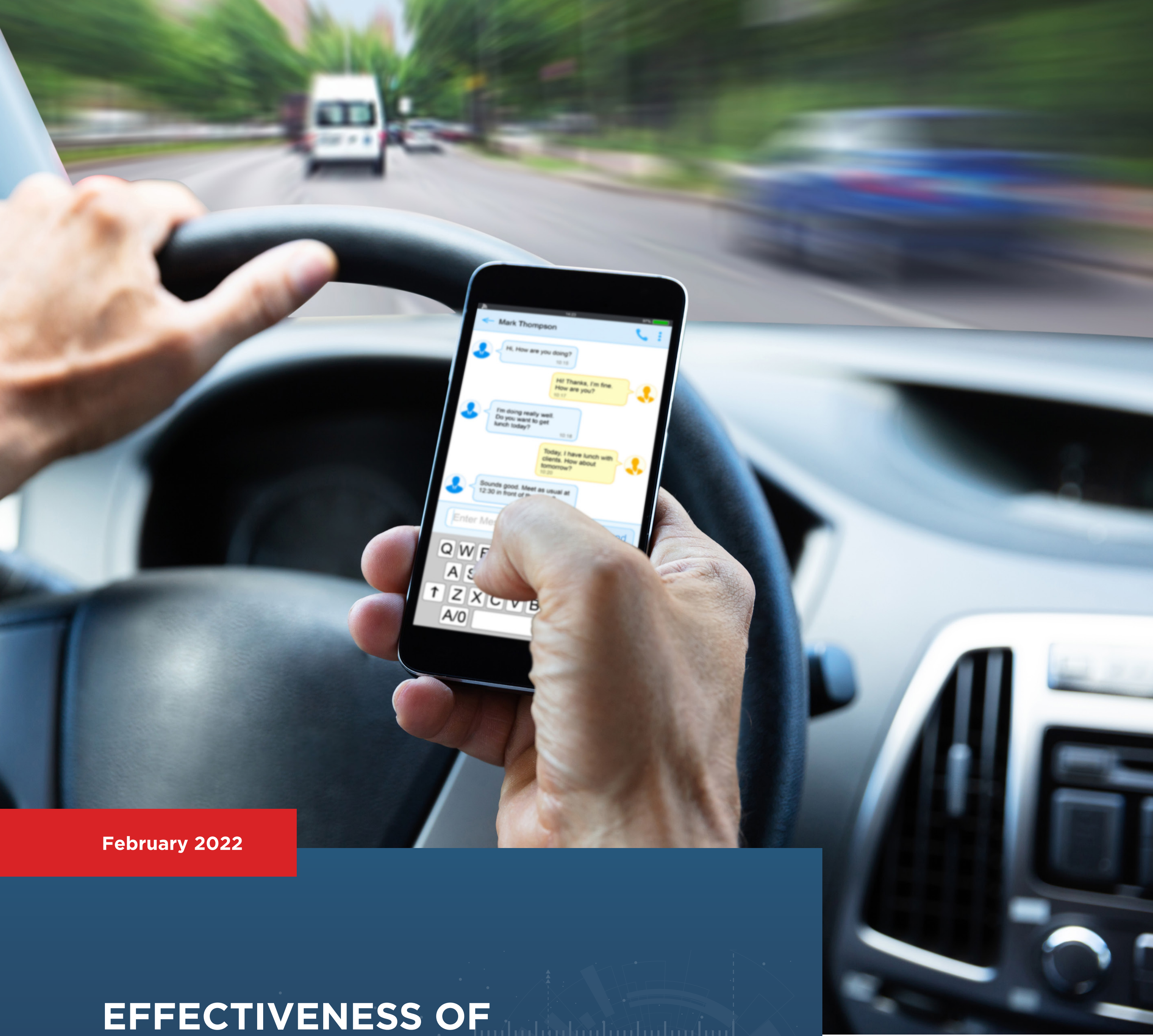

February 2022

EFFECTIVENESS OF DRIVER MONITORING SYSTEMS

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ABSTRACT

Active driving assistance (ADA) systems are becoming increasingly popular and sometimes marketed under confusing names leading some consumers to overestimate system capabilities. Currently available ADA systems are classified by SAE International®[1] as a Level 2 partial driving automation feature, meaning that constant driver supervision is required. To mitigate misuse of these systems, a driver monitoring component is integrated. Within this study, driver monitoring systems are classified as either **direct** or **indirect**. Direct systems integrate a driver-facing camera to detect driver distraction or disengagement. In contrast, indirect systems only utilize steering wheel input for the detection of driver distraction or disengagement. To evaluate the performance of driver monitoring systems with respect to system type, four popular vehicles equipped with an ADA system were evaluated by simulating driver disengagement (common behaviors such as texting, reading, watching videos, or general manipulation of a mobile device) in a real-world highway environment.

Research Questions:

1. How effective are driver monitoring systems at mitigating typical driver disengagement modes in daytime and nighttime lighting conditions?
    - Scenario A: driver looking down with head facing forward and hands off the steering wheel
    - Scenario B: driver facing away from the roadway with hands off the steering wheel
2. Can drivers consistently circumvent driver monitoring systems?
    - Daytime and nighttime lighting conditions

Key Findings:

1. Direct driver monitoring systems were significantly more effective at mitigating driver disengagement than indirect driver monitoring systems in all lighting conditions. On average, the percent of time drivers were engaged was approximately five times greater for direct systems compared to indirect systems.
    - Scenario A: on average, evaluated direct systems issued an alert 50 seconds sooner than indirect systems for both lighting conditions.
    - Scenario B: on average, evaluated direct systems issued an alert 51 seconds sooner than indirect systems for both lighting conditions.
2. Both system types were susceptible to active circumvention attempts. On average, evaluated indirect and direct systems allowed over 5 and 2 minutes, respectively, of simulated driver disengagement. At 65 mph, this translates to approximately six miles of driver disengagement for indirect and two miles of driver disengagement for direct systems.
    - Lighting condition was not a significant factor for evaluated driver monitoring systems.

[1] Society of Automotive Engineers

CONTENTS

I. INTRODUCTION

The availability of active driving assistance (ADA) systems continues to increase across various automotive manufacturers and represents the most advanced driver assistance system available to the public. These systems provide sustained lateral and longitudinal vehicle control, defined by SAE standard J3016 [1] as a Level 2 partial driving automation system. In addition to current functionality, ADA systems are significant because they can be viewed as a precursor to higher levels of automation. Specifically, much of the associated research and development can be iteratively refined to support future autonomous systems.

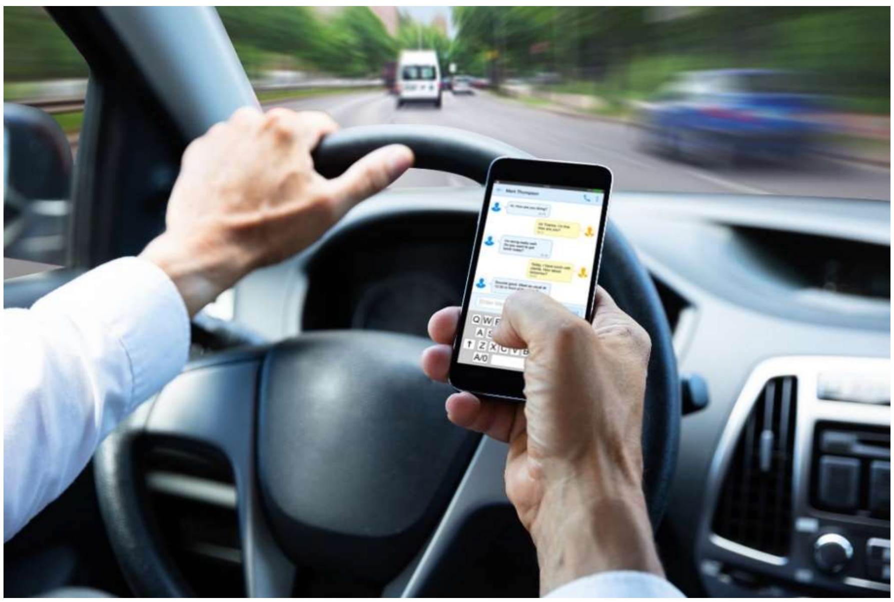

Figure 1: Driver distraction is a significant challenge for safe implantation of ADA systems Image Source: AAA

Unfortunately, confusing and sometimes misleading names for ADA systems are commonplace throughout the industry. Manufacturer names developed specifically for marketing purposes can cause consumers to overestimate the capability of current ADA systems, which require constant driver supervision regardless of the driving environment. In 2018, a survey conducted by AAA found that 40 percent of Americans expect ADA systems with names like Autopilot or Pilot Assist to have the ability to drive the car by itself [2], indicating a discrepancy between consumer understanding and reality.

With constant driver engagement as a prerequisite to the safe operation of ADA systems, a robust driver monitoring component is imperative to mitigate system misuse. It is important to note that “robust” does not explicitly refer to direct monitoring systems. The purpose of this research is to provide insight into the effectiveness of existing driver monitoring systems in the context of mitigating ADA system misuse during highway driving in both daytime and nighttime lighting conditions. This study selected four popular vehicles equipped with ADA systems for evaluation in a real-world highway setting. All testing activities were conducted with a lead vehicle and a safety spotter and consisted of various driver disengagement modes involving gaze direction and head placement in combination with hands removed from the steering wheel. Additionally, test drivers attempted to defeat driver monitoring systems while simulating disengagement involving head placement, gaze direction, and/or steering wheel movement.

The terms "test driver" and "safety spotter" refer to a AAA researcher conducting respective test activities.

