DSC North America 2003 Proceedings, Dearborn, Michigan, October 8-10, 2003 (ISSN 1546-5071).

An Application for Driving Simulator Technology: An Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control

By

Michael A. Knodler Jr.
University of Massachusetts – Amherst
214C Marston Hall
Amherst, Massachusetts 01003
Telephone: (413) 577-4766
Fax: (413) 545-9569
E-mail: mikeknod@aol.com

David A. Noyce, Ph.D., P.E.
University of Wisconsin – Madison
1210 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
Telephone: (608) 265-1882
Fax: (608) 262-5399
E-mail: noyce@engr.wisc.edu

Kent C. Kacir, P.E.
Siemens Gardner Transportation Systems
7000 S.W. Redwood Lane
Portland, OR 97224
Telephone: (503) 624-7635
Fax: (503) 670-1460
E-mail: kkacir@gardnersys.com

Prepared for the Driving Simulation Conference
North America 2003

Submitted: July, 2003

DSC North America 2003 Proceedings, Dearborn, Michigan, October 8-10, 2003 (ISSN 1546-5071).

ABSTRACT

The objective of this research was to determine the safety and effectiveness of selected protected/permissive left-turn (PPLT) signal displays through driver comprehension evaluations. Driver evaluations were conducted using full-scale, fixed-based, fully-interactive driving simulators located at the University of Massachusetts and the Texas Transportation Institute. PPLT displays were also evaluated in a static environment to provide comparison data.

In an effort to evaluate driver's comprehension of the various PPLT signal displays in use, several traditional study methods have been employed. Commonly, pen and paper comprehension tests are used in which the driver simply marks what he/she believes to be the correct answer. The critique of this methodology has focused on the belief that the study responses provided might not be consistent with the decision made in the actual driving environment. To add more realism to the experiment, computer technology has been employed by providing static photos of actual driving environments and superimposing PPLT signal displays within. Although this technology is believed to be a major step forward in experimentation, the static nature and lack of dynamic cues may still lead drivers through a different decision process.

This paper describes the use of a full-scale dynamic driving simulator as a tool for evaluating driver comprehension of PPLT signal displays. Drivers traversed through a series of signalized intersections created as part of a comprehensive visual world. Road signs were provided in the simulation to direct the driver through a series of left, right, and thru movement maneuvers. Traffic signals varied at each intersection providing the test variable. Vehicles were always present in the opposing lanes at signalized intersections.

Driver comprehension was determined from the distribution of correct and incorrect responses to the different signal scenarios presented. Findings from the driving simulator study showed a high level of comprehension, consistent with the responses one would expect in an actual roadway environment. Drivers were found to use many cues, not always including just the left-turn signal display itself, to make turn decisions. A direct comparison of responses in the simulator and static evaluations was completed by cross-analyzing individual driver's responses in each methodology. The query was undertaken to determine if drivers' comprehension from the static evaluation was consistent with each driver's action in the dynamic simulation. Of the 353 fail critical error responses in the static evaluation (errors that may have lead to a crash), 279 of these did not take place at identical scenarios in the simulator environment. Only 19 percent of the 353 pairs resulted in fail-critical responses in both the simulator and static evaluation.

Overall, the results obtained from this experiment indicate that the driving simulator is an effective method of evaluating driver comprehension of traffic signal displays. Specifically, the results from the driving simulator much more closely mirror behavior in the real world than do the results from the static evaluation. Furthermore, these results may help explain why the low level of comprehension reported in previous research, which used static evaluations to assess driver comprehension of PPLT signal displays, is not consistent with left-turn crash frequencies. Specifically, what drivers say they will do and what they actually do in the driving environment are not always consistent.

INTRODUCTION

The Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) has provided guidance in the selection of signal displays since its first edition in 1935 (1). Furthermore, the MUTCD has been adopted as the national standard for traffic control devices in the United States. Driver confusion in and around the approximately 300,000 signalized intersections in the United States is responsible for an increase in both delay and crash potential (2). Safely and efficiently accommodating left-turning vehicles at signalized intersections is a source of concern for traffic engineers. The benefits of advanced signal phasing, such as protected/permissive left turn (PPLT) signal phasing, can only be realized if the information is correctly presented, and more importantly comprehended by the driver. PPLT information is presented to the driver through the illumination of circular- and arrow-shaped indications within a traffic signal display. The meaning of all signal indications is transmitted through a combination of color, shape, orientation, and position of the signal display. As appropriate additional information may be provided to the driver in the form of supplemental signage.

