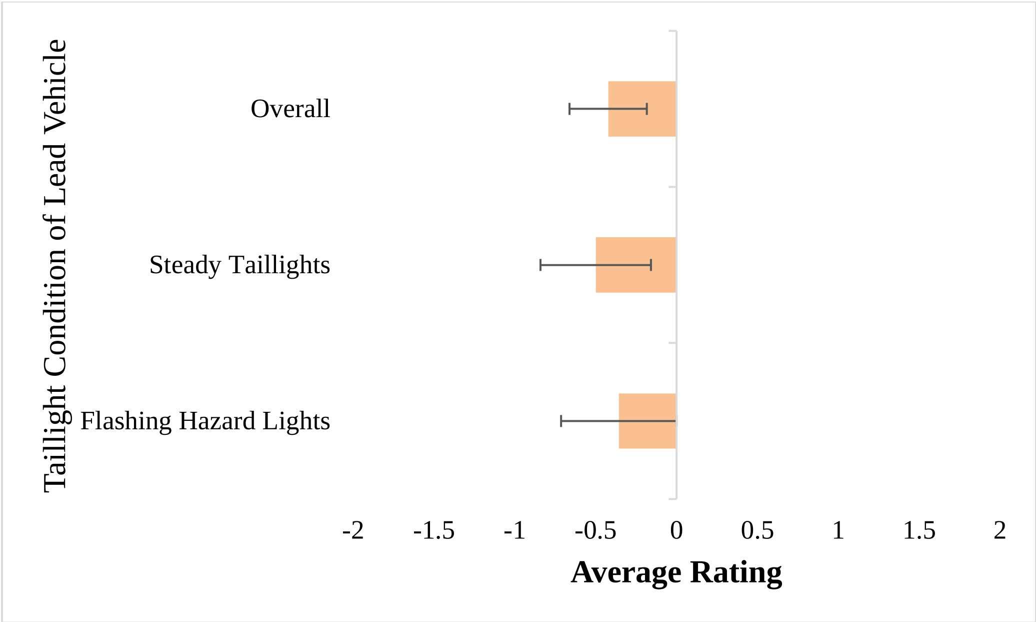

Figure 11. Bar graph. Question 3-B results: Regarding transfixing on taillights.

Question 3-C proposed the statement, “I used the tail lamps of the lead vehicle for guidance.” This question was asked to gain insight about whether drivers were mindful of the route or simply followed the lead vehicle once they were accustomed to the route. As Figure 12 shows, most answers hovered around neutral; however, followers of the flashing taillights did slightly disagree with the statement more than those who followed simple taillights.

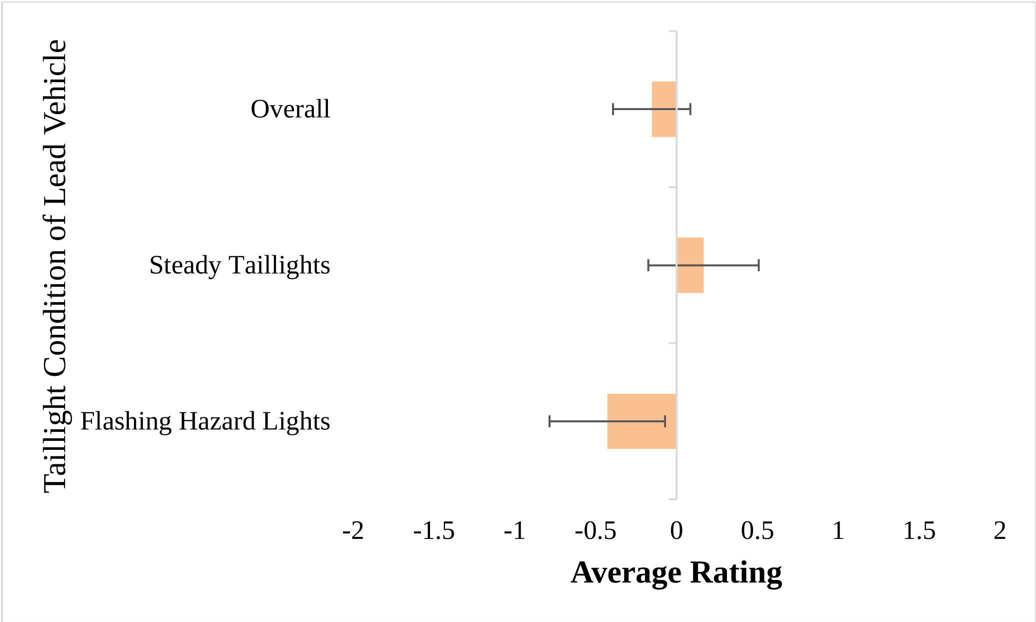

Figure 12. Bar graph. Question 3-C results: Regarding use of taillights as guidance.

Question 3-D proposed the statement, “I was attentive to my surroundings while driving.” This question was another way of asking about mesmerization and distraction while driving. The results shown in Figure 13 indicate generally neutral responses; however, in concert with Question 3-A regarding vehicle distraction, those following the hazard lights indicated they were less aware of the surroundings and more distracted by the flashing lights during their drive.

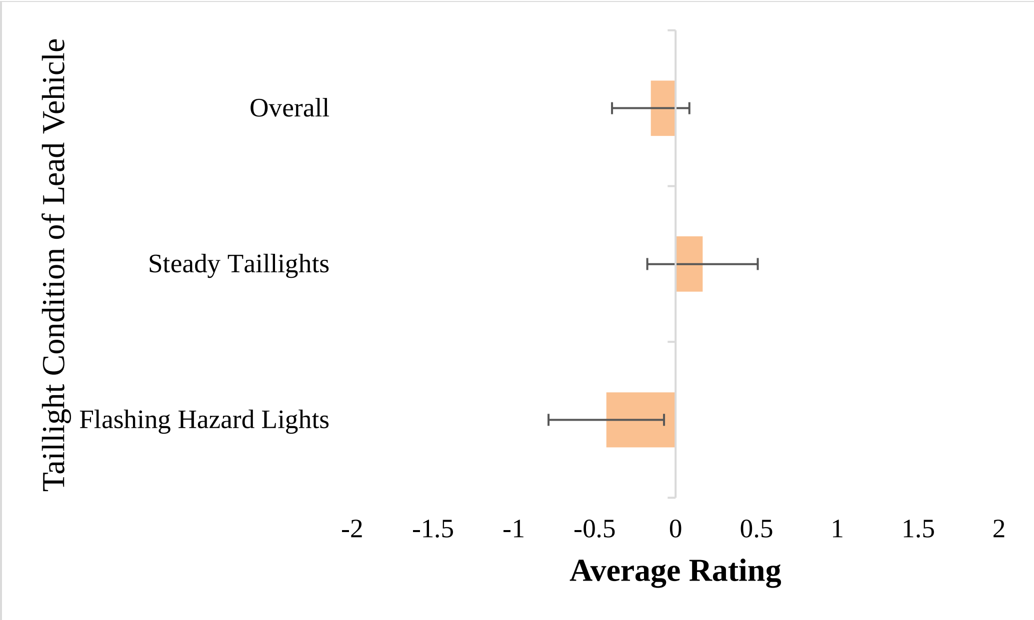

Figure 13. Bar graph. Question 3-D results: Regarding attention to surroundings.

Question 3-E proposed the statement, “I was anticipating an event to take place involving the lead vehicle.” This question was posed to gain insight about whether the attentive state of the participants could be attributed to their expectancy of an event given that they were participating in a research study. The average response was 0.34, very close to neutral and indicating that most participants likely did not anticipate any unforeseen maneuver by the lead vehicle.

Content Analysis

A content analysis was performed for the participants who answered the survey after the drive. The content analysis highlights key terms and phrases used by participants to provide a general answer for the question. The answers are already provided in the participant section; the content analysis is intended to provide a more general insight into each answer.

Question 4-A

Please describe your alertness/drowsiness following the lead vehicle throughout the study:

Four participants indicated that they were perhaps more tired, fatigued, or drowsy than they would typically be comfortable with while driving.

- “Very, very, very drowsy until he pulled over, getting worse and worse.”

- “Progressively got sleepy. Tried moving head left to right biting my tongue to stay awake.”
- “I started out awake but became very sleepy.”
- “On 3 or 4 occasions, I had to really work to keep myself awake.”

Six participants indicated they became bored or somewhat drowsy, but perhaps no more than they typically were while driving in similar conditions.

- “Became drowsy and bored.”
- “Somewhat drowsy.”
- “Became less alert after following lead vehicle after a while.”
- “There was a definite decline to the point I began yawning near the end.”
- “My alertness/drowsiness was not consistent at the start, went downhill about half way through and at the end.”
- “Two-thirds to three-quarters of the way through I was starting to get tired and distracted.”

Three participants indicated they were mostly alert or perhaps only had slightly diminished alertness over the course of the drive.

- “Alert, probably for an event.”
- “I felt alert most of the entire time.”
- “Only slight diminishment during hour. Could have gone a couple more at least before needing to stretch or take a brief break.”

Question 4-B

Please describe your account of the event when the lead vehicle merged to the shoulder in front of you:

Four participants indicated that they were caught by surprise or became refocused when the event took place:

- “It took me a second to respond.”
- “I was startled….”
- “Sharpened my focus and was more alert.”

- “Caught me by surprise.”

The one participant who exhibited the closest moth-effect behavior by following the vehicle a few feet off the road before steering back into their lane, responded as follows:

- “Caught me by surprise, but I stayed on track.”

The remaining responses to this question simply detailed the actions participants took to maneuver around the vehicle and provided no insight into whether they felt mesmerized or transfixed prior to or during the event.

Question 4-C

Please describe your account of the event when you approached the vehicle already parked on the shoulder:

This question sought to elicit answers based on the final event where participants drove by an already parked vehicle on the shoulder. However, because this event immediately followed the previous merging event, participants were more alert, and the data indicated no deviations in lane keeping, speed, or behavior related to the final event.

Question 4-D

If you have other comments about your experience with the study, please add them in the space below:

Two comments referred to the comfort level of the eye-tracking goggles, which motivated their removal for a subset of participants:

- “Try to make the goggles less painful, otherwise it was great.”

- “The goggles gave me a headache.”

One participant indicated that because the term “moth” was used on the informed consent, they predicted the purpose of the study, which may have impacted their alertness.

- “By the fact that it was called moth study, I assumed it had something to do with being attracted to light. I was thinking I should not get too close or transfixed.”

FIXATION ANALYSES

This section details subsequent analyses performed using the acquired data. To attempt to determine the extent of fatigue, the eye-tracker data were used to determine changes in fixation lengths over time.

Fixation Duration

Several studies indicate that fixation duration cannot be used to predict fatigue (Galley & Andres, 1996; Saito, 1992). However, it has been argued that links can be made between fixation and fatigue depending on the environment. Driving fatigued in an urban environment is said to produce shorter fixations than driving fatigued in a rural environment due to the amount of visual information present. Research has found that fixations longer than 900 ms were related to periods of low alertness and microsleeps (i.e., a brief episode of sleep lasting between less than a second to 10 seconds) (Schleicher, Galley, Briest, & Galley, 2008).