II. BACKGROUND

Since ADA systems essentially control all aspects of vehicle motion in highway driving scenarios, it is possible for drivers to become distracted or disengaged regardless of intent. The Yerkes-Dodson law describes an inverted U-shape relationship between stimulation and cognitive performance [3]. Specifically, performance will decline when stimulation is either too low or too high relative to the particular type of task. For a relatively complex task such as driving, performance gradually improves with stimulation, such as interacting with the surrounding environment up to a point, after which performance declines.

With the activation of an ADA system, it can be theorized that driver stimulation will be minimized as the system controls both lateral and longitudinal vehicle motion. The Yerkes-Dodson law implies that performance will be impaired if intervention is abruptly required. Research by Biondi et al. supports this assumption; average response times significantly increased when participants were operating a vehicle with an ADA system in use compared to manual vehicle operation [4]. Similar findings with other types of advanced driver assistance systems, such as adaptive cruise control, have been reported by Stanton and Young [5], as well as Vollrath et al. [6].

While driver monitoring systems in isolation do not fully address the effects of ADA system activation on cognitive performance, they nonetheless represent a primary means of mitigating ADA system misuse. The most common techniques for assessing driver engagement include measuring steering wheel torque, utilizing capacitive touch sensors integrated within the steering wheel, and/or relying on a driver-facing camera (visual or infrared) to detect head placement/gaze direction. Within this study, systems that integrate a driver-facing camera are referred to as a **direct** driver monitoring system. Systems utilizing only steering wheel input are referred to as an **indirect** driver monitoring system.

In recent years, a number of high-profile crashes resulting in numerous fatalities have received significant media, industry, and regulatory attention. These incidents are related in that driver inattention in conjunction with ADA system use was a primary cause of these crashes. Other organizations such as Consumer Reports have referenced these events as evidence that robust driver monitoring systems, resistant to defeat and capable of detecting gaze direction, are an imperative component of ADA systems [7]. AAA advocates for integrating robust driver monitoring within any ADA system characterized as SAE Level 2 operation. Regardless of specific system design, the capability to detect various types of driver disengagement modes and purposeful attempts to utilize ADA systems without driver engagement is essential.

The purpose of this study is to evaluate driver monitoring systems in terms of detection performance for a variety of driver disengagement modes. Four popular vehicles equipped with ADA systems were selected for evaluation; an equal number of direct and indirect driver monitoring systems were evaluated.

Four AAA researchers operated each test vehicle on a real-world highway and simulated three distinct driver disengagement modes with the ADA system activated. Specifically, all researchers simulated each driver disengagement mode in separate ten-minute segments conducted on consecutive testing days. This sequence was performed for both daytime and nighttime driving conditions and repeated such that each researcher operated each test vehicle for equivalent segments. Detailed test methodology is provided in Section VI and Section VII.

III. VEHICLE SELECTION METHODOLOGY

AAA researchers utilized industry sources and information from owner's manuals to verify test vehicles were equipped with an ADA system. To be characterized as a Level 2 system by SAE J3016, an ADA system must provide sustained lateral *and* longitudinal vehicle motion control within its operational design domain. Sales data and vehicle MSRP were considered to ensure that the test vehicles were a representative mix of popular models across various price points.

Evaluating driver monitoring system design in terms of driver disengagement detection was done using an equal number of direct and indirect systems. Specifically, two of each design type were included for evaluation.

Additionally, the following criteria were utilized for vehicle selection:

- The ability for a system to function at speeds up to 70 mph
- Inclusion of domestic and import original equipment manufacturers (OEMs)
- Variety of manufacturers (only one vehicle per manufacturer will be tested)
- The vehicle model was not previously evaluated in 2020

Based on the preceding requirements, the following vehicles were selected for testing:

- 2021 Cadillac Escalade with "Super Cruise™" (direct monitoring)
    - Includes driver-facing infrared camera
        - Build Number: gm/full_gminfo35c_gb/gminfo35c:6.0.1/MIH21B-381/v.int09161704:user/release-keys

- 2021 Subaru Forester with "EyeSight®" and "DriverFocus™" (direct monitoring)
    - Includes driver-facing infrared camera
        - Software Version: Rel_UA.19.36.70

- 2021 Hyundai Santa Fe with "Highway Driving Assist" (indirect monitoring)
    - No driver-facing camera
        - Software Version: TM_FL.USA.S5W_M.V005.001.201120
        - Firmware Version: TMFL.USA.301.201012.MICOM.D

- 2020 Tesla Model 3 with "Autopilot" (indirect monitoring)
    - Includes cabin camera; not utilized for driver monitoring
        - Software Version: v10.2 (2021.4.18.2 6c676ce09ea5)

IV. TEST EQUIPMENT AND RESOURCES

A. Racelogic VBOX Video HD2 with Micro Input Module

Racelogic units were outfitted with two cameras capable of recording video at 1080p with a corresponding frame rate of 30 FPS. One camera was mounted on the roof of the vehicle to capture an "overhead" forward perspective. The second camera was mounted on the headliner to capture an overall perspective of the AAA researcher as they operated the test vehicle. Vehicle kinematic data were captured at a rate of 10 Hz.

A Racelogic Micro Input Module was interfaced with the VBOX unit to capture input from a custom-fabricated box with four single-pole-single-throw (SPST) buttons. Each button served as an event marker to facilitate post-processing. The four buttons correspond to the following events:

1. Beginning/end of complete test cycle comprised of three simulated driver distraction mode segments
2. Beginning/end of each simulated driver distraction mode segment
3. Driver monitoring system alert
4. Driver disengagement following system alert

B. Racelogic Video VBOX Pro

Each test vehicle was simultaneously instrumented with a Racelogic Video VBOX Pro consisting of four Sony HQ1 Super HAD ExView 550/580L NTSC cameras. To capture a detailed perspective of driver activity, road conditions, and ADA system status, cameras were focused on the following points of interest:

- Test driver's face
- Instrument cluster
- Each side of the test vehicle to capture lane positioning

C. Test Route

A limited access toll road was traversed in a 24-mile loop (12 miles in each direction) for all testing for naturalistic highway evaluation. A segment of CA-241 between E. Santiago Canyon Road and Los Alisos Blvd was selected due to its consistency with open traffic moving at or near the posted speed limit of 65 mph.

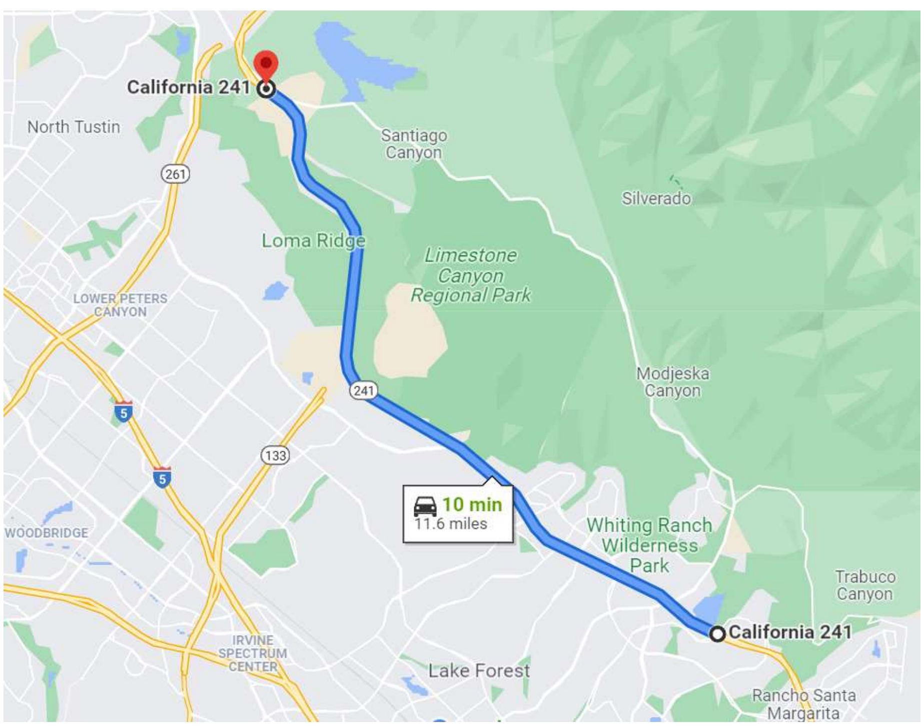

Figure 2: Section of CA-241 utilized for driver monitoring system evaluation Image Source: Google Maps

This type of naturalistic (real world) environment (i.e., open freeway consisting of freely moving traffic), was selected to minimize the introduction of concomitant variables resulting from erratic ADA system performance. Previous AAA research in 2018 found that ADA systems performed most consistently in open freeway conditions. A detailed discussion of this finding can be found on page 48 of the full research report [8].

V. VEHICLE PREPARATION

All vehicles were procured directly from manufacturers or specialty rental fleets. ***Any vehicles procured from a specialty rental company were sourced directly from the inventory of a new vehicle dealership.*** Vehicles provided by the manufacturer were verified by the OEM to be suitable for testing. To ensure the proper functioning of the ADA system, all test vehicles were serviced at Los Angeles–area dealerships to include a four-wheel alignment and recalibration of the ADA system before commencing naturalistic testing. Each dealership provided documentation to ensure ADA systems were calibrated according to manufacturer specifications.

All test vehicles were verified to be equipped with an ADA system with integrated driver monitoring. Systems were verified to be enabled and free of modifications. The odometer reading of all test vehicles was between 200 and 7,000 miles at the start of testing.

Additionally, vehicles were inspected to verify testing suitability according to the following checklist:

- No warning lights illuminated
- All system components free of damage and unaffected by any technical service bulletins and/or recalls
- Any stored diagnostic trouble codes were resolved and cleared
- All fluid reservoirs filled to at least the minimum indicated levels
- Tires inflated to placard pressure following stabilization at ambient temperature in a shaded environment

VI. INQUIRY 1: HOW EFFECTIVE ARE DRIVER MONITORING SYSTEMS AT MITIGATING COMMON DRIVER DISENGAGEMENT MODES IN DAYTIME AND NIGHTTIME LIGHTING CONDITIONS?