In an effort to evaluate driver's comprehension of the various PPLT signal displays in use, several study methods have been employed. Traditionally, pen and paper comprehension tests are used in which the driver simply marks what they believe to be the correct answer. The critique of this methodology has focused on the belief that the study responses provided might not be consistent with the decision made in the actual driving environment. To add more realism to the experiment, computer technology has been employed by providing static photos of actual driving environments and superimposing PPLT signal displays within. Although this technology is believed to be a major step forward in experimentation, the static nature and lack of dynamic cues may still lead drivers through a different decision process.

This paper describes the use of full-scale dynamic driving simulators as a tool for evaluating driver comprehension of selected PPLT signal displays. Driving simulation places drivers in a fully interactive dynamic scenario just as if they were actually driving. To test the effectiveness of the simulator, driver comprehension was evaluated for selected PPLT signal displays using both driving simulator technology and a video-based static evaluation. A comparison of a data sets collected using the driving simulator and static evaluation is presented.

BACKGROUND

PPLT signal phasing provides a protected phase as well as a permissive during which left turns can be made if sufficient gaps in the opposing traffic stream exist, all within the same signal cycle. Current MUTCD recommendations for PPLT signal phasing include various five-section arrangements and include the circular green permissive indication and green arrow protected indication (1). A recurring issue with PPLT signals phasing centers around the circular green permissive indication.

Many traffic engineers believe that the MUTCD circular green permissive indication is adequate and properly presents the intended message to the driver. Other traffic engineers believe that the circular green permissive indication is not well understood and therefore inadequate. The latter belief is based on the argument that left-turn drivers may interpret the circular green permissive indication as a protected indication, creating a potential safety problem.

To overcome this potential problem, traffic engineers have developed at least four variations of PPLT permissive indications. These variations replace the circular green permissive indication with a flashing circular red, flashing circular yellow, flashing red arrow, or flashing yellow arrow indication. Additionally, variations in signal display arrangement and placement are applied. This variability has led to myriad PPLT signal displays and permissive indications throughout the U.S. that may confuse drivers and lead to inefficient and unsafe operations. Evaluating driver comprehension of existing and alternative PPLT signal displays has become a critical component of the evaluation of PPLT signal displays.

Compared to traditional methods of evaluating driver comprehension, driving simulator technology is believed to provide a vastly improved mechanism for conducting driver behavior and comprehension research. Although research conducted in the actual driving environment is considered to be optimal, the use of a driving simulator allows for multiple variables and scenarios to be evaluated in a timelier and cost effective manner without losing the *field* credibility.

Several studies with left-turn applications have been conducted using various forms of driving simulation. Staplin conducted an experiment using simulation comparing the willingness of drivers to select a left-turn gap for drivers traveling at 30 and 60 mph (3). The study recorded driver information using a 20-inch monitor, a large screen video projector, and a large screen cinematic display. Additionally, he conducted actual field tests for comparative purposes. Staplin found that only the large screen cinematic display corroborated what was occurring in the field, for which the minimum gap length increased as the speed increased. In conclusion, Staplin reported that higher levels of realism provided by the large screen medium provided more accurate results consistent with the driving environment (3).

Noyce and Smith tested driver comprehension of five-section PPLT displays with varying permissive indications using both a driving simulator and a static survey instrument (laptop computer) (4*)*. The researchers concluded that the added level of realism provided in the simulation experiment appeared to provide drivers with cues consistent with those found on the roadway. The driving simulator was effective in the evaluation of driver comprehension of PPLT signal displays (4*)*.

One concern with simulator experiments is the potential of simulator sickness, which has been likened to motion sickness. Although a number of factors have been identified that may trigger the onset of simulator sickness, they believe that ultimately it is caused from, “inconsistent information about body orientation and motion received by the different senses, known as the cue conflict theory. For example, the visual system may perceive that the body is moving rapidly, while the vestibular system perceives that the body is stationary” (5, 6).

METHODOLOGY

The objective of this research was to evaluate the applicability of driving simulator technology as a research tool for evaluating driver comprehension of PPLT signal displays. Similar driving simulators at the University of Massachusetts (UMass) and the Texas Transportation Institute (TTI) were used to complete the experiment. Both simulators used were fixed-base, fully-interactive, dynamic driving simulators in which drivers are capable of controlling the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusts accordingly to the driver’s actions. The vehicle base of both driving simulators is a four-door Saturn sedan. Three separate images are projected to a large semi-circular projection screen creating a “visual world” field-of-view which subtends approximately 150-degrees. The UMass and TTI driving simulators are each pictured in Figure 1.