Generally, fixation duration is defined as the time between two saccadic movements (i.e., any movement of the eye between two fixation points). Saccadic movements are quite rapid and frequent in addition to being very small.

The eye-tracking data used in this study were not used to determine saccadic eye movements at a granular level. Instead, fixation duration in this research paper refers to time spent staring at the rear of the lead vehicle interrupted only by obviously looking away. If the driver looked away or looked down at their speedometer, then the fixation was considered broken. Neither were blinks counted as a break in fixation in this analysis. It is important to note this difference in definition, as the fixation durations detailed in this section will be far longer than those that consider small saccadic movements as fixation breaks.

The average uninterrupted time that drivers stared at the lead vehicle's taillights is shown in Figure 14. A Student-Newman-Keuls multiple comparisons test, robust to violations of normality and generally used to compare means such as those in this scenario, indicated that a statistical difference existed only between lap 7 and lap 1. The differences shown between laps 2 and 6 were gradual and not significantly different enough to draw any statistical conclusions. It is important to note that each lap took drivers approximately 8–10 minutes to complete, so the *x*-axis can also be attributed to driving duration.

Once again, if the driver blinked and their focus was still on the lead vehicle, this was still considered part of the fixation time. It is also noteworthy that eye-tracking data collected at the point the vehicle merged are not included here, as participants would likely stare at the merged vehicle as it performed that maneuver. Here, we are simply considering the fixation behaviors of drivers throughout the uneventful part of the drive.

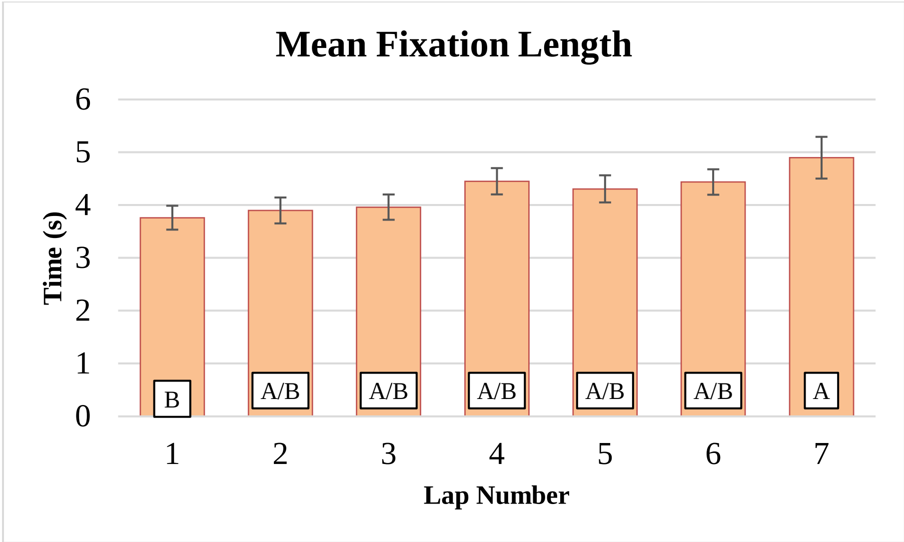

Figure 14. Bar graph. Mean fixation length (both taillight conditions).

When broken down by the lead vehicle's taillight condition, the fixations on the flashing hazard lights were generally longer than the steady taillights, a trend that is more pronounced for the latter laps. Figure 15 shows the differences in the fixations for the two types of lead vehicle rear lighting. Though the data do not include the moment of the merge event where the lead vehicle's maneuver would likely grab the participant's visual attention, fixations for lap 7 appear particularly longer for the hazard light condition. The trend of slightly increased fixation durations over the course of the drive could suggest that the presence of flashing lights, like those of the hazard lights, may increase drivers' fatigue. While the available data cannot definitely lead to that conclusion, the fixation durations do indicate that drivers fixated on the hazard lights for up to an average of 2 seconds longer than the steady taillights on the final lap and after almost an hour of following the lead vehicle.

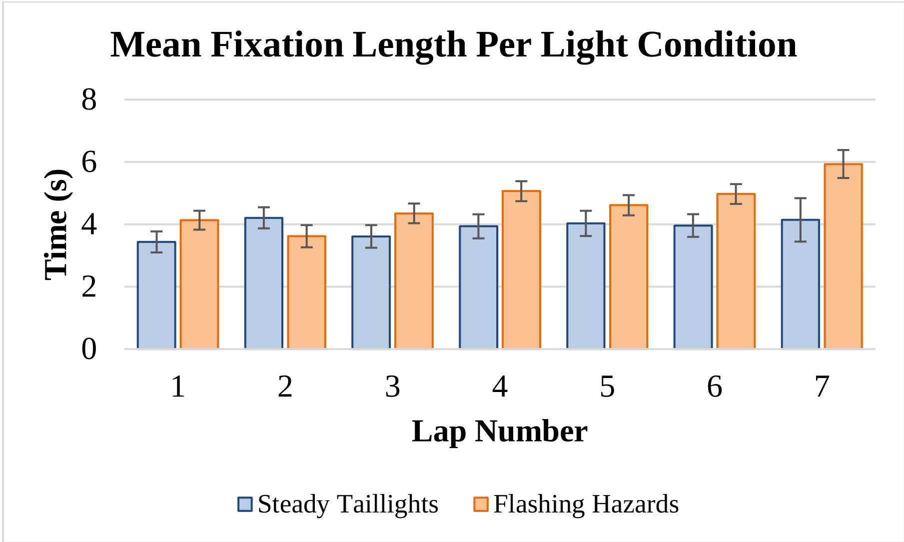

Figure 15. Bar graph. Mean fixation length per light condition.

CHAPTER 4. DISCUSSION

The purpose of this research was originally to determine the factors associated with the moth effect phenomenon. It was determined very early in the process of developing a research plan that this goal would be difficult to achieve in typical research conditions, as the moth effect is generally believed to be associated with fatigue, inebriation, or intoxication, which are difficult to control for and implement safely. The research goal was therefore adjusted to attempt to create a scenario where participants driving a vehicle on a test track may succumb to enough fatigue and attentional deficit that they might perform an action attributable to the moth effect within the limitations of practicing safe research.

The research plan was designed to treat each participant session as its own study and present each individual with slightly different variables. The limitations and restrictions associated with this plan were numerous, especially given the decision to use participants who were subject to a different study in the same night. Participants who agreed to participate in both studies were given the option to decline the second study if they felt too tired after the first. The study could also not be performed in inclement weather, and due to the already restricted subject pool, it was not possible to control for gender, age, or any other demographic. Additionally, the number of participants were limited to the number of total nights the other study was to be performed. The moth effect study could only take a single agreeing participant from the other study each night due to the subtleties of participation interaction and stimulation limitations, which would be affected by a second vehicle. In the end, 21 total participants were included and only one participant, the final participant, exhibited any signs of succumbing to the moth effect.

METHODOLIGICAL APPROACH AND LIMITATIONS

The small modifications made to the study's protocol aided slightly in learning how participants attached themselves to the lead vehicle. Early concepts hypothesized that a longer following distance preventing participants from seeing the lead vehicle merge would allow the maneuver to go under their radar, perhaps causing them to exhibit the moth effect and follow the lead vehicle off the roadway. However, this behavior was not observed. Researchers learned that by decreasing the following distance, participants resisted looking at their speedometer as much, allowing them to increase their attention to the lead vehicle. With longer following distances, participants were observed almost obsessively keeping tabs on their speed to adhere to the 35-mph speed limit, as instructed. With a shorter following distance, within 200 feet, drivers were able to use the easily discernable distance as an indication of their speed, which allowed them to focus their attention on the rear of the lead vehicle to increase the average duration of fixation. This, in turn, may have increased the rate of fatigue.

The eye tracker, while a good tool for determining drivers' eye fixation positions, may have limited the amount of fatigue experienced by some participants due to the build-up of discomfort over the course of the drive. Any further research related to the visual behavior of fatigued drivers should consider eye-tracking technology that is both operable at night and non-wearable.

Participant 18 through Participant 21 were exposed to the lead vehicle occasionally skimming the white edge line with its right tires. The lead vehicle was instructed to do this at intermittent intervals at random locations along the roadway so that participants could not determine a routine throughout the laps. This behavior was implemented primarily to increase the participants' steering tolerance, which was likely more rigid due to the research setting. It was believed that if participants witnessed the lead vehicle approach the white edge line on a number of occasions, it would be less jarring when the vehicle merged onto the shoulder during the final lap.

DISCUSSION OF RESULTS

It was not possible to aggregate the results of this study for proper statistical analyses due to the chosen methodology of observing individuals. However, the results still offer a number of findings that warrant discussion.

Survey

Survey results appear to show that the method of inducing mild fatigue in participants was successful. Only 3 of the 13 total participants surveyed indicated that they experienced no fatigue or any term associated with fatigue during their drive. Both the surveyed participants and the participants who were not surveyed remarked either in the survey and/or verbally that they experienced fatigue. These responses added credence to the methodology chosen for building fatigue.

However, the survey results did not shed any light on the moth effect itself. In general, participants stated they had become drowsy or fatigued, but also implied that this did not impair their attention or driving. This is perhaps a limitation of having only 13 questionnaire responses. Four participants responded that they were surprised or felt their reaction to the merged vehicle was perhaps delayed due to their lowered alertness. Surprise or reengagement in the driving task during the vehicle merging event may suggest that drivers were experiencing increased fatigue or some form of "highway hypnosis." Participant 21, who came the closest to exhibiting a moth effect by steering just across the white edge line during the event, claimed they were surprised by the event as well, but made no comment as to what compelled them to steer off the roadway.

Fixation

In general, research has found that flashing lights are more conspicuous and better for drawing attention (Laxar & Benoit, 1993; Rothblum, Reubelt, & Lewandowski, 2015) than steady lights. This is true even when the flashing light is of less intensity than a steady counterpart (Rothblum et al., 2015). In this scenario, it would be expected that participants' attention would be drawn to the vehicle in front of them, regardless of whether that lead vehicle used flashing hazard lights or default taillights, due to the absence of surrounding stimuli. However, the data show that participants fixated longer on the flashing hazard lights than the steady taillights. This held true for each lap, but was especially prevalent in later laps when it was presumed that drivers were more fatigued. No link can be drawn between longer fixations on flashing hazard lights and the propensity to succumb to a moth effect since only one moth effect behavior was observed during this study. Nevertheless, an interesting notion is presented here in that flashing light, while more conspicuous and better overall for drawing human attention than a steady light, may increase the rate of fatigue after prolonged exposure. Additionally, longer fixations may correlate to a higher likelihood of steering toward the light, as research shows drivers do tend to steer where they look

(Grasso et al., 1996; Land & Lee, 1994; Martin, 1940; NHTSA, 2007; Wann, Swapp, & Rushton, 2000; Wann & Swapp, 2000).