A. Objective

Evaluate the performance of driver monitoring systems in terms of detecting driver disengagement. Disengagement modes are characterized by the test driver's hands removed from the steering wheel and head placement/gaze direction away from the roadway such that driver attention may be insufficient to control the vehicle actively.

B. Methodology

Naturalistic highway testing was performed to evaluate driver monitoring systems in conditions representative of their typical operating environment. Depending on the system, one or more driver inputs (including steering wheel torque and/or head/eye position) are monitored to detect driver disengagement. All test vehicles were evaluated utilizing identical methodology regardless of system design to ensure repeatable and consistent test conditions within the bounds of a naturalistic environment.

Within this study, driver disengagement was simulated via two distinct modes in conjunction with ADA system use. Both driver disengagement modes included the complete removal of hands from the steering wheel during the simulation. Additionally, test drivers had their gaze either (i) directed towards the bottom of the steering wheel with their head facing up and towards the roadway or (ii) directed towards the lower center console with their head facing down and to the right. To ensure consistent head and gaze direction between researchers, markers were placed on the bottom of the steering wheel and the center console and served as a focal point for each researcher.

Each driver distraction mode was performed in separate and consecutive ten-minute segments. The 12-mile section of CA-241 between E. Santiago Canyon Road and Los Alisos Blvd in both directions was utilized for all testing. After entering the highway, the researcher began the first ten-minute test segment. After completing the first segment, researchers exited the highway and proceeded to re-enter the opposite direction for the next segment. Each driving researcher was supported by a safety spotter in the passenger seat and a lead vehicle directly in front of the test vehicle. Two test vehicles were simultaneously evaluated; test and lead vehicle pairs were spaced out throughout testing to minimize mutual influence.

It is important to note that all driver disengagement modes consisted of simulated inattention. In compliance with California Vehicle Code 23123.5, at no point were electronic devices utilized by test drivers. Additionally, the lead vehicle was directly in front of the test vehicle for all evaluations to insulate the test vehicle from leading traffic. The primary responsibility of the safety spotter was to monitor traffic ahead and notify the driver to discontinue testing if necessary. Secondary responsibilities of the safety spotter included timing the duration of driver disengagement modes and utilizing event markers during evaluation periods; both responsibilities consisted of single-action movements not requiring the safety spotter to look away from the roadway at any point while the test driver was simulating disengagement.

The safety spotter engaged both data loggers and ensured proper operation as the lead vehicle and test vehicle entered the highway to initiate testing. To complete test segments and avoid merging vehicles, both vehicles traveled at 63 mph in the center lane throughout the all test segments. Once steady-state speed was reached and the ADA system was activated, the test driver began simulating the prescribed disengagement mode until the driver monitoring system provided an audible, visual, or haptic alert. Immediately upon discerning the alert, the test driver refocused on the roadway and placed their hands back on the steering wheel for approximately five seconds before resuming the disengagement currently under simulation. This sequence was repeated until ten minutes elapsed as measured by the safety spotter via stopwatch. After completing the first test sequence, the vehicles exited the highway and proceeded in the opposite direction to simulate the remaining driver disengagement mode. (The third disengagement mode relates to an active attempt by the test driver to circumvent driver monitoring alerts; test methodology and results are described in further detail in Section VII.)

After the test driver completed all disengagement modes, the vehicle exited the highway and data collection was stopped. Researchers then swapped their test driving and safety spotting roles and repeated the above procedure. Once both researchers had simulated each driver disengagement mode in daylight conditions, testing was paused until at least one hour after sunset. Testing was repeated in the same sequence relating to driver disengagement mode and order of test driver for nighttime testing.

1) Minimizing Variables: It is important to note that each simulated driver disengagement mode was separated into distinct segments with no test overlap to minimize introduction of secondary tasks, such as the requirement of the test driver to track the sequence of driver disengagement types for equal representation mentally. Additionally, the single highway section utilized for simulating all distraction modes was beneficial due to the minimal introduction of environmental variables between sequences, test days, test drivers, and lighting conditions. Also, testing began at approximately the same time on all testing days to minimize significant variations in traffic.

To minimize test variation between direct and indirect driver monitoring systems, two test vehicles were simultaneously evaluated at different points along the roadway; each pair of test vehicles simultaneously evaluated consisted of both system types. Two teams of researchers completed all testing within these test vehicles over two days. For the remaining two testing days, the remaining two test vehicles were evaluated on the same schedule. Any variations in driver performance during the progression of the four-day testing week would be equally distributed among the driver monitoring system types, minimizing the possibility for systematic variation resulting from human factors.

2) Quantifying Driver Engagement: For each driver disengagement mode, driver monitoring performance is quantified by the percentage of driver engagement and average disengagement time over the ten-minute test duration. The engagement time varied between test drivers (greater or less than the directed five seconds after alerts) due to human variability and the occasional instance of road and traffic conditions requiring prolonged driver engagement. For each system alert, the driver engagement time was adjusted to five seconds for calculation purposes, regardless of the actual engagement time. This adjustment to driver engagement times affected the total drive time as well. To calculate the percentage of driver engagement, the total number of alerts was multiplied by five seconds; this engagement time was divided by the total adjusted drive time. The average driver disengagement time is reported herein without adjustment.

3) Percent of Driver Engagement: This study's driver engagement metrics depend on reengagement duration and the number of alerts per evaluation period. For each system alert, test drivers paused simulated disengagement for approximately five seconds. A specific re-engagement time was selected such that the calculated percent of driver engagement directly correlated to the frequency of system alerts within the evaluation period. This driver re-engagement duration was not intended to serve as a definitive representation of a typical reengagement period for the population of licensed drivers in the United States. As such, the percent of driver engagement reported herein are not intended to serve as an absolute measurement of driver disengagement associated with ADA system use. Additionally, researchers do not suggest the percent of driver engagement as described herein would equal 100 percent if measured for a fully engaged driver. However, this metric represents a repeatable and quantitative means of comparing direct and indirect driver monitoring systems.

For every evaluation period averaged across test drivers, test vehicles (for driver monitoring system type), and lighting conditions, the percent of driver engagement is equal to the ratio of engagement time and simulated disengagement time over a representative ten-minute period characterized by a specific disengagement mode.

C. Test Results

In the following figures and corresponding discussion, driver disengagement modes are referenced as follows:

- Scenario A: Hands off the steering wheel, head up and facing toward the road ahead, gaze directed downward.
- Scenario B: Hands off the steering wheel, head and gaze directed downward to the right towards the center console.

For all test vehicles and driver disengagement modes, distraction times were averaged and percent engagement was calculated for distinct testing days. These parameters were again averaged to provide equal weighting for each test segment regardless of variation in disengagement frequency and adjusted drive time among test drivers on distinct testing days.

$$i = test\ segment\ (day\ 1, night\ 1, day\ 2, night\ 2)$$

$$j = test\ driver\ (1, 2, 3, 4)$$

$$k = test\ vehicle\ (Cadillac, Hyundai, Subaru, Tesla)$$

$$Distraction\ time\ for\ segment\ i, driver\ j, vehicle\ k\text{: } DT_{ijk}$$

$$Average\ distraction\ time\ for\ driver\ j, vehicle\ k\text{: } Avg\ DT_{jk} = \frac{\sum_{i=1}^{4} DT_{ijk}}{4}$$

$$Average\ distraction\ time\ for\ vehicle\ k\text{: } Avg\ DT_{k} = \frac{\sum_{j=1}^{4} Avg\ DT_{jk}}{4}$$

Figure 3: Equations utilized to calculate average distraction time for each vehicle. Image Source: AAA

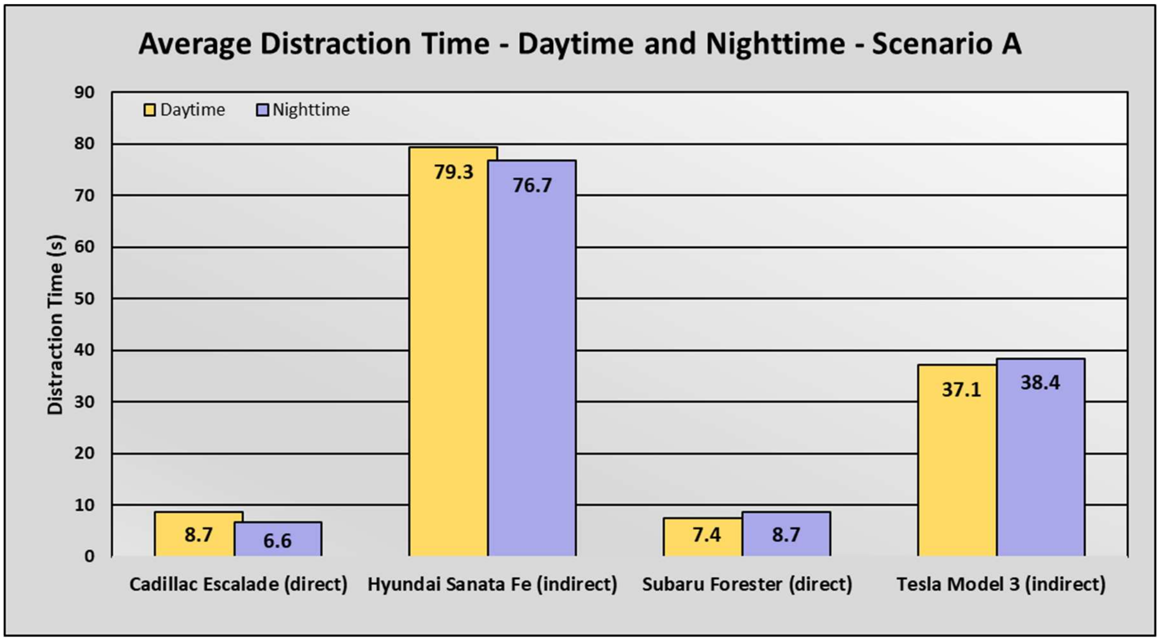

Figure 4: Average distraction time for each test vehicle for lighting condition, scenario A. Image Source: AAA

Figure 4 illustrates scenario A average distraction time for each test vehicle for daytime and nighttime lighting conditions. Figure 3 includes calculations utilized for average distraction times throughout this report.