FIGURE 1 Driving Simulators at UMass and TTI.

Development of Simulation

A “visual world” of intersections was created for use in both the UMass and TTI driving simulators. One intersection approach was created for each of 12 experimental PPLT signal displays depicted in Figure 2. The selected PPLT signal displays contained either the CG permissive indication (the current standard) or a promising alternative permissive indication based on research findings to date. A typical intersection from the UMass driving simulator experiment is presented in Figure 3. The characteristics of each approach were identical, thus minimizing confounding variability.

Additionally, several intersections that required the driver to turn right, proceed straight, or to turn left on a protected green arrow indication were included as part of the visual worlds. The additional movements were included to provide experimental variability and reduce the probability of drivers keying in on the nature of the evaluation. Further experimental variability was provided by creating multiple driving modules and starting positions. In both the UMass and TTI experiments, four modules were developed, each presenting a different order of the experimental displays. At UMass, each module was a continuous loop with drivers starting and ending at the same location after passing through 14 intersections, six with experimental displays, within each module. At TTI, each module had six intersections, half of which were experimental displays. Drivers observed each of the 12 experimental displays only once by traversing two modules at UMass and all four modules at TTI.

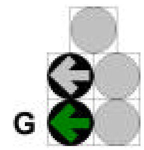
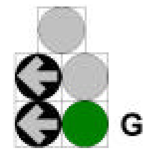
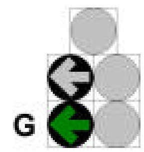
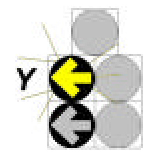
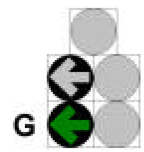
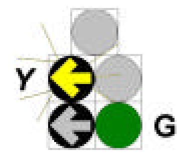
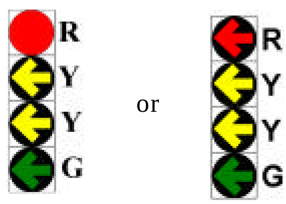
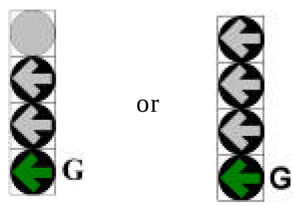
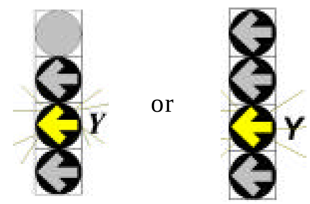
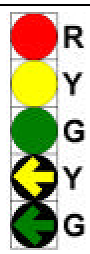
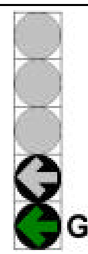
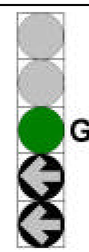
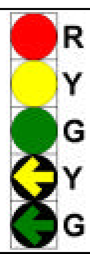
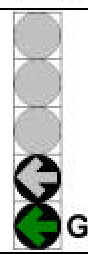
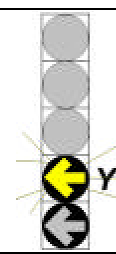
All experimental signal displays within the simulation rested in a circular red or arrow indication as drivers approached the intersection. Signal displays changed to the *test* indications as the driver approached the intersection. Approximately 30 meters prior to the intersection stop bar, the PPLT signal display was “triggered” and changed from the red indication to the selected permissive or protected indication. Similarly, the through movement indication either stayed with the circular red indication or changed from a circular red to a circular green indication.

Each of the PPLT signal displays were evaluated with opposing traffic at the intersection. Opposing traffic required drivers to simultaneously evaluate the PPLT signal display, traffic movement, and opposing gaps to complete a safe permissive left-turn maneuver. This methodology was used to replicate the decision process required during actual operations.

Opposing traffic was presented in predetermined gaps at each of the experimental intersections. The critical gap concept was used to select the gap sizes. The Highway Capacity Manual (HCM) indicates that a critical gap value of five-and-a-half seconds for permissive left-turn maneuvers in the design of a four-lane roadway (7). Therefore, a gap size was selected below the critical gap that most drivers would not accept (three seconds) and a gap size was selected above the critical gap that most drivers would accept (seven seconds). Providing a consistent sequence of three and seven second gaps prevented gap size selection from being a significant variable in the PPLT analysis.