Lane-Keeping Behavior

Participants' lane-keeping behavior was the most telling aspect of whether or not a moth effect had occurred. The results of lane keeping showed that most participants (19 of 21), provided at least a slight buffer to the merged vehicle by veering toward the oncoming lane during the pass. In a true moth effect, drivers would be expected to veer toward the rear of the merged vehicle due to fatigue and perhaps mesmerization by the rear lights of the vehicle. One of the participants did not react at all in terms of steering but did slow down as they passed. Finally, the last participant did veer toward the merged vehicle before correcting their steering back toward the lane of travel. Again, lane keeping-behavior was considered a stronger metric for determining a moth effect than other measures, including fatigue and eye movement, and while many drivers in the study became fatigued and fixated for long periods on the rear of the lead vehicle, most did not steer toward the lead vehicle after it merged to the shoulder.

It is important to note that the changes in following distance affected the implications of this research slightly. In general, the moth effect is regarded as a scenario in which a vehicle happens upon a parked roadside vehicle and steers into it. By introducing a close following distance, a new scenario is developed in which a vehicle follows another vehicle off the roadway. The research team believes that both scenarios are tied to a reduction in driver alertness, which is perhaps caused by the scenarios and methodology used in this work.

CHAPTER 5. CONCLUSION

Over the course of observing 21 participants complete the session with various adjustments to following distance, flashing and steady lights, lead vehicle steering behavior, and exposure to an eye-tracking device, we can conclude that the following factors may contribute to a moth effect.

- The Virginia Smart Road is comparable to a rural highway due to its length, sparseness, and lack of curvature. Roadways that do not require the constant active attention of drivers, such as rural sections of interstate with light traffic and consistent geometries are likely prime areas where a moth effect may occur.

- Flashing lights, such as hazard lights, caution lights on work vehicles, and emergency lights on police, fire, and ambulance vehicles all may contribute to longer approaching driver fixations. Drivers tend to steer toward the direction of their gaze, and longer fixations increase the probability of steering toward a roadside vehicle.

- Reduced alertness, which is attributable to numerous causes, including drowsiness, fatigue, inebriation, or intoxication, may increase the likelihood of the moth effect. In this study, all participants were purposefully fatigued, so no comparisons to non-fatigued drivers were made; however, there are no reports or cases to be found in the literature or public data sets of an alert driver inexplicably rear-ending a parked vehicle on the shoulder of a roadway. The concept of “highway hypnosis” may also play a substantial role in the phenomenon.

- The vehicle-following task incorporated in this experiment was designed so that participants would become use to another vehicle sharing the restricted-access test track with them. A lead vehicle need not be present for the moth to effect occur; however, similar to the event lap in this study, a roadside stimulus, such as a parked vehicle with taillights or flashers, is part of the effect. While this was tested in this effort, no useful results came from it, as participants suspected the parked vehicle to move or perform an action and thus appeared to approach it with extra caution.

- Fixation durations increased when drivers could follow the lead vehicle closely and manage a following distance instead of continually monitoring their own speed. While the use of cruise control was permitted, no participant used it due to the Smart Road’s steep inclines and declines. In general, the use of cruise control or reliance on following distance lessens the attention required for maintaining speed and may increase the rate of fatigue.

RECOMMENDATIONS FOR FUTURE RESEARCH

No causal factors can be determined from this research, but the research team believes that this study narrowed down the factors that could contribute to the moth effect. Using the building blocks of this effort, future research should attempt to control for or provide more accurate measures of fatigue. Future research should also consider measuring gaze direction and fixations using a non-wearable eye tracker suitable for low-light situations. Lastly, consideration should be given to lane departure warning systems and how well they can refocus the attention of a fatigued driver who may drift from their lane.

Studying the moth effect related to a parked vehicle, instead of the following vehicle used in this study, is perceptibly difficult. On the restricted access Virginia Smart Road, placing a parked vehicle on the shoulder of the road would likely result in participants driving cautiously around it and providing a substantial buffer, as was shown in the results here once the lead vehicle had merged, as they are aware they are being observed. In the event the parked vehicle was only presented once, this new stimulus would rouse a participant driver from the fatigue that had been built over the course of previous laps and likely result in their behavior being similarly cautious and aware. This is why the following task was utilized in this research as a means of maintaining a focal point and lulling driver’s attention.

It is possible that a parked vehicle could be used in the future if a guise was used so participants knew that the vehicle was not going to move. For example, if there was no driver in the vehicle and it was treated as a disabled vehicle. After multiple laps, drivers may quit being overly cautious. However, this also should be piloted prior to testing with this scenario.

A better means of understanding the impact of the moth effect when vehicles are parked on the shoulder may require placing a parked vehicle on a real roadway and using a naturalistic research method. Pointing radars and cameras back toward approaching traffic, researchers could glean information on how drivers approach the parked vehicle through the course of one night or several. Whether traffic strays from the lane of travel and heads toward the parked vehicle when different lighting modes are engaged could be assessed. However, this approach raises ethical and safety concerns, particularly if a moth effect were to actually be elicited and cause a passing motorist to crash into a parked research vehicle.

APPENDIX A. POST-DRIVE SURVEY

Please rate your answers for the first two questions by placing an “X” or checkmark in the appropriate space based on your experience. For example, if asked to represent snow, one might answer like this:

Ice ___:_X_:___:___:___:___:___ Water

1) Please rate your ***alertness at the beginning*** of the study by placing a checkmark in a blank for the following pairs of terms.

Drowsy ___:___:___:___:___:___:___ Awake

Tired ___:___:___:___:___:___:___ Alert

Fatigued___:___:___:___:___:___:___ Active

Sleepy ___:___:___:___:___:___:___ Refreshed

2) Please rate your ***alertness for the final lap*** of the study by placing a checkmark in a blank for the following pairs of terms:

Drowsy ___:___:___:___:___:___:___ Awake

Tired ___:___:___:___:___:___:___ Alert

Fatigued___:___:___:___:___:___:___ Active

Sleepy ___:___:___:___:___:___:___ Refreshed

3) Circle the answer that best describes your experience driving in this study for the last few laps.

   a) I was distracted by the tail lights of the lead vehicle.

|------------------------|------------------------|------------------------|------------------------|

Strongly Disagree Disagree Neutral Agree Strongly Agree

   b) I was transfixed on the tail lights of the lead vehicle.

|-----------------------|-----------------------|-----------------------|-----------------------|

Strongly Disagree Disagree Neutral Agree Strongly Agree

c) I used the tail lamps of the lead vehicle for guidance.

|-----------------------|-----------------------|-----------------------|-----------------------|

Strongly Disagree Disagree Neutral Agree Strongly Agree

d) I was attentive to my surroundings while driving.

|-----------------------|-----------------------|-----------------------|-----------------------|

Strongly Disagree Disagree Neutral Agree Strongly Agree

e) I was anticipating an event to take place involving the lead vehicle.

|-----------------------|-----------------------|-----------------------|-----------------------|

Strongly Disagree Disagree Neutral Agree Strongly Agree

Please describe your alertness/drowsiness while following the lead vehicle throughout the study:

Please describe your account of the event when the lead vehicle merged to the shoulder in front of you:

Please describe your account of the event when you approached the vehicle already parked on the shoulder:

If you have other comments about your experience with the study, please add them in the space below:

APPENDIX B. PARTICIPANT CASE STUDIES 1 THROUGH 17

PARTICIPANT 1

<u>Following distance</u>: At least 600 feet
<u>Following laps</u>: 4 total (lap 4 through lap 7)
<u>Lead vehicle light condition</u>: Steady (no hazards)

The first participant experienced four non-following laps and four following laps and did not exhibit any indication of the moth effect. When passing the lead vehicle on the right shoulder, Participant 1 slowed from 29.6 mph to 25.7 mph and cautiously drifted into the left lane to go around the parked vehicle (Figure 16). This provision of a safe buffer to the shoulder vehicle as they navigated past it indicated the driver's attentiveness.

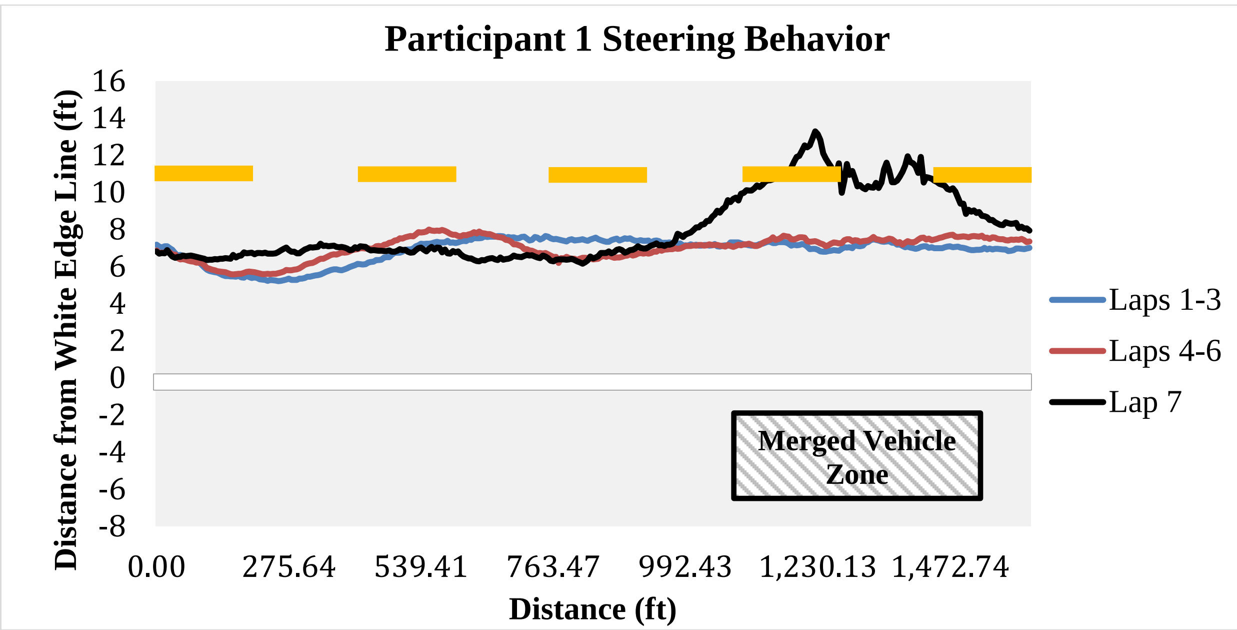

Figure 16. Diagram. Participant 1 steering behavior.

PARTICIPANT 2

<u>Following distance</u>: At least 600 feet
<u>Following laps</u>: 4 total (lap 4 through 7)
<u>Lead vehicle light condition</u>: Flashing hazard lights

The second participant experienced the same protocol as the first, with one exception: instead of following the steady rear taillights of the lead vehicle, the lead vehicle engaged the hazard lights throughout the following scenario. This was to determine if the pulsating flashes of the lead vehicle's rear lights would increase the driver's mesmerization or level of distraction.