Among all test vehicles, no notable differences in average distraction time for lighting conditions were noted. This implies that regardless of system design (i.e., indirect or direct), driver disengagement detection is not adversely impacted by low-light environments relative to daytime performance. However, due to the lack of a driver-facing camera, indirect systems can be assumed not to be affected by lighting conditions in the context of a consistently reoccurring driver disengagement mode.

Regarding direct systems, scenario A in nighttime lighting conditions could be viewed as challenging for the driver monitoring system due to gaze direction being the only system input with little to no ambient lighting. But due to the integration of an infrared camera in both the Cadillac Escalade and Subaru Forester, the impact of low ambient lighting conditions on system performance is minimized. This is an encouraging finding as detecting driver disengagement is critically important at night when drivers may be more prone to increased reaction times due to lowered roadway visibility and/or unintentional lapses in engagement such as drowsy driving.

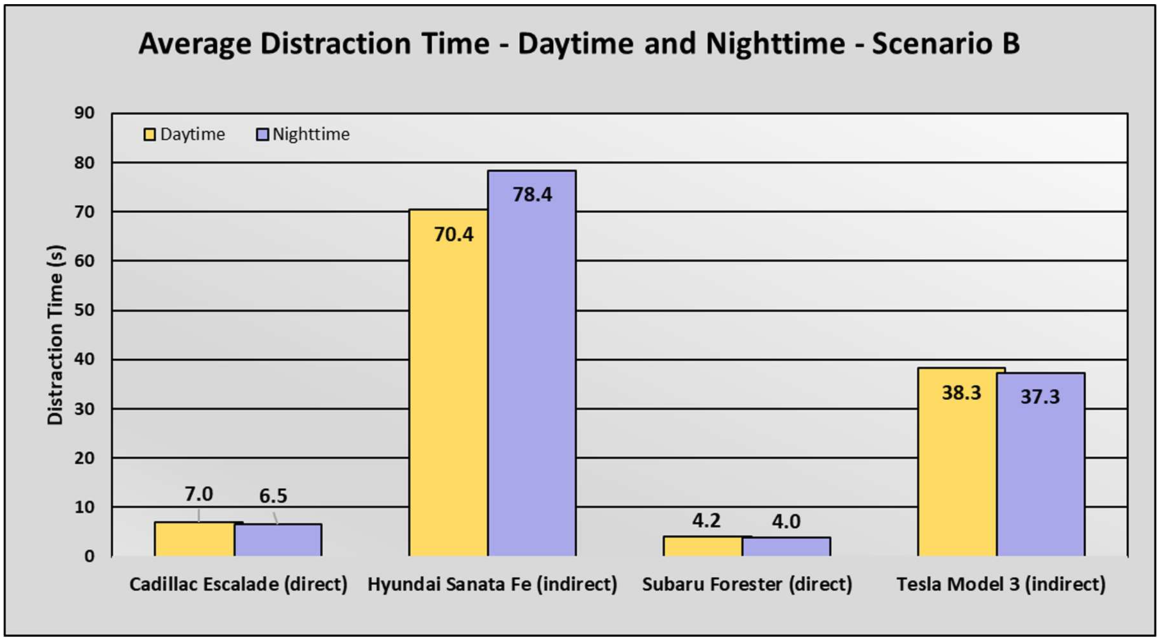

Figure 5: Average distraction time for each test vehicle for lighting condition, scenario B. Image Source: AAA

Figure 5 illustrates scenario B average distraction time for each test vehicle for daytime and nighttime lighting conditions. Among all test vehicles, no significant differences in average distraction time for lighting conditions were noted. This again implies that regardless of system design (i.e., indirect or direct), disengagement detection is not adversely impacted by low-light environments in the context of a consistently reoccurring disengagement mode.

Regarding direct systems, scenario B could be viewed as less challenging for the driver monitoring system in all lighting conditions relative to scenario A due to gaze direction and head placement serving as distinct system inputs. Like scenario A, no significant difference in direct system performance for lighting conditions was exhibited for scenario B.

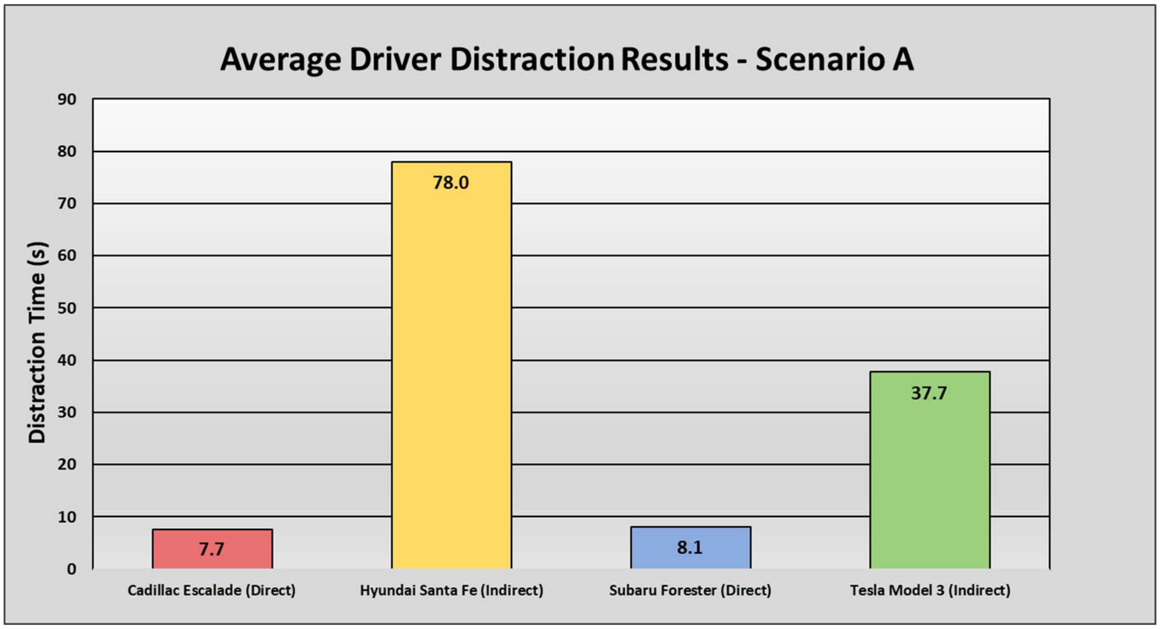

Figure 6: Average distraction time by test vehicle, scenario A. Image Source: AAA

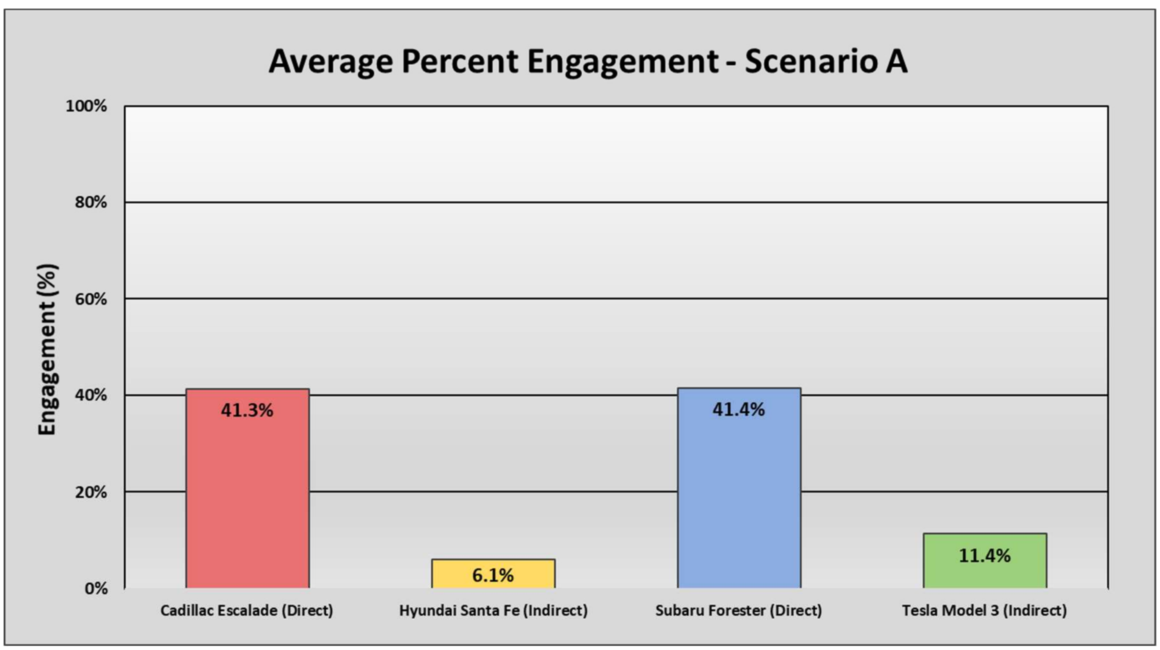

Figure 7: Average percent engagement by test vehicle, scenario A. Image Source: AAA

For each test vehicle, all test driver distraction times and percent engagement were averaged for each lighting condition on each testing day; these metrics were again averaged to provide equal weighting to each lighting condition and testing day. Calculated metrics for Scenario A are provided in Figures 6 and 7.