Six opposing vehicles were used to create this gap sequence. Two vehicles were always positioned at the stop bar in the two through lanes opposing the left-turn driver. The remaining four vehicles were positioned further upstream in a three and seven seconds series of seven-three-seven-seven; therefore, opposing vehicles crossed the intersection seven, 10, 17, and 24 seconds behind the two initially queued opposing vehicles.

A second trigger, similar to that used to change the signal indications, was placed approximately four feet from the left-turn stop bar at each PPLT intersection to release the opposing traffic. This trigger position required drivers to make a decision as to the meaning of the PPLT signal indication and desired action before knowing the actions of the opposing traffic.

Scenario[a]	Lens Color and Arrangement	Left-Turn Indication[b]	
		Protected Mode	Permissive Mode
1, 2			
3, 4			
5, 6			
7, 8			
9, 10			
11, 12			

R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[a] 1, 3, 5, 7, 9, 11 – Circular green through indication; 2, 4, 6, 8, 10, 12 – Circular red through indication

[b] The indication illuminated for the given mode is identified by the color letter

FIGURE 2 PPLT Signal Displays Evaluated in Driving Simulator Experiment.

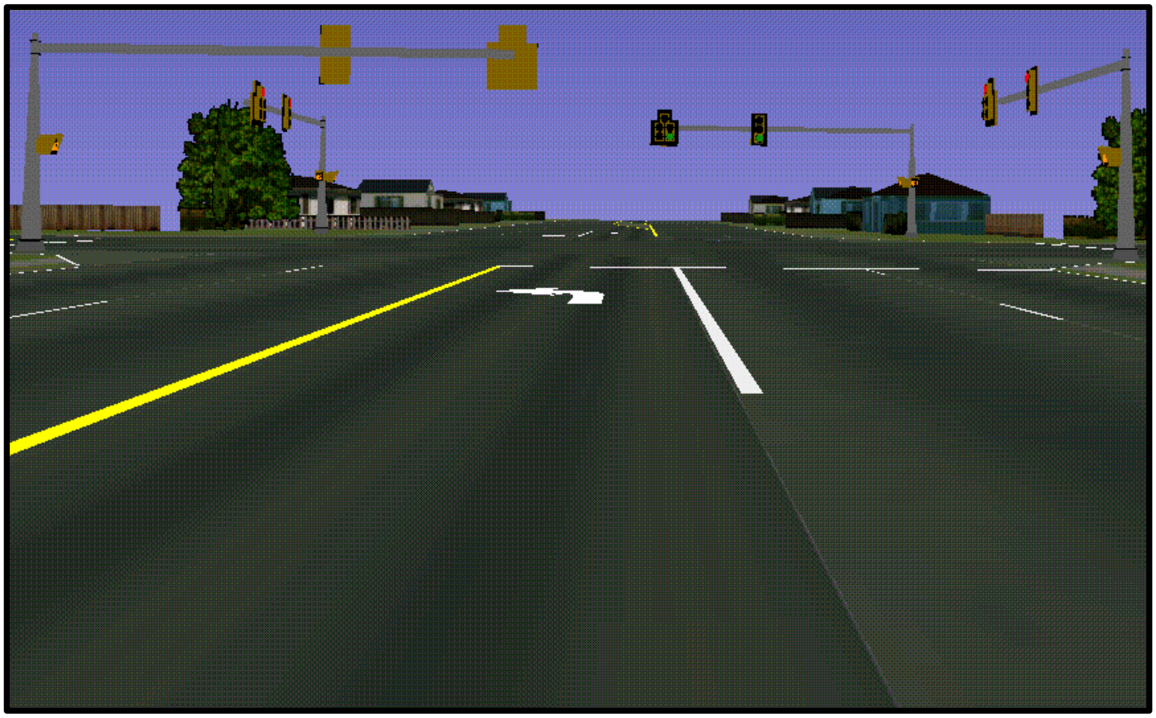


FIGURE 3 Typical Experimental Intersection from UMass Simulator.

Simulation Experimental Procedure

Following completion of a practice course, used to orient drivers to the simulator vehicle, drivers completed the experimental modules. To avoid the need for verbal communication during the experiment, drivers were navigated through the modules by guide signs provided on each intersection approach. In addition, drivers were asked to observe speed limit signs (30 mph), providing a higher level of realism and speed control during the experiment. The driving portion of the experiment, including the practice module, required between 15 and 20 minutes to complete.