At the point that the participant sensed they were closing in on the lead vehicle after it had moved to the shoulder, their speed slightly decreased from 36.6 mph to 34.9 mph. Once the participant saw that the lead vehicle was stopped on the shoulder, they resumed their original speed and moved very slightly toward the center dotted line to give a wider berth to the shoulder vehicle while passing (Figure 17). The slight decrease in speed occurred at approximately 611 feet from the shoulder vehicle; this ample reaction distance indicates that the participant's attention was focused on the lead vehicle.

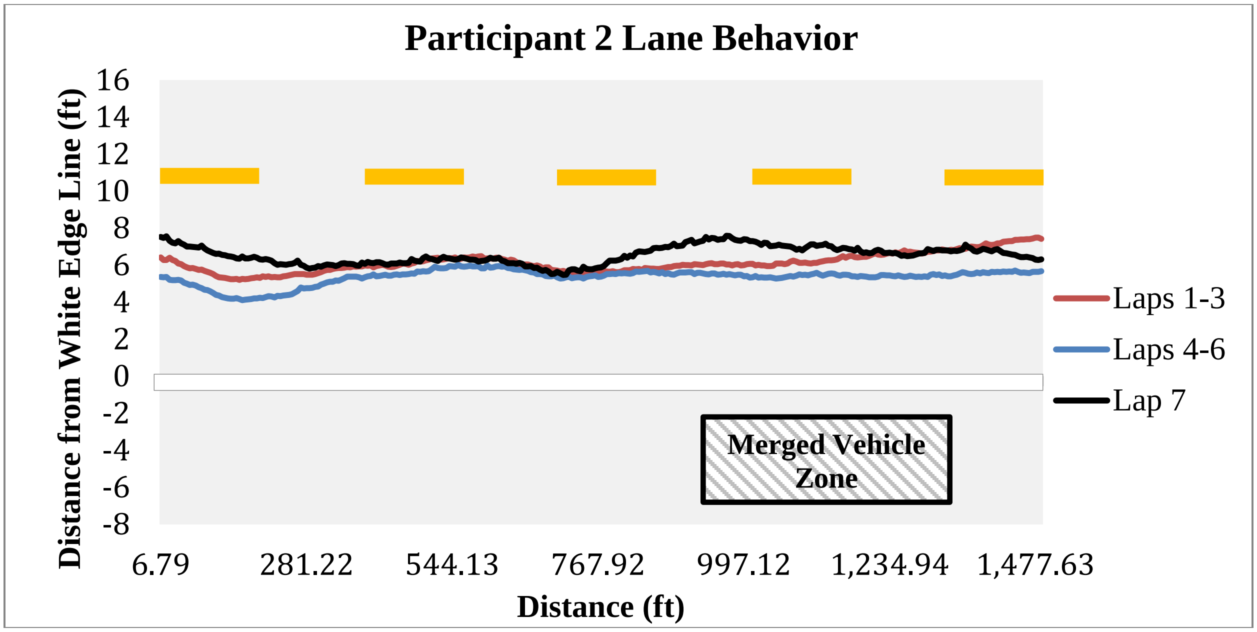

Figure 17. Diagram. Participant 2 lane behavior.

PARTICIPANT 3

> *<u>Following distance</u>: At least 500 feet*
> *<u>Following laps</u>: 4 total (lap 4 through lap 7)*
> *<u>Lead vehicle light condition</u>: Steady (no hazards)*

The protocol was slightly adjusted for the third participant so that the distance between the lead vehicle and participant vehicle was shortened by about 100 feet. Based on the two prior participants' behavior, it was determined that the previous separation distance may have been too great for participants to fixate on the taillights continuously. It was believed to be important for the following vehicle not to lose sight of the lead vehicle's taillights so that some mesmerization or fixation could occur.

At approximately 412 feet from the lead vehicle, which had pulled onto the shoulder, the participant remarked, "He's pulled over" as they approached the vehicle. The participant's speed slightly decreased from 33.8 mph to 31.9 mph as they continued their approach and eventually passed the lead vehicle. The participant slightly moved away from the shoulder vehicle during the pass (Figure 18). There was no indication of any mesmerization or moth effect during this test; however, the participant did exhibit signs of fatigue, such as yawning, during their drive.

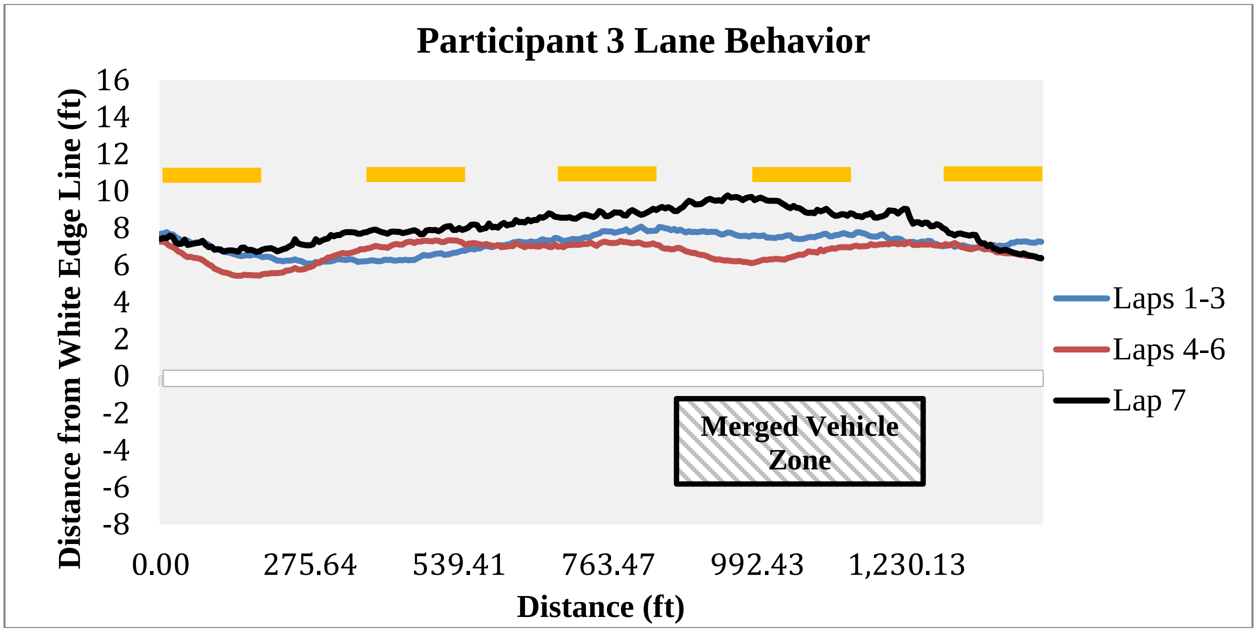

Figure 18. Diagram. Participant 3 lane behavior.

PARTICIPANT 4

Following distance: At least 500 feet
Following laps: 4 total (lap 4 through lap 7)
Lead vehicle light condition: Flashing hazard lights

Participant 4, per eye-tracking data, did fixate on the taillights of the lead vehicle for the lead-vehicle following laps. However, on lap 7 (the event lap), the participant asked the experimenter how much longer the study would take and diverted their attention away from the lead vehicle and their eyes from the forward roadway as the lead vehicle merged over to the shoulder. There was no moth effect present, although the participant's gaze patterns indicated a strong fixation on the lead vehicle for a majority of the drive. It could be that the lull of the task, the time of night (approximately midnight), and the mounting discomfort of the eye tracker encouraged the inquiry about the remaining study duration. The vehicle data for this participant could not be retrieved, and therefore no other insights could be obtained.

PARTICIPANT 5

Following distance: At least 400 feet
Following laps: 7 total
Lead vehicle light condition: Steady (no hazards)

The protocol was modified so the distance between the lead vehicle and the following vehicle was shortened by about 100 feet. This adjustment was made with the hypothesis that decreasing the distance would strengthen fixation and the following relationship between the participant and the lead vehicle.

With the goal of increasing the amount of fixation on the rear of the lead vehicle, another protocol adjustment was made. Previously, the first four laps consisted of the participant driving alone at 35 mph on the Smart Road, with the lead vehicle entering after the fourth lap. This plan was altered so the lead vehicle was present for all laps. This was done for two reasons. First, previous participants continually gazed at the lead vehicle, which was parked on the side of the road before it entered the roadway. Having just completed a police lighting study, some participants verbalized a suspicion that this was some sort of unmarked law enforcement vehicle, and drove with increased vigilance as a result. Second, the entrance of the lead vehicle roused drivers to a new stimulus. By having participants follow the lead vehicle with no change in the task for seven laps, the amount of time for boredom, fatigue, and fixation to occur was lengthened.

As the participant approached the lead vehicle, which had already merged to the shoulder, they slowly neared the white edge line. At approximately 297 feet from the lead vehicle, the participant suddenly applied the brake and slightly steered back toward the center of the lane (Figure 19). The participant reduced their speed from 34 mph to 31.7 mph as they passed the lead vehicle. This reaction indicated that a fixation on the rear of the lead vehicle and a desire to follow that vehicle were present but not strong enough to cause the participant to steer off the roadway. They did, however, appear to be jolted alert upon realizing that they were approaching the lead vehicle faster because it had merged and stopped.

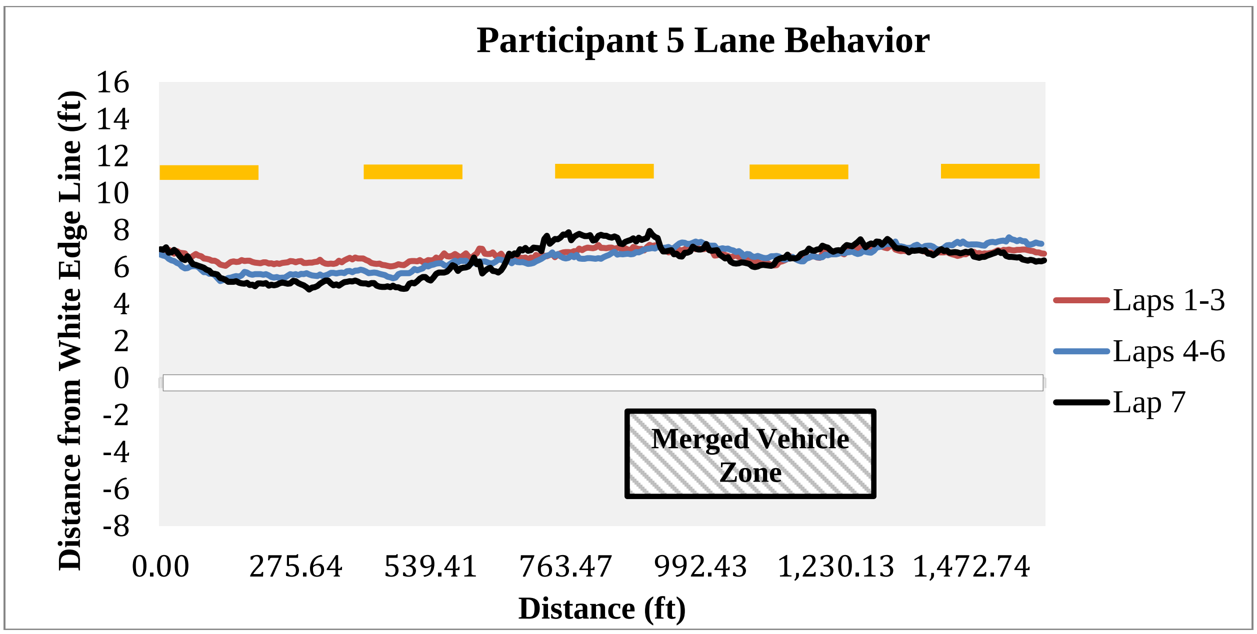

Figure 19. Diagram. Participant 5 lane behavior.