The indirect systems utilized in the Hyundai Santa Fe and Tesla Model 3 exhibited significantly higher average distraction times and lower corresponding percent engagements relative to both direct driver monitoring systems integrated within the Cadillac Escalade and Subaru Forester.

It was noted that the driver monitoring system in the Hyundai Santa Fe would vary alert timing during evaluations. Specifically, alert timings would vary from approximately 2 minutes to less than 20 seconds from the point at which the test driver removed their hands from the steering wheel. This finding was consistent for both lighting conditions and all test drivers. In contrast, the driver monitoring system of the Tesla Model 3 provided consistent alert timings of approximately 37 to 39 seconds for both lighting conditions and all test drivers throughout the 10 minute evaluation period.

For all test drivers, direct systems integrated within the Cadillac Escalade and Subaru Forester were consistent in alert timing from when test drivers focused their gaze downwards throughout the ten-minute evaluation period. However, both systems exhibited some sensitivity to direct illumination of the test driver's face due to low sun angle. In these cases, the time between alerts was modestly increased relative to periods during which sun angle was not a factor, and the overall results were not significantly affected.

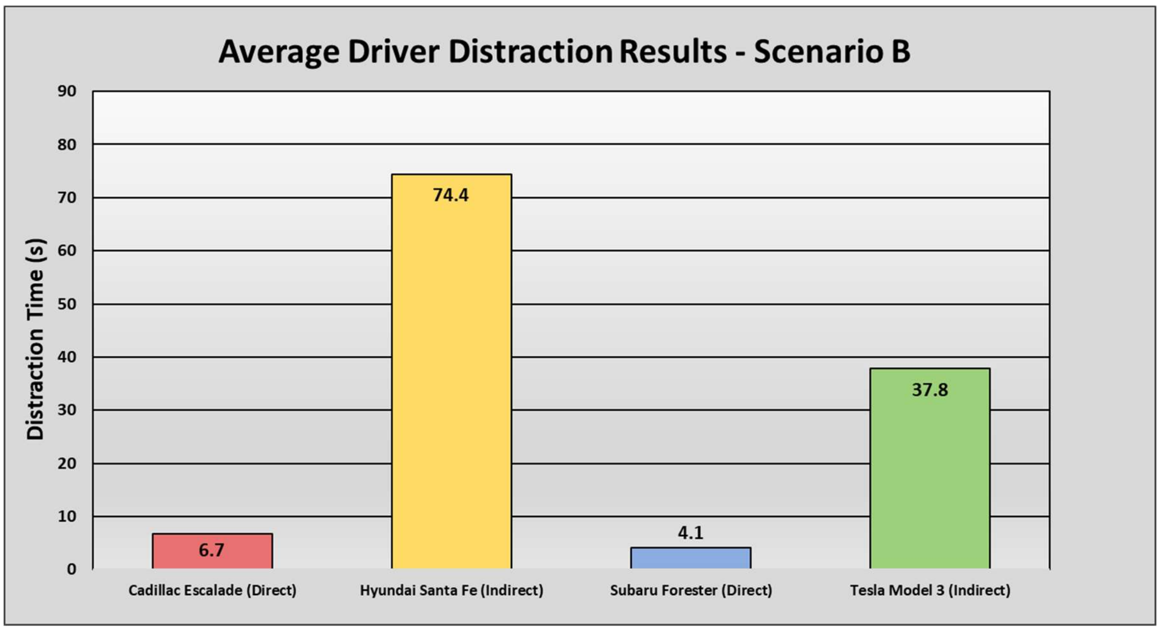

Figure 8: Average distraction time by test vehicle, scenario B. Image Source: AAA

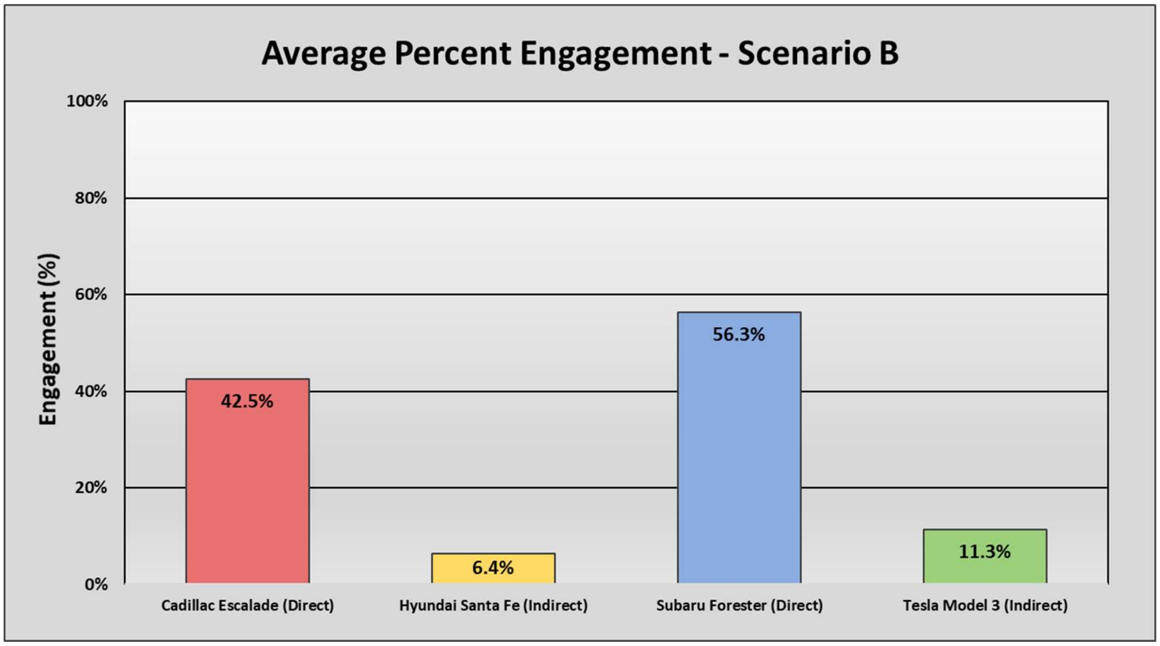

Figure 9: Average percent engagement by test vehicle, scenario B. Image Source: AAA

For each test vehicle, average distraction time and percent engagement for scenario B were calculated as previously described for scenario A; these metrics are provided in Figures 8 and 9. Both indirect systems in the Hyundai Santa Fe and Tesla Model 3 exhibited significantly higher average distraction times and lower corresponding percent engagements relative to direct systems integrated within the Cadillac Escalade and Subaru Forester.

As noted previously, the driver monitoring system in the Hyundai Santa Fe would vary alert timing during evaluations from less than twenty seconds to approximately two minutes. This finding was consistent for both lighting conditions and all test drivers. In contrast, the driver monitoring system integrated within the Tesla Model 3 provided consistent alert timings of approximately 37 to 39 seconds for both lighting conditions and all test drivers throughout the 10 minute evaluation periods.

For all test drivers, the direct systems of the Cadillac Escalade and Subaru Forester were consistent in alert timing measured from the point at which test drivers turned their head toward the center console throughout the ten-minute evaluation period. While alert timing did not significantly differ between disengagement modes for the Cadillac Escalade, the average alert timing decreased by 4 seconds. The percent engagement increased by 15 percent for scenario B relative to scenario A for the Subaru Forester.

For scenario B, neither system was significantly influenced by direct illumination of the test driver’s face due to low sun angle.

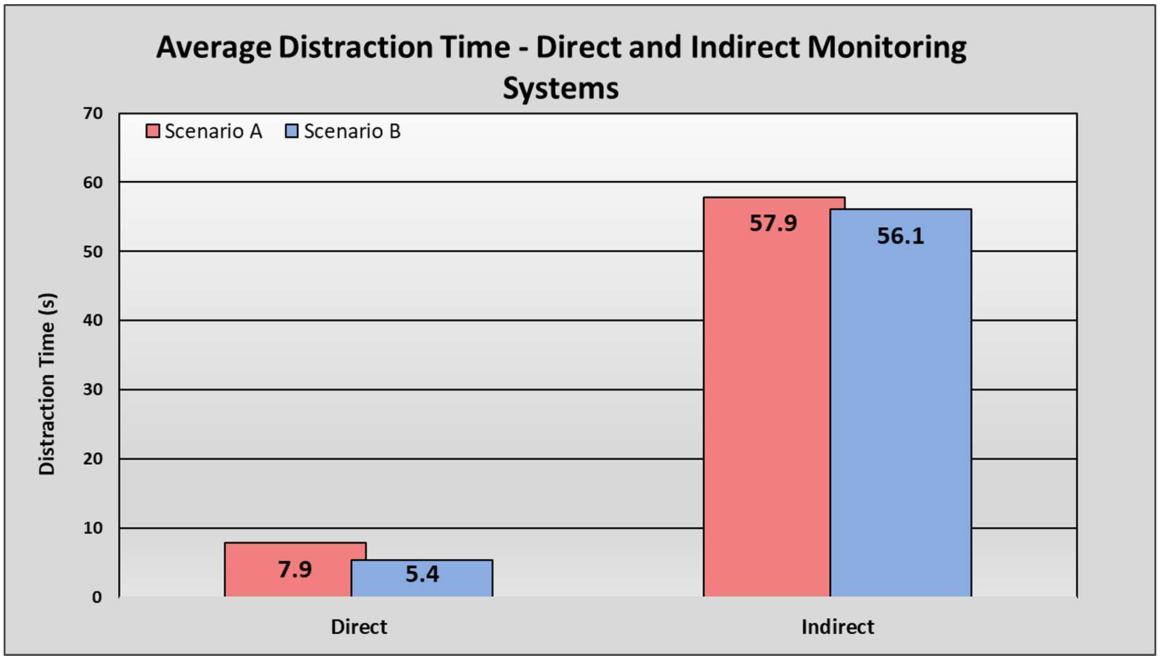

Figure 10: Average distraction time for driver monitoring type, scenarios A & B. Image Source: AAA

Distraction times provided in Figures 6 and 8 are averaged with respect to driver monitoring system type and illustrated in Figure 10. For indirect systems, average alert timing was consistent regardless of driver disengagement mode or lighting condition. This finding was anticipated because these systems lack a driver-facing camera.

