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Driver Situation Awareness and Cognitive Workload Effects of Novel Interchange Configurations and Associated Signage

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ABSTRACT

There have been a number of prior studies on the design of grade-separated interchanges (GSIs) towards increasing the overall capacity of intersections and resolving physical intersection constraints. However, few, if any, investigations have addressed how to safely implement signage with different intersection configurations. To address this research gap, the present study designed and conducted a driving simulation experiment to compare young and middle-aged driver situation awareness (SA) and cognitive workload in negotiating a standard intersection vs. novel GSI (contraflow and quadrant) conditions. The experiment also manipulated driver exposure to different configurations of lane assignment and decision point signs. Results of the experiment revealed driver SA and cognitive workload significantly differ among interchange configurations, but there were no significant differences detected for age group or the use and placement of the signs. Correlation analyses revealed the SA and workload responses to be complimentary and to constitute unique measures for assessing human performance in this type of driving research.

Keywords: Grade-separated interchange, Lane assignment sign, Decision point sign, Situation awareness, Cognitive workload

INTRODUCTION

Rapid growth in transportation demands and traffic have resulted in serious roadway congestion issues, especially at urban intersections. Compounding this situation, there are locations where increasing infrastructure capacity is not feasible or cost-effective. In addition, enlarging intersections can create complexity for signal operations and pedestrians, and significantly increase travel time variability and crash rates (Eyler, 2005). Considering limitations on enlarging intersections and needs to reduce congestion and limit roadway user conflicts, some researchers have proposed redesigning the configurations of existing intersections.

Alternative intersection and interchange (AII) designs re-route some traffic movements to non-traditional patterns to reduce major conflict points. As a subset of AIIs, grade-separated interchanges (GSIs) eliminate intersecting movements through grade separation. In a GSI configuration, traffic occurs at multiple levels but roadways remain signalized. Unfortunately, some previous studies have shown certain forms of GSIs to be susceptible to wrong-way driving (WWD). For example, based on 6 years of crash data, Zhou et al. (2012b) identified compressed diamond and diamond interchanges as the top-two interchanges for WWD crashes. Having noted this, there is a paucity of guidance in the literature on how to appropriately sign at GSIs to achieve effective driver awareness and performance (towards reducing WWD incidents).

Among the studies on GSIs, few investigations have focused on how to implement signage safely for different intersection configurations. Inman et al. (2006) found that for roundabout configurations, as the number of items on signs increased, the accuracy of driver lane selection decreased significantly. Qiao et al. (2007) attempted to identify optimal advance placement of roadway signs based on the actual physical position of signs and driver behaviors. Experiment results revealed viewing distance to be crucial in sign placement. Still other studies (Zhang et al., 2013; Kaber et al., 2015; Zahabi et al., 2017) have compared specific sign information content and effects on driver distraction and performance under different driving conditions. However, none of these studies investigated positioning and content manipulations for critical routing signs, including lane assignment and decision point, at on-ramps of interchanges. In summary, there is an outstanding need to examine how traffic signs should be displayed at different GSIs in order to effectively guide drivers without introducing distractions and WWD events.

To address this research gap on the design and placement of GSI signage, this study specifically examined the influence of lane assignment and decision point sign use and placement on driver situation awareness (SA) and cognitive workload at GSIs. Based on prior research on the use of guide signs at conventional interchanges, it was expected that lane assignment signs at an interchange would increase driver SA and decrease cognitive workload (Hypothesis 1). Considering driver visual attention patterns, it was also expected that overhead mounted decision point signs would increase driver SA and decrease driver cognitive workload at interchanges, as compared with less visually accessible side-mounted signs (Hypothesis 2). Novel GSI designs, including contraflow and quadrant, were expected to lead to degraded SA and increased driver cognitive workload (due to potential driver confusion), as compared to standard intersection design (Hypothesis 3). This expectation was based on the complexity of traffic flows and required gaze patterns in driver negotiation of contraflow and quadrant interchanges.

METHOD

Participants and Apparatus

A total of 48 participants with 20/20 vision (natural or corrected) and a valid driver's license participated in the driving simulator experiment. All

Table 1. Sign options configuration.

Types of sign options	Lane assignment sign status	Decision point sign position
Sign Option 1	Present	Side
Sign Option 2	Present	Overhead
Sign Option 3	Absent	Side
Sign Option 4	Absent	Overhead

participants were compensated at a rate of $20 per hour. They were divided into two groups, according to their ages, with a convenience sample of young (18-24 years) and middle-aged drivers (25-64 years). A high-fidelity and full-motion (Moog platform) driving simulator was used in this study. During test trials, drivers sat in a 1/4-cab and used a full-size steering wheel, accelerator and brake pedals, and dashboard controls. Drivers controlled the simulated vehicle to maintain and change lanes and accelerate or decelerate.