PARTICIPANT 6

<u>Following distance</u>: At least 400 feet
<u>Following laps</u>: 7 total
<u>Lead vehicle light condition</u>: Steady (no hazards)

The protocol for Participant 6 was the same as the protocol for Participant 5. Due to the previous participant's reaction to the lead vehicle during the lap 7 event, no changes were made.

On the fifth lap, an event occurred where the lead vehicle spotted some deer and radioed an alert to the participant vehicle. The in-vehicle experimenter announced the presence of a deer just as it crossed in front of the vehicle (Figure 20). The driver had to apply the brakes forcefully and come to a complete stop in the road to avoid a collision. This event is believed to have aroused the participant's focus, attention, and adrenaline for the remainder of the session. The participant's gazes were more active from this point on, with fixations of shorter durations for the remainder of the session.

Figure 20. Screenshots. Participant 6 encounter with wildlife.

At the point of the merge event, the participant let off the accelerator when it appeared they had detected that the gap to the lead vehicle was decreasing due to the lead vehicle's slow merge maneuver. At this point, the lead vehicle was approximately 458 feet away, and that distance was closing. The participant reduced their speed slightly from 35.6 mph to 32.3 mph before regaining speed and passing the shoulder vehicle. The participant slightly veered toward the center line during the pass (Figure 21). It is assumed that the near collision with the deer two laps earlier increased the participant's vigilance and therefore no moth effect took place.

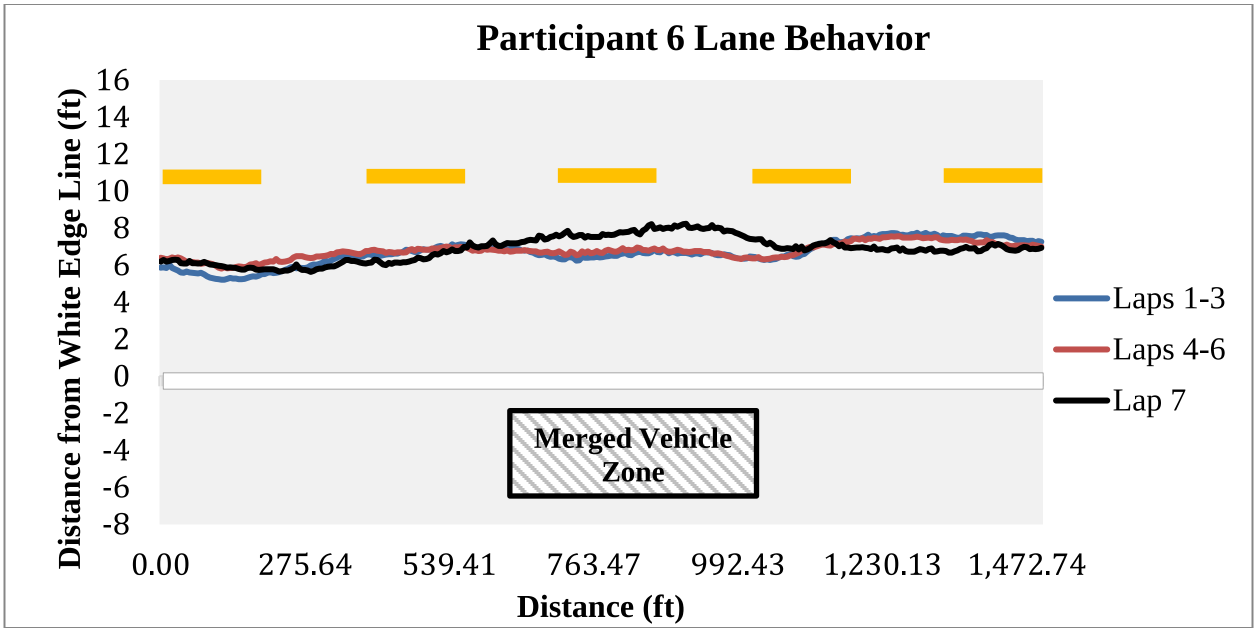

Figure 21. Diagram. Participant 6 lane behavior.

PARTICIPANT 7

> *Following distance*: *At least 400 feet*
> *Following laps*: *7 total*
> *Lead vehicle light condition*: *Steady (no hazards)*

This participant received an identical protocol to Participants 5 and 6. The consistent protocol followed for these three participants was reflective of the belief that the protocol could elicit a moth effect under ideal circumstances.

The participant let off the accelerator and slowed from 34.9 mph to 31.8 mph over the span of 90 feet beginning approximately 321 feet from the shoulder vehicle. The distance of this reaction indicated no significant lack of attention or mindless fixation on the lead vehicle. There was no apparent fixation to the lead vehicle and no change in lane keeping except for a pronounced veer toward the center line when passing the shoulder vehicle (Figure 22) to provide a wider berth when passing. The participant admitted to being a "night person," and reported not being very fatigued at the end of the study.

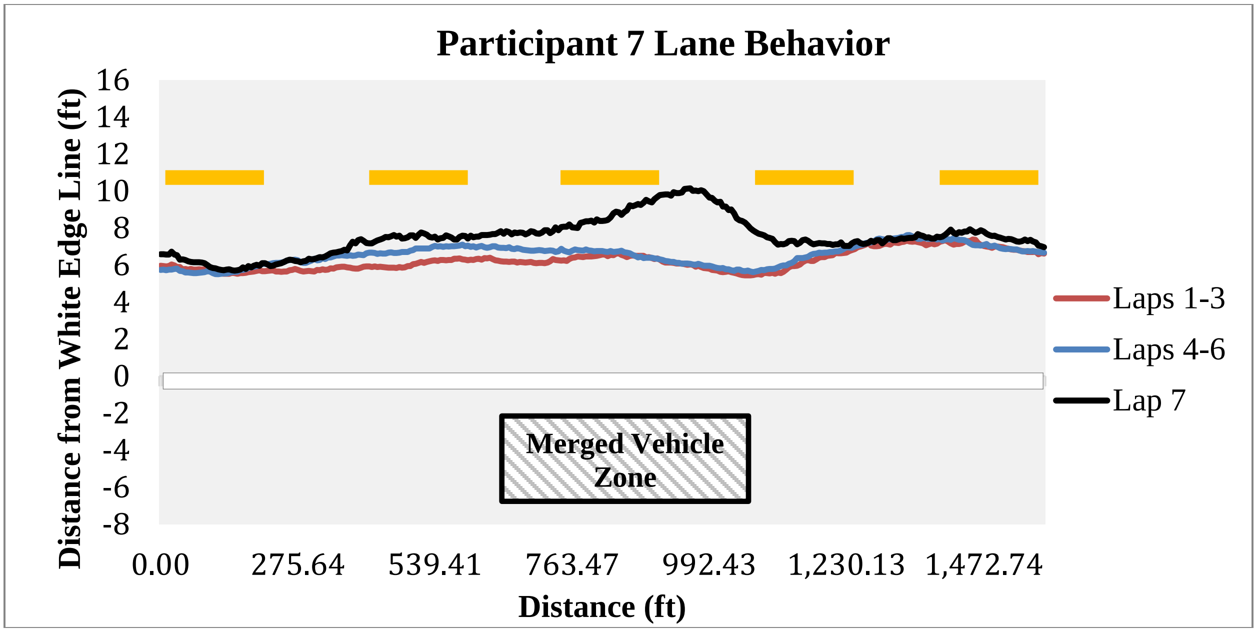

Figure 22. Diagram. Participant 7 lane behavior.

PARTICIPANT 8

> *Following distance: At least 400 feet*
> *Following laps: 7 total*
> *Lead vehicle light condition: Flashing hazard lights*

The use of cruise control was permitted for this and all following participants, though none chose to engage it. This change in protocol was made after reviewing previous participants' eye-tracker data. This data led the research team to believe that the use of cruise control may relieve the pressure on drivers of maintaining the 35-mph speed limit on the Smart Road's inclines and declines, allowing them to instead focus their attention forward.

Participant 8 let off the accelerator at 478 feet from the merged vehicle to decrease their speed from 35.5 mph to 32.7 at about 336 feet away. The participant then regained their speed while passing the merged vehicle. At the same time, they released the accelerator, the participant steered closer to the center line and barely crossed into the opposing lane to give space to the merged vehicle while passing (Figure 23). Nothing in the participant's behavior during this event indicated a prolonged fixation or lack of attention.

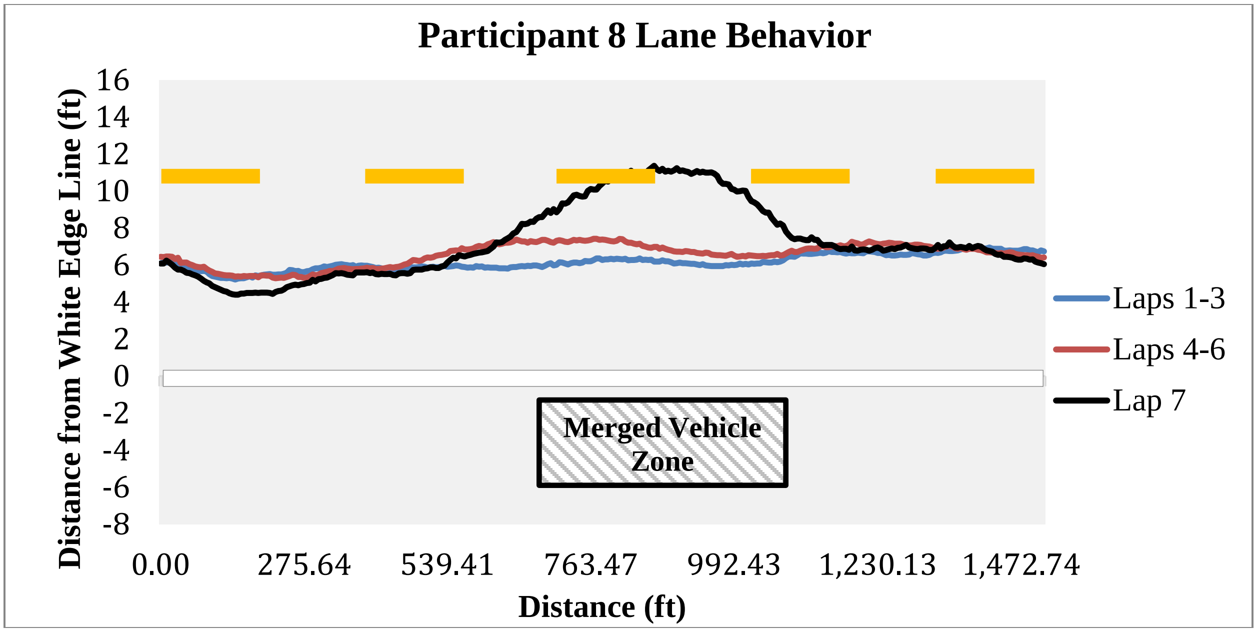

Figure 23. Diagram. Participant 8 lane behavior.