AAA researchers are encouraged that the direct systems did not significantly differ in performance between daylight and nighttime conditions. In addition to consistent detection performance throughout the ten-minute evaluation periods, the direct systems issued an alert 50 seconds sooner than the indirect systems for scenario A, on average. For scenario B, the difference in alert timing for system type was 51 seconds, on average.

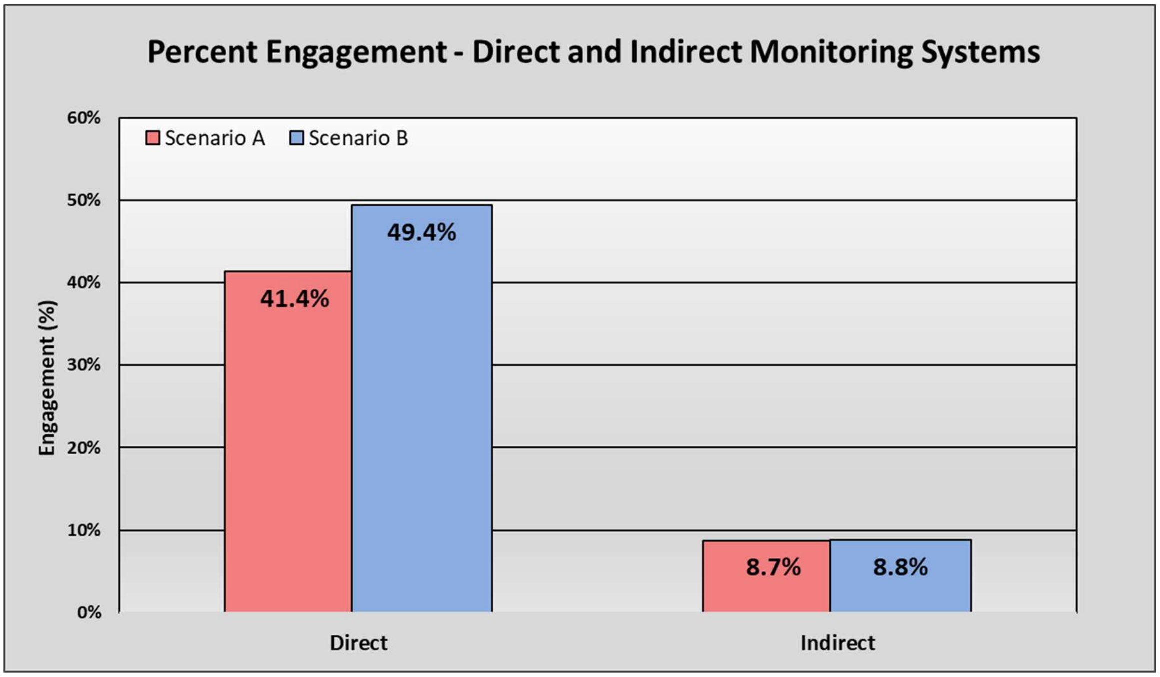

Figure 11: Average percent engagement for driver monitoring type, Scenarios A & B. Image Source: AAA

Percent engagement provided in Figures 7 and 9 are averaged for driver monitoring system type and illustrated in Figure 11. As anticipated, indirect systems were consistent for average percent engagement regardless of driver disengagement mode.

For the direct systems, the average percent engagement for scenario B increased 8 percentage points relative to scenario A. This difference is mainly attributable to the driver monitoring system integrated within the Subaru Forester, which provided more alerts when test drivers turned their heads away from the roadway than when they only turned their gaze away.

In aggregate, the percent engagement for direct systems was 33 percentage points higher than indirect systems for scenario A, on average. For scenario B, percent engagement increased 41 percentage points, on average. In other words, the percent of time that test drivers were engaged was approximately five times greater for the direct systems compared to indirect systems for both driver disengagement modes.

D. Discussion

Regardless of disengagement mode or lighting condition, evaluated direct driver monitoring systems significantly outperformed evaluated indirect driver monitoring systems. This finding was consistent for each test driver on each day of testing. For scenarios A and B, indirect driver monitoring systems allowed over 50 more seconds of simulated driver disengagement between alerts than direct driver monitoring systems. As a result, the percent of time that test drivers were engaged was approximately five times greater for direct systems than indirect systems.

In a theoretical sense, indirect driver monitoring systems (which do not monitor the driver's face or eyes) would allow test drivers to utilize an ADA system while being completely unaware of their surroundings for nearly a minute, on average. At a typical highway speed of 65 mph, a vehicle will travel 4,767 feet (0.90 miles) in the span of 50 seconds. While driver disengagement for this period is hazardous in any capacity, this finding is especially concerning in the context of AAA's recent ADA system evaluation in the naturalistic environment.

In 2020, AAA found that throughout 4,000 miles of real-world driving, five test vehicles equipped with an ADA system experienced some type of issue every 8 miles, on average [9]. If a driver remains disengaged between alerts from an indirect driver monitoring system, a problem with ADA system performance will likely occur while the driver is disengaged. Depending on the severity of the issue, a driver may be unprepared to take adequate corrective action, possibly resulting in a crash.

Comparatively, evaluated direct driver monitoring systems allowed 5 to 8 seconds of simulated driver disengagement between alerts on average depending on disengagement mode. While this period is still too long for a driver to be disengaged, the relative persistence of alerts for both disengagement modes can discourage prolonged unintentional disengagement by the driver.

In terms of average percent engagement, evaluated direct systems were 41 percentage points higher than evaluated indirect systems for simulated disengagement characterized by head and gaze direction downwards towards the center console. For simulated disengagement characterized by head direction ahead towards the roadway and gaze directed downwards, evaluated direct systems were 33 percentage points higher than evaluated indirect systems, on average. In other words, the percent of time that test drivers were engaged was approximately five times greater for the direct systems compared to indirect systems for both disengagement modes.

VII. INQUIRY 2: CAN DRIVERS RELIABLY CIRCUMVENT DRIVER MONITORING SYSTEMS?

A. Objective

Evaluate the propensity of driver monitoring systems to be circumvented by common strategies, including periodic head/eye movements and/or steering wheel input.

B. Methodology

Unfortunately, there are many documented instances of ADA system misuse. In these cases, drivers actively attempt to keep the ADA system operational while purposefully disengaging from the act of driving. Techniques vary depending on the individual and/or vehicle, but they usually involve random steering wheel movement via hands or an attached inanimate object.

To evaluate driver monitoring system vulnerabilities for intentional circumvention, AAA researchers attempted to prevent driver monitoring system alerts via periodic head/eye movements and/or steering wheel input with the ADA system engaged. Researchers were given discretion in developing their circumvention strategy for each vehicle under test. As intentional misuse of ADA systems via driver monitoring circumvention is unsafe outside of controlled testing conditions, specific circumvention strategies are not provided herein. It is important to note that no tools or aids were used to circumvent driver monitoring systems in this evaluation. Only driver inputs (steering wheel input and head and eye movement) were utilized. Specifically, as test drivers acclimated to the characteristics of each monitoring system, they would adjust the frequency of steering wheel input and vary their head and gaze placement periodically.

To ensure consistency with previously described driver disengagement modes, circumvention testing was conducted in the same manner as described within Section VI.B and performed immediately after completion of scenario B.

C. Test Results

In the following figures and corresponding discussion, circumvention testing is referenced as scenario C.

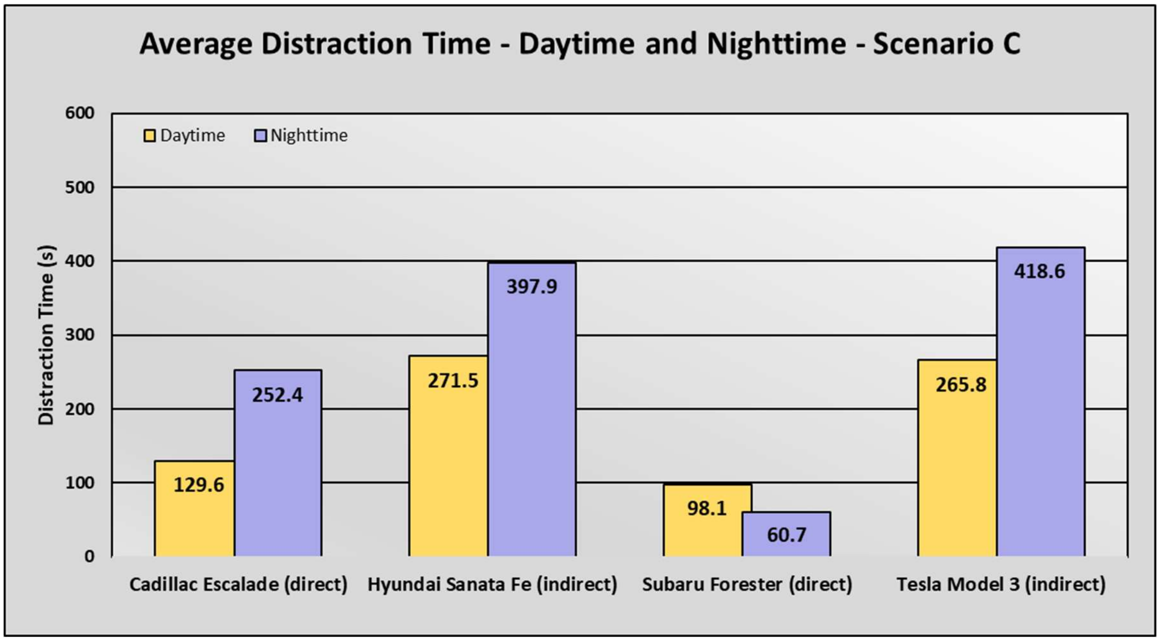

Figure 12: Average distraction time for each test vehicle for lighting conditions, scenario C. Image Source: AAA

Figure 12 illustrates the average distraction time for each test vehicle for daytime and nighttime lighting conditions. Among three of the four test vehicles, average distraction time significantly increased during nighttime evaluations. Because average distraction time increased for both direct and indirect systems at night, and because distraction time decreased for one of the two direct systems, it is surmised that this finding is a function of test drivers becoming increasingly familiar and more proficient with evading system detection, rather than lighting condition. It should be noted that there was no notable difference in performance for daytime or nighttime lighting conditions for scenarios A and B.