Experiment Design

This study followed a $2\times2\times3\times2$ mixed within-subject and between-subjects experiment design, with two lane assignment sign settings (present and absent), two types of decision-point sign positions (side-mounted and overhead), three types of interchange design (standard, contraflow, and quadrant), and two driver age groups (young and middle-aged). Each participant was assigned to one unique sign combination with exposure occurring across the three types of interchanges with replication. Crossing the two-lane assignment sign settings and the two decision point sign positions yielded four signage options (see Table 1). The participant was then repeatedly exposed to this particular combination across the various interchanges. Exposure to the interchange designs was replicated in order to assess within-subject performance variability. Two 3x3 latin squares were applied for randomly scheduling trials for half of the participants in each age by signage combination group, which was intended to limit occurrence of carryover effects among trials.

Experiment Procedures

Prior to participating in the driving simulator experiment, participants completed an informed consent form, as required by the Institutional Review Board (IRB) of NCSU, and a Pre-exposure Simulator Sickness Questionnaire (PSSQ). This questionnaire provided the research team with information on participant physical and mental health before the experiment, which served as a benchmark for sickness assessments during experiment trials. Subsequently, each participant completed simulator driving training. The training included right turns, straightaways & curves, left turns. After the driving training, participants completed a workload demand component ranking form, including mental, physical, temporal, performance, effort, and frustration as part of the NASA-Task Load index (NASA-TLX) methodology.

For experiment test trials, participants drove on a short segment of highway and were asked to stop at a specific location with a stop sign or signalized intersection. At these stopping points, the driving simulation was frozen all

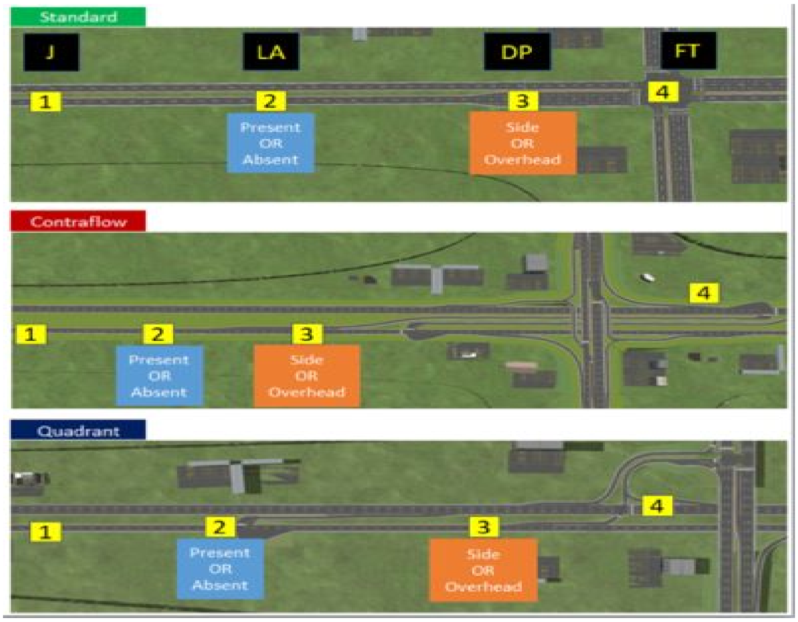

Figure 1: Three types of interchange scenarios.

displays were shut down. Participants were presented with a tablet computer (in cab) to respond to SA queries. At the same time, experimenters recorded the ground-truth of the simulation at a control station. (This information was used for SA response analysis purposes.) Once the SA surveys were complete, the simulator displays were reactivated and the driving simulation resumed until completion of the scenario (i.e., driver route selection (left turn) based on signage). At the end of each trial, participants were once again provided with a tablet computer to complete NASA-TLX demand ratings on a 100-point scale.

There was a 10-minute break after every two test trials. During each break, participants completed the SSQ to ensure that they did not suffer any symptoms during the experiment. For each participant, the entire experiment took approximately 1.5 hours.