PARTICIPANT 9

<u>Following distance</u>: At least 400 feet
<u>Following laps</u>: 7 total
<u>Lead vehicle light condition</u>: Flashing hazard lights

The protocol for Participant 9 was the same as that for Participant 8, with the exception that a questionnaire was administered after the final lap. Questionnaires were given to all subsequent participants as well to better understand drivers' alertness and thought processes. From this point forward, responses to the questionnaire will be provided for each participant.

The participant's speed had crept beyond the 35-mph speed limit to 39.8 mph at the time of the event, perhaps indicating waning attention. This participant was a bit closer to the merged vehicle than previous participants (330 feet) when they released the accelerator in reaction to the shoulder vehicle. The participant eventually slowed to 33.6 mph before regaining speed and moving slightly further away when passing the shoulder vehicle (Figure 24).

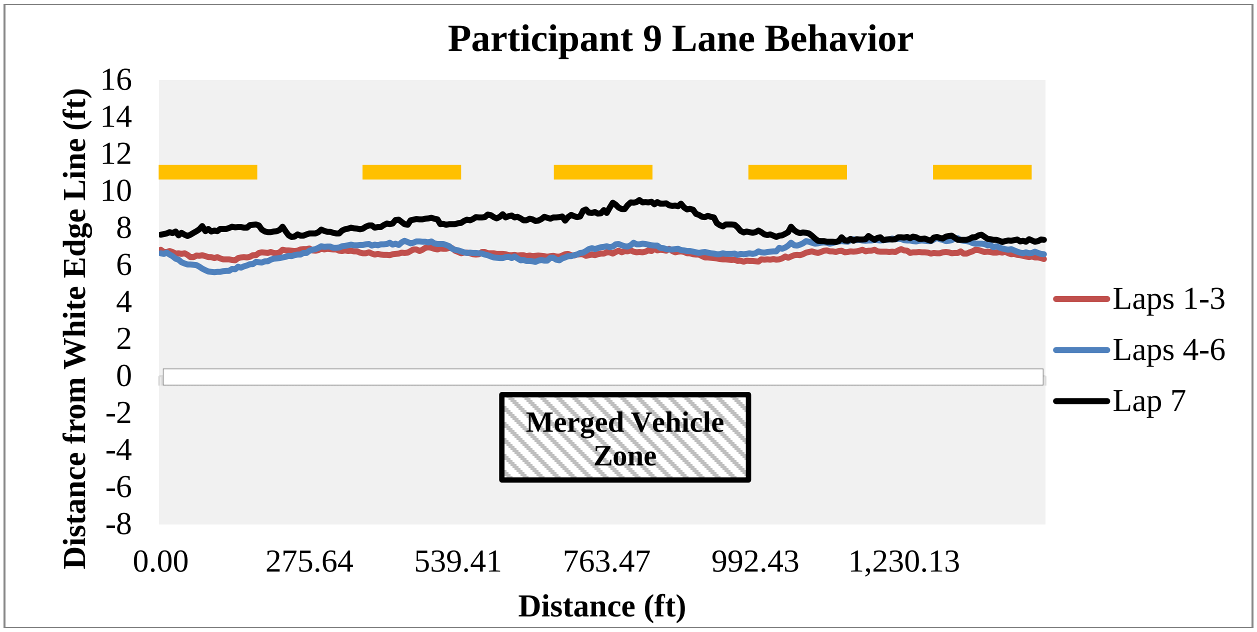

Figure 24. Diagram. Participant 9 lane behavior.

This participant's response time to the merged vehicle was longer than the average participant's response time, and the participant noted aloud that they were "mesmerized" by the lead vehicle's flashing lights vehicle and had been mindlessly following it.

For this and following participants, the long-form responses to the questionnaire are provided.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *Alert, probably for an event.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *Was stopped on shoulder and I continued on.*
>
> ***Other comments.***
> *None.*

PARTICIPANT 10

> *Following distance: At least 400 feet*
> *Following laps: 7 total*
> *Lead vehicle light condition: Steady (no hazards)*

When Participant 10 had narrowed the 400+ foot gap to approximately 195 feet, they were traveling at 32.8 mph. At this point, the participant released the accelerator and applied the brake, indicating they had noticed the lead vehicle crossing the edge line. They reduced their speed to 24.8 mph before inquiring if they could pass and reapplying the accelerator. The participant then passed the vehicle when they felt it was safe to do so, giving the merged vehicle a wide berth in the process (Figure 25). The participant's speed adjustment reaction occurred later than some other participants', but was not so late that a potential collision was possible. The participant may have realized the gap was closing, but may have been unable see that the lead vehicle was no longer in the same lane until a distance of about 200 feet. This may have been due to the reach of their vehicle headlamps and the curve offsetting their ability to determine whether the lead vehicle was straight ahead and still in their lane.

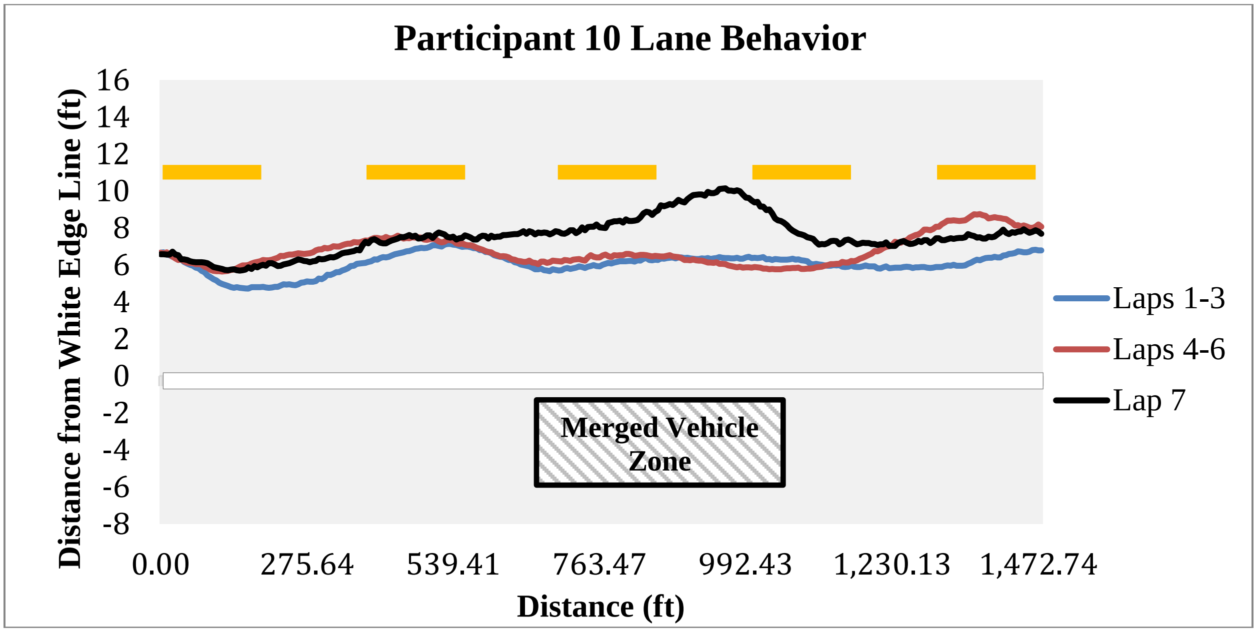

Figure 25. Diagram. Participant 10 lane behavior.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *On 3-4 occasions, I had to really work to keep myself awake.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *Following along, I noticed he drifted to the right and I asked if I could pass. Receiving affirmation, I passed.*
>
> ***Other comments.***
> *None.*

PARTICIPANT 11

> *<u>Following distance</u>: At least 400 feet*
> *<u>Following laps</u>: 7 total*
> *<u>Lead vehicle light condition</u>: Flashing hazards*

The protocol for Participant 11 was the same as for the previous participant, save for the use of flashing hazard lights.

The participant did not react to the merged vehicle by adjusting their speed, but did merge toward the oncoming lane when passing (Figure 26).

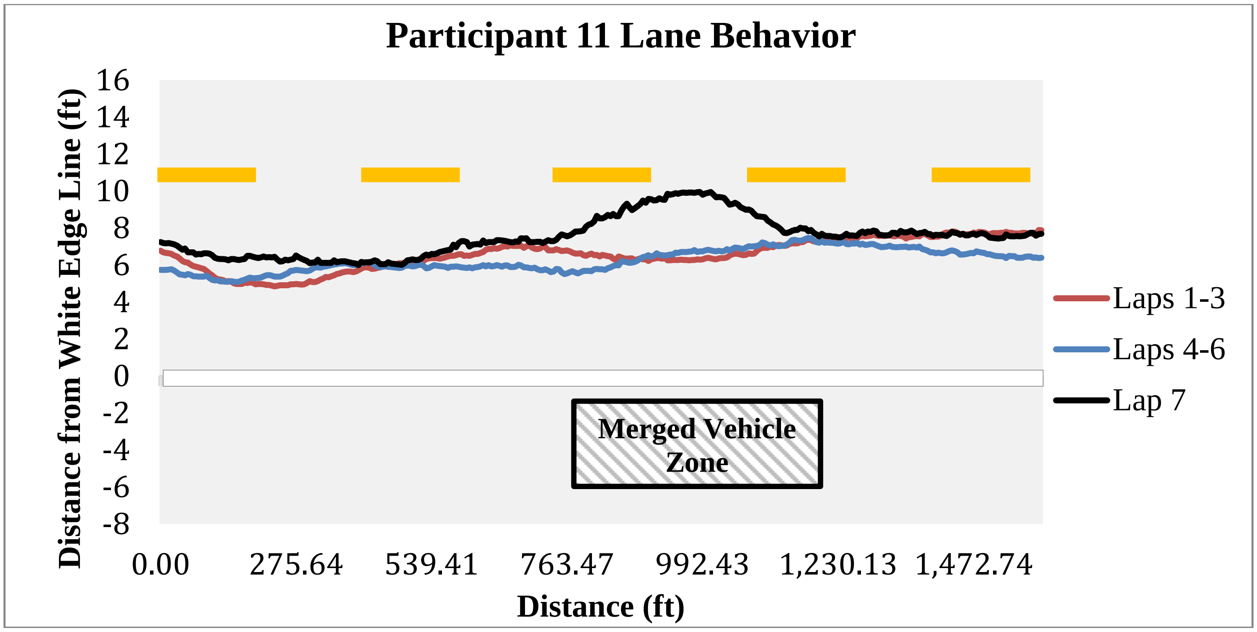

Figure 26. Diagram. Participant 11 lane behavior.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *I felt alert most of the time. The lead vehicle was there but not at focal points. Looking for deer was my attention point.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *I saw it move to the shoulder. I then asked if it was pulling off. I drove by at 35 mph, since it was not in need of help.*
>
> ***Other comments.***
> *Try to make the goggles less painful, otherwise it was great.*

PARTICIPANT 12

> *<u>Following distance</u>: At least 400 feet*
> *<u>Following laps</u>: 7 total*
> *<u>Lead vehicle light condition</u>: Steady (no hazards)*

The protocol for Participant 12 was the same as that for Participant 10.