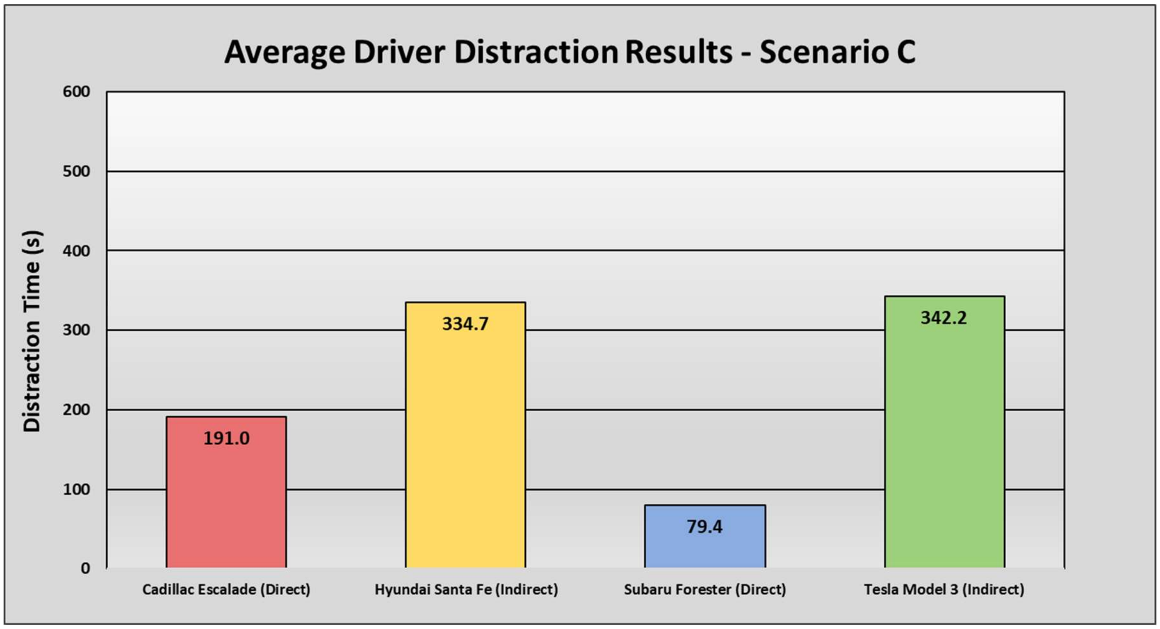

Figure 13: Average distraction time by vehicle, scenario C. Image Source: AAA

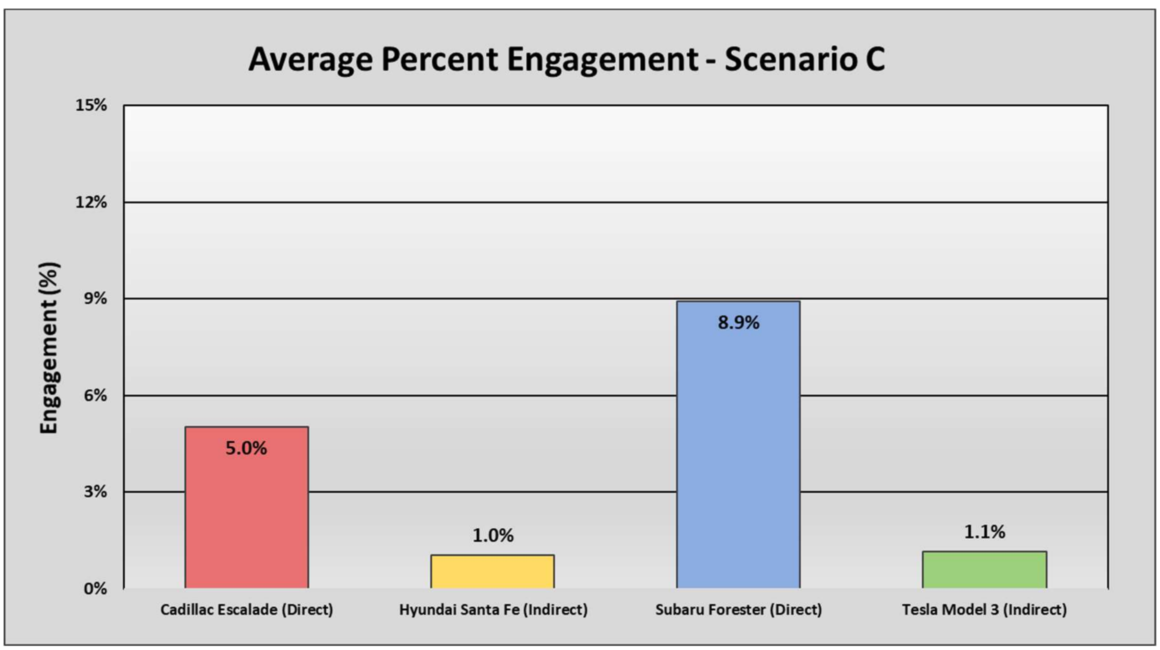

Figure 14: Average percent engagement by vehicle, scenario C. Image Source: AAA

For each test vehicle, average distraction time and percent engagement for scenario C were calculated as previously described for scenario A; these metrics are provided in Figures 13 and 14. Both indirect driver monitoring systems (in the Hyundai Santa Fe and Tesla Model 3) exhibited significantly higher average distraction times and lower corresponding percent engagements relative to the direct driver monitoring systems integrated within the Cadillac Escalade and Subaru Forester.

However, both direct and indirect system performance was significantly impacted by active circumvention attempts relative to fixed disengagement modes evaluated within Inquiry 1. For both vehicles with indirect systems, well over five minutes elapsed between alerts, on average. All test drivers were able to obtain this metric with minimal challenge relative to direct systems.

Direct systems were also adversely affected by active circumvention attempts by all test drivers. However, test drivers generally found it more challenging to evade detection on a prolonged and consistent basis. With additional effort to evade detection relative to indirect systems, direct systems may discourage continual and intentional misuse of ADA systems to a greater extent.

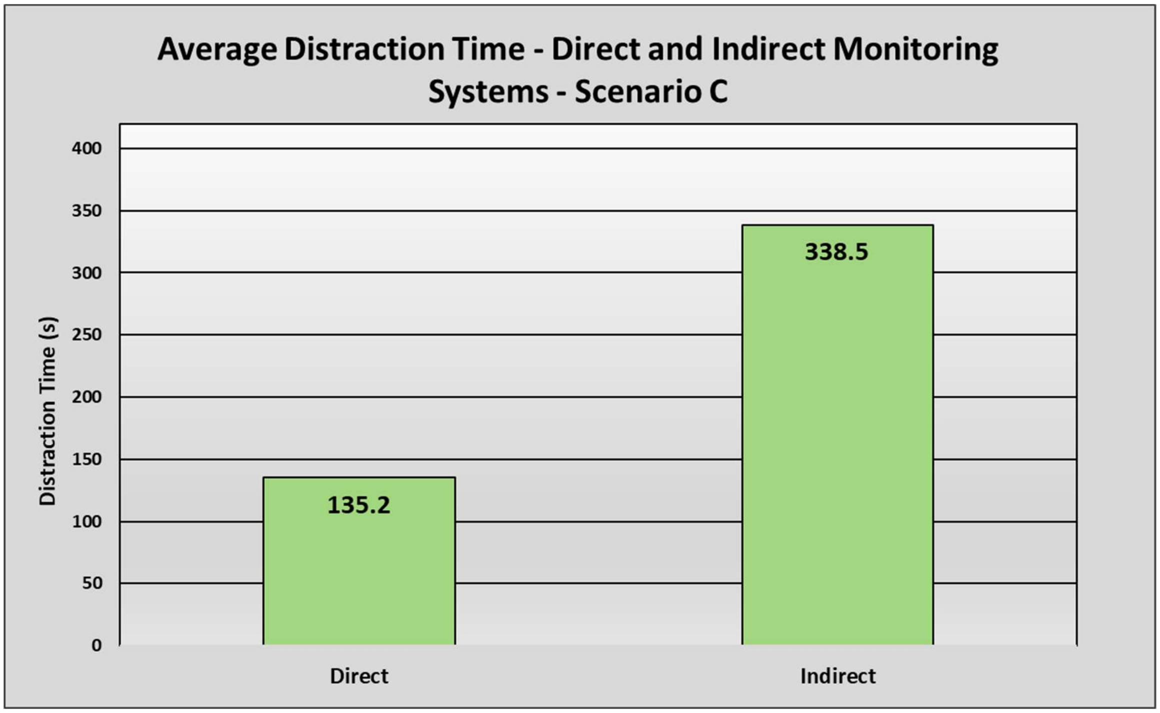

Figure 15: Average distraction time for driver monitoring type, scenario C. Image Source: AAA

Distraction times provided in Figure 13 are averaged for driver monitoring system type and illustrated in Figure 15. For evaluated indirect and direct systems, the average alert timing was 4 minutes, 42 seconds and 2 minutes, 8 seconds longer, respectively, for scenario C than for scenarios A and B. Distraction times reported herein may increase in real-world scenarios because owners of vehicles with these systems may adapt to system characteristics over time.