Driving Task

The driving simulator presented an urban environment and a medium-sized car (sedan). All intersections accommodated cross-traffic flows (north, south, east and west) with four-lane roadways running in each direction. Participants were given a destination of "Garden St, North" for all trials. For each scenario, there were four possible locations (Positions 1-4) at which signage could occur. Position 1 presented Junction Information and Position 4 presented Final Turn Information without change across all trials. However, Position 2 was used to present the lane assignment sign (if present) and Position 3 presented the decision point sign (overhead or right-side mounted). The exact signage locations were determined based on the geometry of each interchange configuration (see Figure 1).

During each test trial, drivers maintained their vehicle speed at a limit of 45 mph. They were also directed to exhibit normal driving behavior, such as lane selection, until seeing further destination guidance information. Drivers were permitted to make lane changes based on ambient traffic and to decelerate to enter a left-turn lane at an interchange. Following a full stop, drivers waited for traffic and/or a signal to turn left.

Response Measures

As a basis for analyzing driver behavior in negotiating the various interchange configurations, we collected data on several different response measures during the experiment. The measures included driver SA assessments and cognitive workload surveys.

Situation Awareness. Sometime ago, Endsley (1995) defined SA as the perception of elements within a volume of time and space (Level 1), comprehension of their meaning (Level 2), and projection of their status in near future (Level 3). The Situation Awareness Global Assessment Technique (SAGAT; Endsley, 1995) is considered to be an objective method of measuring SA, as it involves queries of operator dynamic knowledge in real-time. SAGAT is also considered to be a global measure of SA as queries are targeted at all three levels, as identified by Endsley. We used the Qualtrics survey software to present SA queries to drivers in an electronic format with all queries being randomly selected from a large pool regarding the simulated driving environment. All queries were based on the driver's goals and decisions. For example, we asked the driver how many green guide signs they saw before stopping (Level 1); what was his or her average speed before slowing down for the first turning motion (Level 2); and what action will (s)he take next to get to the destination (Level 3). Driver responses to the SAGAT queries were graded based on recordings of ground-truth simulator settings to determine the score for query. There were 1728 queries administered with 1114 correct responses and 614 incorrect responses. There were no missing values. Percentage of correct responses was calculated for each trial. Among all participants, the average SA score was 0.65 and the standard deviation was 0.22.

Cognitive Workload. According to previous human factors studies (Endsley & Kaber, 1999; Kaber & Endsley, 2004; Zahabi et al., 2019), the NASA-TLX (Hart & Staveland, 1988) is a commonly used measure of cognitive workload and has demonstrated reliability. We used this index to determine the cognitive load imposed on drivers by the signage conditions in negotiating the various types of interchanges. The NASA TLX was calculated as the rank-weighted sum of the demand ratings scaled from 0 to 100 points. There were 48 sets of demand rankings from participants and 288 sets of demand ratings, across trials. During the experiment, one subject's demand rankings, and demand ratings at the close of four test trials, were missed. These values were replaced with the mean values for all other subjects assigned to and tested under the same signage conditions.

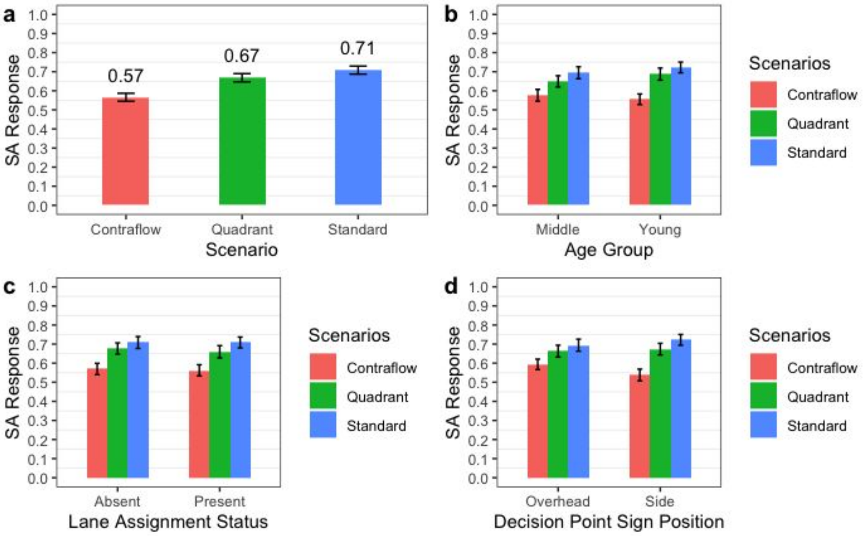

Figure 2: (a) Mean of SA response for different scenarios; (b) mean SA response by scenario types and age group; (c) mean SA response by scenario type and lane assignment sign use; (d) mean SA response by scenario type and decision point sign position.