The participant did not adjust their speed to indicate the point at which they realized the lead vehicle was no longer traveling in their lane. The participant merged into the oncoming lane starting at 215 feet from the merged vehicle and remained in that lane for the duration of the pass (Figure 27), an action which indicates that no moth effect took place.

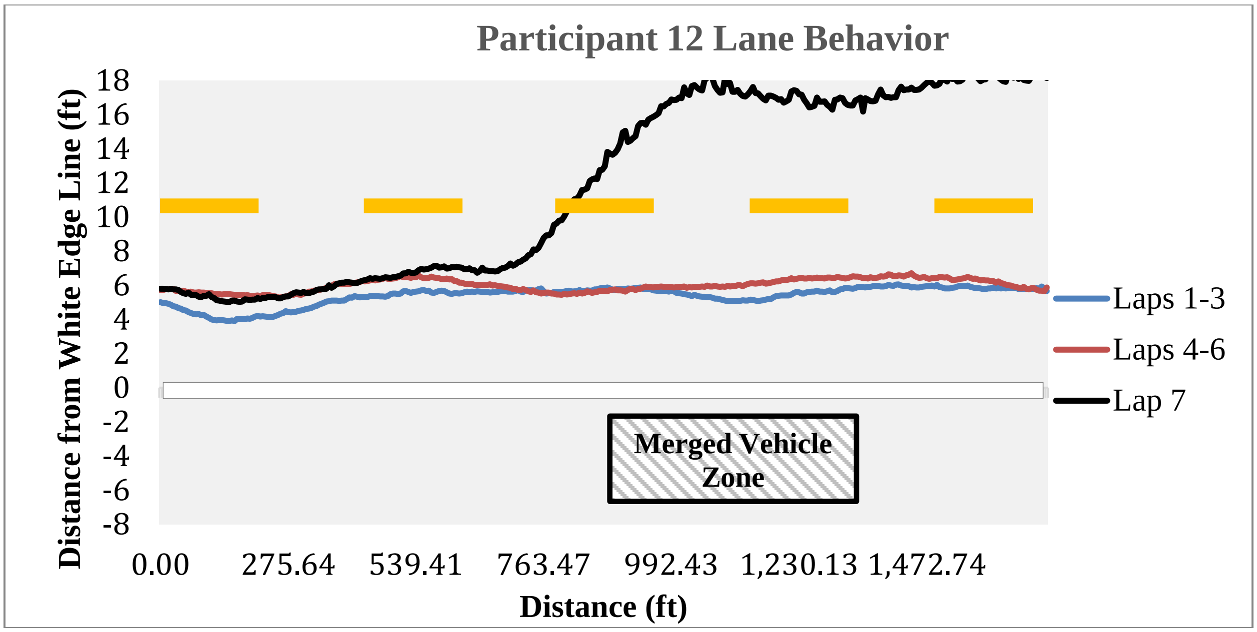

Figure 27. Diagram. Participant 12 lane behavior.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *Only slight diminishment during hour. Could have gone a couple more at least before needing to stretch or take a brief break.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *Wasn't sure why. Passed in left lane, but remained there longer than normal before getting back in right lane since I knew there was no oncoming traffic and wasn't sure what the other vehicle would attempt to do.*

Other comments.
None.

PARTICIPANT 13

Following distance: At least 400 feet
Following laps: 7 total
Lead vehicle light condition: Flashing hazards

The protocol for Participant 13 was the same as that for Participant 11.

The participant first began to slow at approximately 368 feet away, while both vehicles were still moving, but the lead vehicle was slowing. At this point, the participant released the accelerator and reduced their speed from 34.6 mph to 31.1 mph. At 184 feet from the rear of the merged vehicle, the participant began to merge toward the oncoming lane and traveled on the center line for the duration of the pass (Figure 28), actions which, again, indicate that the lead vehicle caused the participant no distraction or inattention.

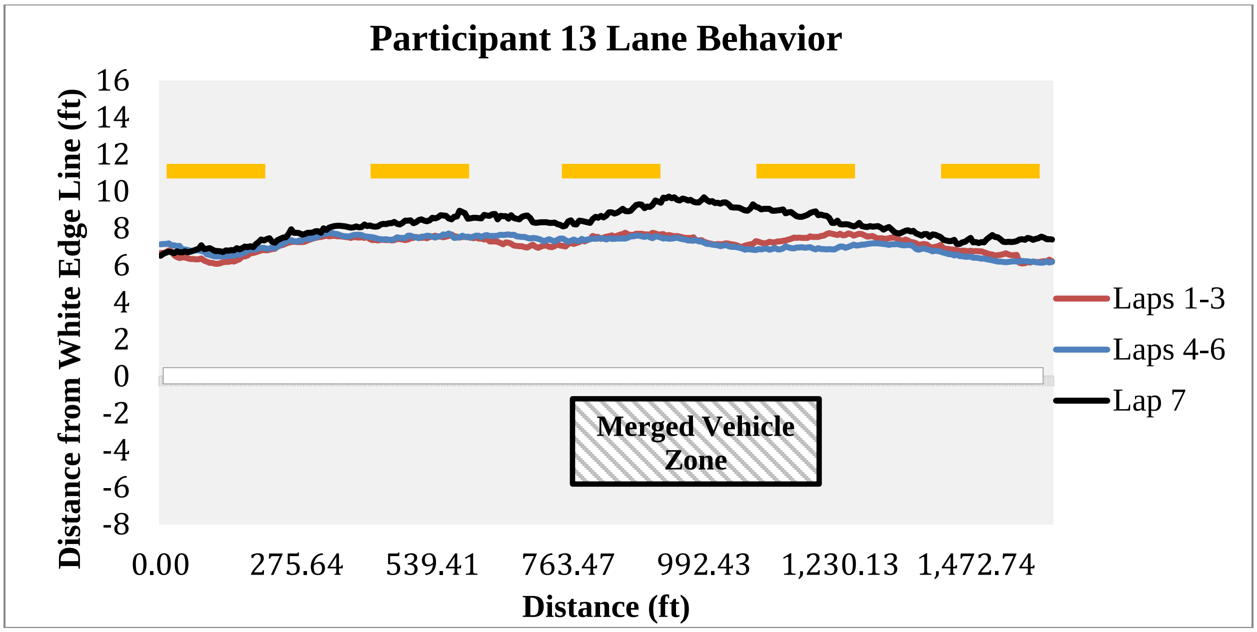

Figure 28. Diagram. Participant 13 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
Became drowsy and bored.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
It took me a second to respond.

Other comments.
By the fact that it was called a "moth" study, I assumed it had something to do with being attracted to light. I was thinking if I should not get too close or transfixed.

PARTICIPANT 14

<u>Following distance</u>: At least 400 feet
<u>Following laps</u>: 7 total
<u>Lead vehicle light condition</u>: Steady (no hazards)

The protocol for Participant 14 was the same as that for Participant 12.

The participant's speed did not change during the event. They did, however, veer closer to the center line during the pass to provide a wider berth to the merged vehicle. There was no indication of a lack of attention or moth effect response for this participant. While the participant indicated in the questionnaire that the lead vehicle used a turn signal to merge, review of the data file did not indicate that this was the case. However, the lead vehicle did merge sooner than intended, resulting in the event taking place a few hundred feet before it was supposed to (Figure 29).

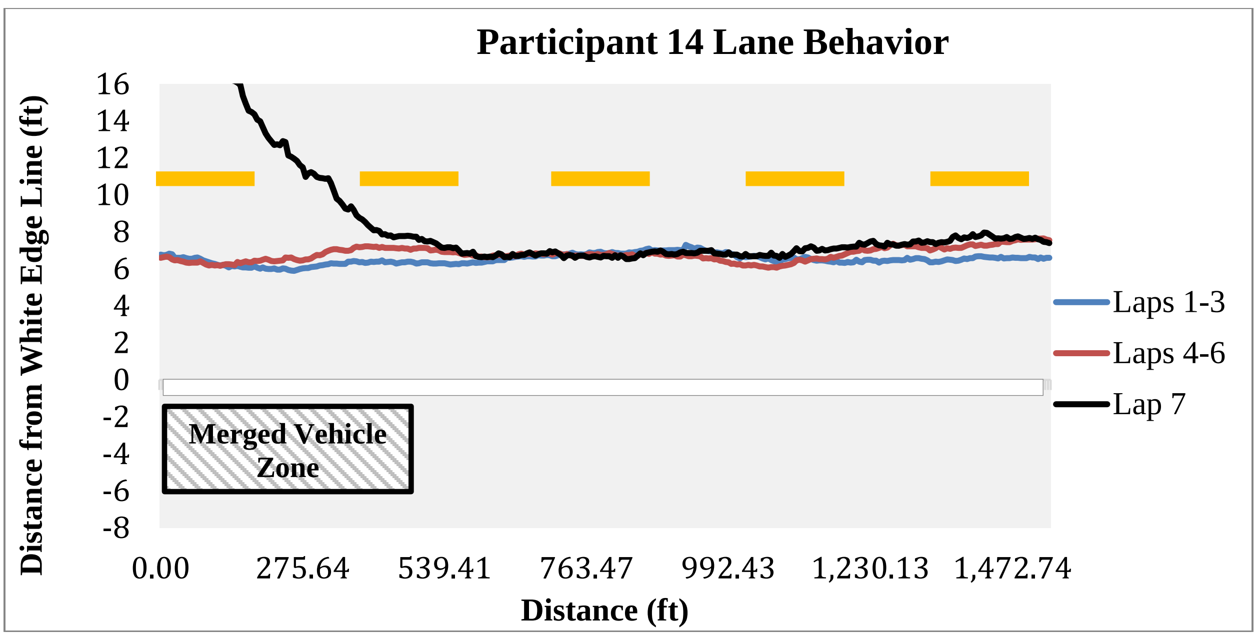

Figure 29. Diagram. Participant 14 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
Became less alert after following lead vehicle after a while.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
Vehicle faded onto shoulder of road after signaling with turn signal.

Other comments.
None.

PARTICIPANT 15

<u>*Following distance*</u>*: At least 300 feet*
<u>*Following laps*</u>*: 7 total*
<u>*Lead vehicle light condition*</u>*: Steady (no hazards)*

The protocol was altered again for Participant 15; for this trial, the participant was not made to wear the eye tracker. A meeting with project stakeholders suggested attempting the experiment without the device, as it was postulated that the discomfort caused by the device, though mild, could distract drivers enough to prevent their attention from slipping. Secondly, wearing the eye tracker let participants know that their gazes were being recorded, which may have resulted in a Hawthorne effect.