While evaluated direct systems exhibit a significant performance advantage relative to evaluated indirect systems in the context of a consistently repeated and defined disengagement mode, it is concerning that active circumvention attempts significantly impaired the performance of direct systems evaluated in this study. However, direct systems maintained a performance advantage over indirect systems in terms of average distraction time and increased difficulty for drivers to evade detection consistently.

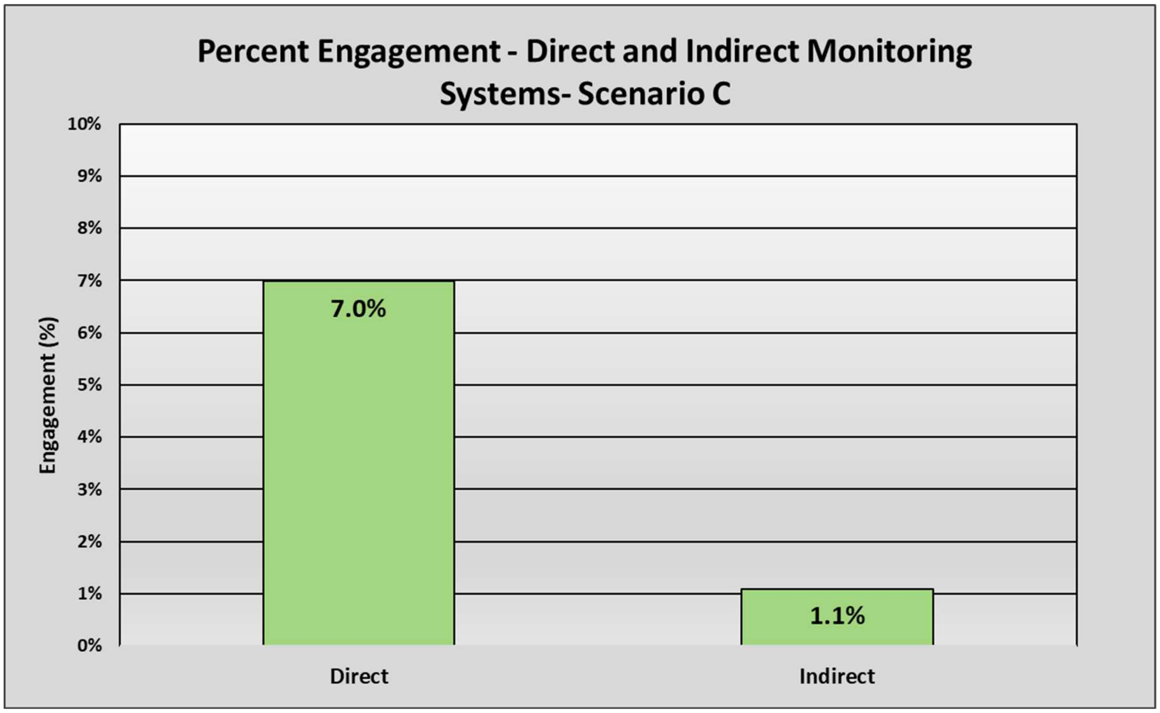

Figure 16: Average percent engagement for driver monitoring type, scenario C. Image Source: AAA

Percent engagement metrics provided in Figure 14 are averaged for driver monitoring system type and illustrated in Figure 16. The average percent engagement was 8 and 38 percentage points lower, respectively, for evaluated indirect and direct systems than for scenarios A and B.

For evaluated direct systems, the average decrease in percent engagement indicates significant susceptibility to persistent circumvention efforts by all test drivers. However, these percent engagement metrics likely represent a lower bound as the additional effort required to evade detection may discourage continued circumvention in a naturalistic sense. This extra effort may interrupt disengaged behavior to the point where drivers perceive intentional system misuse to be untenably cumbersome, thereby achieving some measure of the designer's intended goals.

For evaluated indirect systems, the average decrease in percent engagement is less pronounced than for direct systems. This is attributed to the poor performance of these systems for scenarios A and B rather than a reduced susceptibility to persistent circumvention efforts.

D. Discussion

Regardless of driver monitoring system type, all evaluated systems were susceptible to active circumvention attempts. Specifically, both system types allowed test drivers to simulate disengagement for over two minutes, on average. Actual owners could be expected to become attuned to system characteristics over time. This familiarity will facilitate more effective circumvention techniques if drivers intend to utilize an ADA system while disengaged and unaware of their surroundings.

For indirect driver monitoring systems, minimal effort was required to reduce, or in some cases, eliminate system alerts over the ten-minute evaluation period. On average, indirect systems allowed 339 seconds (5 minutes and 39 seconds) of simulated disengagement between alerts. Theoretically, this would allow drivers to utilize an ADA system while utterly unaware of their surroundings for over six miles at highway speeds. Generally, this finding illustrates the ineffectiveness of indirect driver monitoring systems to mitigate intentional ADA system misuse.

While direct systems were more challenging to circumvent than indirect systems, all test drivers significantly increased average distraction times and decreased the percent of driver engagement relative to fixed disengagement modes previously described in Inquiry 1. On average, direct systems allowed 135 seconds (2 minutes and 15 seconds) of simulated disengagement between alerts. Theoretically, this would allow drivers to utilize an ADA system while disengaged for over two miles at highway speeds. It is important to note that as intermittent glances towards the roadway were required to prevent system alerts for both direct systems, a driver may be periodically aware of their surroundings relative to indirect systems. Periodic gazes towards the roadway by no means represent an adequate degree of driver engagement; however, direct systems are nonetheless more effective than indirect systems at mitigating ADA system misuse.

VIII. CONCLUSIONS

The findings of this study illustrate that direct driver monitoring systems are more effective than indirect systems at mitigating various types of driver disengagement. Specifically, direct systems issued alerts faster and more persistently than indirect systems for both simulated driver disengagement modes and active circumvention attempts, on average. Evaluated indirect systems were much less effective at mitigating ADA system misuse. For fixed driver disengagement modes, indirect systems allowed over 50 seconds of simulated disengagement between alerts, on average. For active circumvention attempts, indirect systems allowed an average of nearly 6 minutes of continuous simulated driver disengagement between alerts.

While evaluated direct systems exhibited superior performance, it is nonetheless concerning that researchers were able to continuously simulate disengagement over ten minutes without disablement of the ADA system. It is acknowledged that researchers immediately discontinued simulated disengagement once an alert was provided, preventing an escalation of alerts. All researchers accumulated dozens of alerts for direct systems within a ten-minute evaluation period for both disengagement modes evaluated within Inquiry 1. AAA recommends that ADA systems become disabled for the remainder of the drive if too many initial alerts are provided within a given time period, independent of the requirement that drivers ignore a warning one or more times before disablement of the ADA system.

IX. KEY FINDINGS

1. Direct driver monitoring systems were significantly more effective at mitigating driver disengagement than indirect driver monitoring systems in all lighting conditions. On average, the percentage of time drivers were engaged was approximately five times greater for direct systems than indirect systems.
    - For Scenario A, evaluated direct systems issued an alert 50 seconds sooner than indirect systems.
    - For Scenario B, evaluated direct systems issued an alert 51 seconds sooner than indirect systems.
2. Both system types were susceptible to active circumvention attempts. On average, evaluated indirect and direct systems allowed over 5 and 2 minutes, respectively, of simulated driver disengagement. At 65 mph, this translates to approximately six miles of driver disengagement for indirect and two miles of driver disengagement for direct systems.
    - Lighting condition was not a significant factor for evaluated driver monitoring systems.

X. SUMMARY RECOMMENDATIONS

1. ADA systems should include a direct driver monitoring component to mitigate system misuse more effectively.
2. Disablement of the ADA system should occur after some initial driver monitoring alerts are issued within a defined period.
3. Automakers should continually refine the direct driver monitoring system functionality to minimize distraction to the greatest extent possible when using an ADA system.

XI. REFERENCES

[1] SAE International, "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles," 04 2021.

[2] American Automobile Association, "AAA NewsRoom," 14 11 2018. [Online]. Available: https://newsroom.aaa.com/2018/11/americans-misjudge-partially-automated-driving-systems-ability-based-upon-names/. [Accessed 14 10 2021].

[3] R. M. Yerkes and J. D. Dodson, "The Relation of Strength of Stimulus to Rapidity of Habit-Formation," *Journal of Comparative Neurology and Psychology,* vol. 18, no. 5, pp. 459-482, 1908.

[4] F. N. Biondi, M. Lohani, R. Hopman, S. Mills, J. M. Cooper and D. L. Strayer, "80 MPH and out-of-the-loop: Effects of real-world semi-automated driving on driver workload and arousal," *Proceedings of the Human Factors and Ergonomics Society 2018 Annual Meeting ,* pp. 1878-1882, 2018.

[5] N. A. Stanton and M. S. Young, "Driver behavior with adaptive cruise control," *Ergonomics,* vol. 48, no. 10, pp. 1294-1313, 2005.

[6] M. Vollrath, S. Schleicher and C. Gelau, "The influence of Cruise Control and Adaptive Cruise Control on driving behavior - A driving simulator study," *Accident Analysis and Prevention,* vol. 43, no. 3, pp. 1134-1139, 2011.

[7] B. Preston, "Auto Industry and Lawmakers Call for Driver Monitoring Systems to Improve Safety," Consumer Reports, 27 April 2021. [Online]. Available: https://www.consumerreports.org/car-safety/call-for-driver-monitoring-to-improve-car-safety-a3949626347/. [Accessed 18 October 2021].

[8] American Automobile Association, *AAA Level 2 Autonomous Vehicle Testing,* 2018, p. 48.

[9] American Automobile Association, *Evaluation of Active Driving Assistance Systems,* 2020.