RESULTS

Figure 2 (a)(b)(c)(d) show the mean SA responses under the different scenarios, age groups, and the use and placement of signs, accordingly. Among the responses, differences among the different scenarios are more obvious (Standard: 0.71; Quadrant: 0.67; Contraflow: 0.57). To make inferences on the SA scores for the test conditions, we applied a mixed-effects statistical model to the data set. However, due to the limited number of SA queries per trial, the resulting response was discrete. Consequently, the data revealed a normality violation (Q-Q plot with banding; ShapiroâŁ“WilkâŁ™s test: $p<0.01$). Therefore, instead of using a parametric multi-way ANOVA (analysis of variance), we turned to non-parametric methods (Kruskal-Wallis rank sum test, Wilcoxon rank sum test) to analyze the SA dataset.

The Kruskal-Wallis rank sum test revealed significant differences in driver SA under different interchange scenarios ($\chi^2 = 22.12$, $\mathrm{p} = 0.000607$). To identify the specific scenarios that led to this difference, we performed follow-up pairwise condition comparisons using the Wilcoxon rank sum test. Results revealed no significant difference in driver SA between the Standard and Quadrant scenarios ($W = 5117.5$, $p = 0.174$); however, driver SA in Contraflow scenario was significantly lower than that for the Standard interchange ($W = 6312.5$, $p = 5.61 \times 10^{-6}$) and Quadrant ($W = 5830.5$, $p = 0.001103$). However, there were no significant differences in SA detected among age groups ($\chi^2 = 2.9886$, $\mathrm{p} = 0.8103$) and the use (LA) ($\chi^2 = 3.2096$, $\mathrm{p} = 0.7821$) and placement (DP) ($\chi^2 = 2.3136$, $\mathrm{p} = 0.8887$) of signs. Given the non-parametric analysis approach, it was not possible to analyze any interactions between the interchange design settings and use and placement of signs for SA responses.

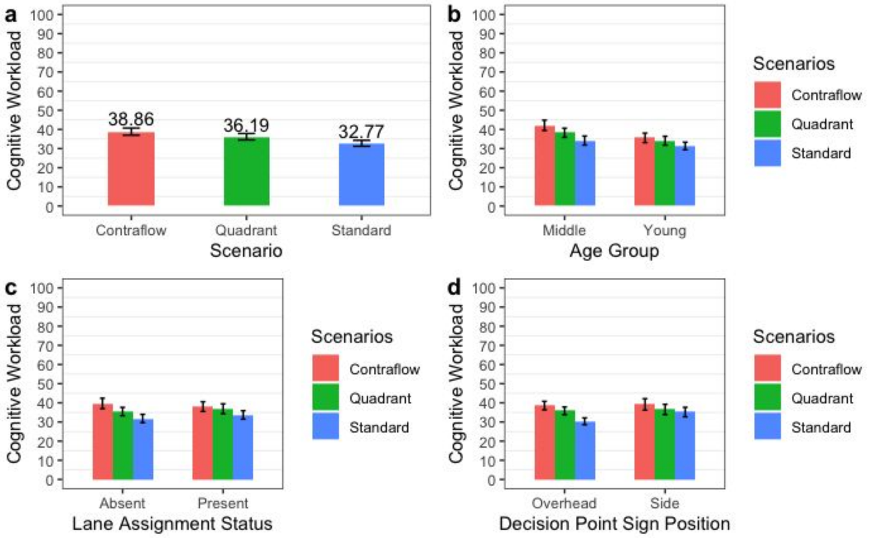

Figure 3: (a) Mean cognitive workload for different scenarios; (b) Mean cognitive workload by scenario type and age group; (c) Mean cognitive workload by scenario type and lane assignment sign use; (d) mean cognitive workload by scenario type and decision point sign position.

Figure 3 (a)(b)(c)(d) presents the mean cognitive workload scores for the different scenarios, age groups, and use and placement of signs, accordingly. Consistent with the SA responses, the cognitive workload of drivers differed among scenarios (Standard: 32.77; Quadrant: 36.19; Contraflow: 38.86). Furthermore, by analyzing the different demand components of cognitive workload, we observed driver perceptions to be largely influenced by their own performance, but less by physical demands and frustration. Given that the NASA TLX is a continuous response, and all experiment independent variables were categorical, we applied a multi-way ANOVA to the workload dataset. The diagnosis of the NASA TLX scores indicated no normality violation of random effects attributable to subjects (Shapiro–Wilk test: $p = 0.2358$). In addition, due to the large and balanced experimental data (288 data points), the central limit theorem applies; thereby, any fixed effects caused by scenarios, age groups, and the use and placement of signs were also approximately normally distributed. (According to Larson (2008), an ANOVA applied to normal data with heterogeneous variance is robust for balanced or near-balanced designs. Therefore, the ANOVA test was considered reasonable for the workload analysis.)