The following distance was only slightly shortened, from approximately 400 feet to 300 feet.

The participant’s speed when the lead vehicle merged was 31.5 mph. The closer following distance made the moment the lead vehicle crossed the white edge line more evident to the participant, resulting in the driver adjusting their speed significantly, down to 25.9 mph, likely in anticipation of what the lead vehicle might do next. The participant almost immediately navigated into the oncoming lane to provide a wider berth to the merged car while resuming their speed (Figure 30). These actions indicate the participant was alert to the lead vehicle merging onto the shoulder.

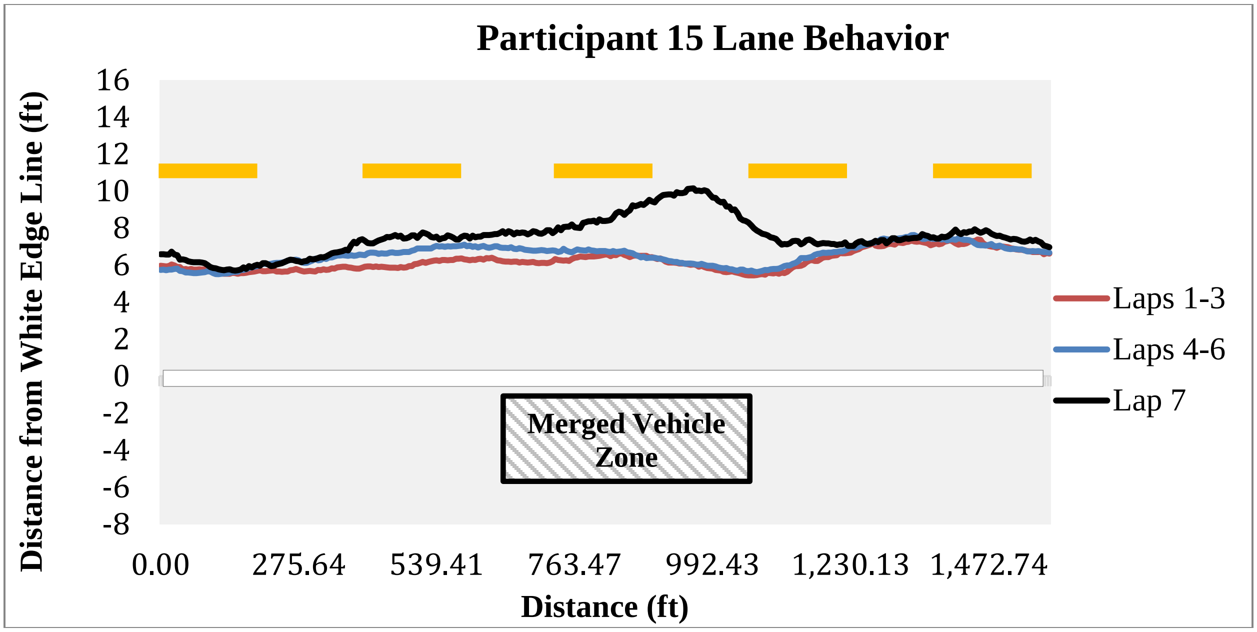

Figure 30. Diagram. Participant 15 lane behavior.

Questionnaire Responses

> ***Describe your alertness/drowsiness while following the lead vehicle throughout the study?***
> *Progressively got sleepy. Tried moving head left to right biting my tongue to stay awake.*
>
> ***Describe your account of the event when the lead vehicle merged to the shoulder in front of you?***
> *I moved over to left lane. Did not think about it was prepared to stop if there had been on-coming traffic in the left lane.*
>
> ***Other comments.***
> *None.*

PARTICIPANT 16

> *Following distance: At least 130 feet*
> *Following laps: 7 total*
> *Lead vehicle light condition: Flashing hazards*

The protocol for Participant 16 was the same as that for Participant 15, with the exception that the lead vehicle engaged the flashing hazard lights. Again, the participant wore no eye tracker for this test.

The following distance was further shortened to strengthen the relationship between the participant and the lead vehicle. The intended distance was approximately 200 feet; however, despite the 35-mph speed limit, the participant tended to drive faster and maintained a distance of approximately 130–150 feet throughout the test.

The participant had closed the gap to within 100 feet at the point of the lead vehicle's merge due to exceeding the 35-mph speed limit. The in-vehicle experimenter did not correct the speed at this time for fear of distracting the driver, as it was believed the neglect of the speed limit was a result of inattention, which was perhaps caused by fatigue. The participant's speed was also not at a dangerous level, only exceeding the 35-mph speed by an average of less than 5 mph. However, when the lead vehicle merged, the participant only slightly decreased their speed and merged completely into the oncoming lane to provide a wider berth for the duration of the pass (Figure 31).

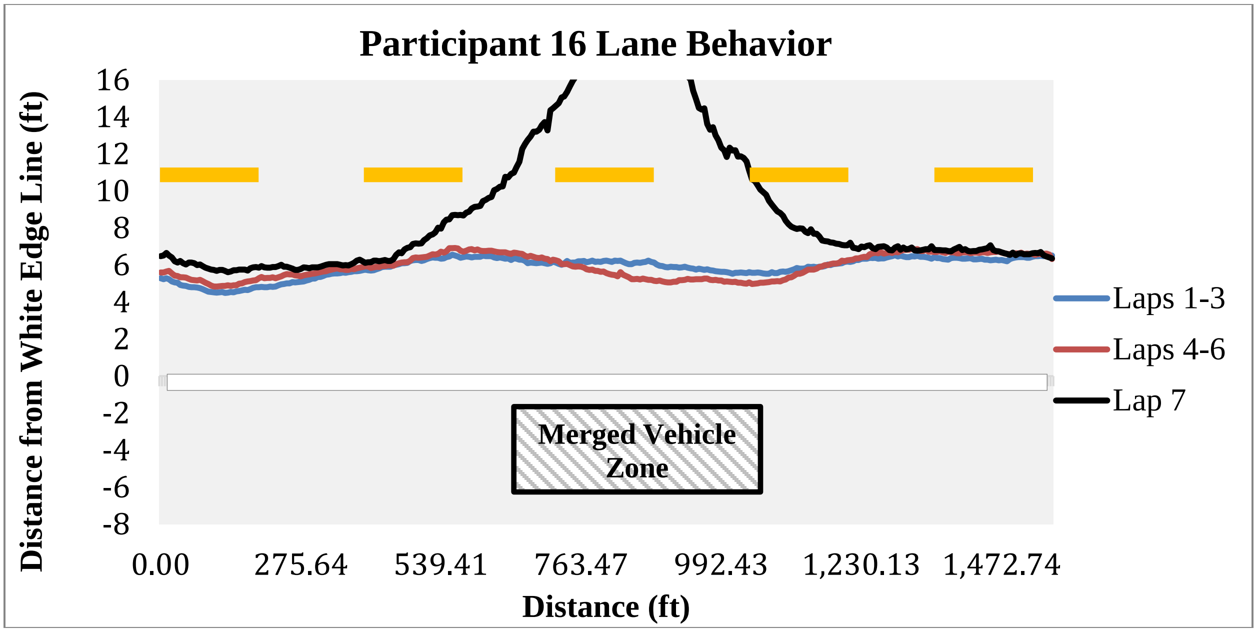

Figure 31. Diagram. Participant 16 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
Very, very, very drowsy until he pulled over, getting worse and worse.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
I was startled then said some stupid stuff, put on my blinker, pulled into the left lane, passed him, changed my blinker, pulled back into the right lane and drove on.

Other comments.
So, so, so sleepy except for the threat of deer.

PARTICIPANT 17

Following distance: *130 feet*
Following laps: *7 total*
Lead vehicle light condition: *Steady (no hazards)*

Participant 17 wore the eye tracker and followed the lead vehicle with steady taillights. The target following distance was just beyond 200 feet and the participant maintained a distance of approximately 130 feet for the duration of the trial. The participant seemed to have a preferred following distance, and the research team believed that allowing them a following distance that they could subconsciously and comfortably maintain could potentially relax their attention.

At the time of the merge, the participant was traveling 34.5 mph and slowed to 29.5 mph as the lead vehicle fully merged to the shoulder. The participant slowly regained their speed and veered slightly away from the merged vehicle to provide a wider berth as they passed (Figure 32). These actions do not indicate any lack of attention due to the moth effect.

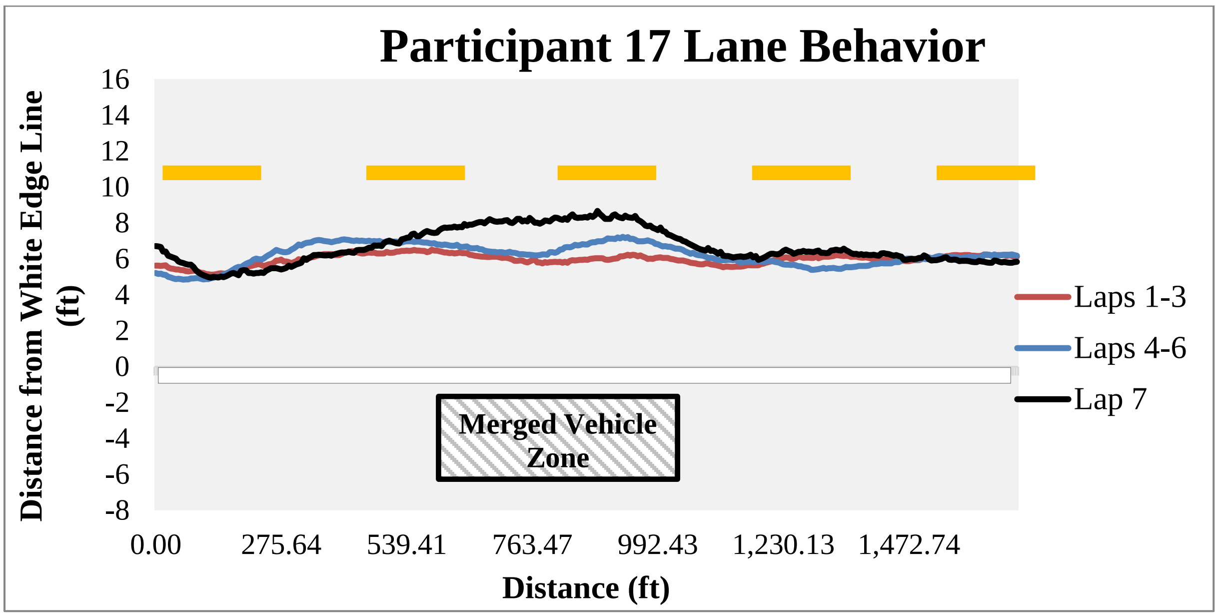

Figure 32. Diagram. Participant 17 lane behavior.

Questionnaire Responses

Describe your alertness/drowsiness while following the lead vehicle throughout the study?
Somewhat drowsy.

Describe your account of the event when the lead vehicle merged to the shoulder in front of you?
Focused on vehicle for longer until I passed, watching for movement.

Other comments.
Relaxing and enjoyable.

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