The workload results were consistent with the SA outcomes, including significant differences in cognitive load under different scenarios ($F_{(2,236)} = 10.7323$, $p = 3.459 \times 10^{-5}$). Post-hoc analysis using Tukey's HSD tests revealed the cognitive workload at Standard intersections to be significantly lower than for the Quadrant ($p = 0.0269$) and Contraflow ($p < 0.0001$) configurations. The cognitive workload of drivers did, however, not differ significantly between the Contraflow and Quadrant ($p = 0.1088$). In addition, there were no significant differences in cognitive workload detected among age groups ($F_{(1,41)} = 1.1126$, $p = 0.2977$) and use ($F_{(1,41)} = 0.0175$, $p = 0.8955$) and placement ($F_{(1,41)} = 0.2316$, $p = 0.6329$) of signs. Having noted this, when we applied the ANOVA to different demand components, we observed an almost identical pattern of results, as with the total cognitive workload, except for the performance component. Consequently, any differences in driver cognitive workload are likely the result of the combined effect of various demands. Finally, no interactions were detected among the interchange designs and use and placement of signs for cognitive workload.

In addition to the multi-way ANOVA, we also performed a correlation analysis on the SA scores and NASA-TLX scores. Considering that the SA scores were discrete, we applied Kendall's tau and Spearman's rank correlation coefficients to assess any statistical associations based on ranks of the responses. Results revealed no significant correlations between SA and cognitive load (Kendall's tau & Spearman coefficient of r=-0.055). We also further analyzed whether the SA score was related to NASA-TLX demand components. However, no non-parametric correlation coefficients were greater than 0.1 or less than -0.1. Therefore, these findings indicate that the SA and workload measures are complementary in terms of analysis of human performance and both maybe necessary to elucidate different effects of highway designs on driver behavior and responses.

DISCUSSION AND CONCLUSIONS

The objectives of this study were to test the influence of novel GSI designs, and use and placement of signs, on driver SA and cognitive workload through a simulation experiment. Results partially supported Hypothesis 3. The contraflow design led to significantly degraded driver SA, likely due to lack of driver familiarity with the configuration, as compared to the standard and quadrant interchanges. However, the quadrant design did not differ from the standard intersection in terms of SA.

Results on cognitive workload revealed significant increases for drivers at both the contraflow and quadrant interchanges, as compared to the standard intersection. However, there was no difference between the contraflow and quadrant designs in terms of cognitive workload. Once again, these findings are likely due to the novelty of the GSI interchanges, lack of driver familiarity, and perceived complexity of navigation of the interchanges.

Based on these observations, signing engineers need to develop novel sign configurations for driver use of contraflow interchanges to offset low SA and high cognitive workload. The quadrant design appears to be a feasible alternative to standard intersections with or without lane assignment signs and when using side-mounted decision point signs. However, novel signs appear to be needed to reduce driver cognitive workload at quadrant interchanges. Consequently, the results of this analysis provide guidance for highway systems engineers on the need for novel signage design to ensure effective driver information processing under unique highway configurations with performance comparable to standard intersections.

Hypotheses 1 and 2 on the use and placement of signs at the simulated GSIs were not supported. To be more specific, use of lane assignment signs at interchanges did not appear to significantly increase driver SA nor decrease driver cognitive workload. Furthermore, overhead mounted decision-point signs did not significantly increase driver SA or decrease cognitive workload at interchanges, as compared to side-mounted signs. Possible explanations for these results include the following: (1) the information included in lane assignment signs may not have been as useful as expected for promoting driver SA and decreasing cognitive workload at specific points in the driving scenarios; and (2) overhead decision-point signs may not have been as visually accessible as expected, relative to side-mounted signs.

Furthermore, there were no significant differences in driver SA responses and cognitive workload between the two driver age groups (younger: 18 to 24 years; middle-aged: 25 to 64 years). This result was likely due to a limited age gap between our study groups. Subsequent to convenience sampling, we observed that 68.75% of subjects were between 18 and 26 years of age, based Pareto chart analysis. For future study, there is a need to collect additional data on elderly drivers to more conclusively determine whether age has an influence on driver SA response at different types of interchanges (standard vs. GSIs).

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