Drivers' responses to each PPLT signal display scenario were manually recorded as correct or incorrect. Incorrect responses were further classified as being fail-safe or fail-critical. A fail-safe response was one in which the driver did not correctly respond to PPLT signal display, but did not infringe on the right-of-way of the opposing traffic. A fail-critical response was an incorrect response in which the driver incorrectly responded to PPLT signal display and impeded the right-of-way of opposing traffic, creating the potential for a crash.

Video-Based Static Evaluation

After completing the driving portion of the study, drivers were asked to participate in a static evaluation of PPLT signal displays. The static evaluation was administered using videocassette recordings of screen captures for the 12 PPLT displays. Specifically, each display presented the scenario as if the driver was positioned at the left-turn lane stop bar, preparing to complete a left-turn maneuver. Each of the 12 experimental displays was shown for 30 seconds during which time the driver was verbally asked the following question:

"You encountered this signalized intersection while driving. At this intersection you made a left turn. Considering the left-turn traffic signal lights shown, what do you believe is the appropriate left-turn action?"

Drivers were then asked to respond with one of the four following choices:

- Go, you have the right-of-way;
- Yield, then go if a gap in the opposing traffic exists;
- Stop first, then go if a gap in the opposing traffic exists; or
- Stop and wait for the appropriate signal.

The data were recorded and combined with the driving simulator data to complete the analysis. A photograph of the static evaluation setup is presented in Figure 4.

FIGURE 4 Setup for Video-Based Static Evaluation.

RESULTS AND ANALYSIS

Demographics

A total of 464 drivers participated in the experiment. Two hundred thirty-one drivers participated in the study at UMass, and 233 drivers participated at TTI. Potential participants were screened for sex and age (under 25, 25 to 45, or over 45) to assure a representative sample of drivers similar to the driving population. Eight subjects at UMass and 24 subjects at TTI elected to retire from the experiment leaving 432 drivers for analysis.

Originally, researchers wanted to explore the effects of two different opposing traffic strategies, by using one method of opposing traffic at UMass and a second at TTI. After the first 116 subjects at TTI were run, a decision was made to use the same opposing traffic strategies at both study sites. Therefore, 116 drivers at TTI were evaluated separately and are not included within this driving simulator analysis. The statistical analysis described was based on the results of 223 drivers at UMass and 93 drivers at TTI.

Initial Driving Simulator Analysis

Drivers at UMass evaluated 2,528 scenarios with experimental PPLT signal displays, and similarly drivers at TTI evaluated 874 scenarios. In total, 32 drivers elected to retire from the experiment shortly after completing the practice driving module. The percentage of correct responses for each of the 12 PPLT signal displays at UMass and TTI are presented in Figure 5. Note that the vertical line segment at the top of the solid bars in Figure 5 represents a 95 percent confidence interval for the results. Overall, drivers at UMass responded correctly to the PPLT scenarios presented 90 percent of the time compared to 93 percent at TTI. Although this overall difference was statistically significant, the data sets were cross-analyzed across each of the 12 experimental displays evaluated by geographic location, and the analysis found no statistically significant differences in the percentage of correct responses across the 12 PPLT signal displays ($p = 0.592$). Based upon this statistical analysis and because the UMass and TTI experiments were procedurally equivalent, the 2,528 scenarios evaluated at UMass and the 874 scenarios evaluated at TTI were combined for analysis.

Initial Static Evaluation Analysis

Four hundred thirty six drivers completed the static evaluation viewing all 12 scenarios. One driver only evaluated 10 scenarios because of an equipment malfunction. In total, 5,230 PPLT signal display scenarios were evaluated. Each driver was asked to respond with one of four choices after viewing the scenario. *Yield, then go if an acceptable gap in the opposing traffic exists* was the correct response for all 12 scenarios. The *stop first, then go if a gap in opposing traffic exists* was also considered a correct response. Driver comprehension was again determined by the percentage of correct responses; however, an analysis of incorrect responses was also completed. The percent of correct responses was 83 percent for all 5,230 scenarios evaluated as correct responses ranged from 73 to 89 percent.

Comparison of Correct Responses

An analysis of correct responses from each methodology was undertaken to identify statistically significant differences. Figure 6 presents the combined percentage of correct responses from the driving simulator experiments versus the correct responses from the static evaluation. As shown in Figure 6, the percentage of correct responses was greater for each of the 12 experimental PPLT signal displays, and for five individual displays the difference was statistically significant at the 95 percent confidence level. Overall the percentage of correct responses was significantly higher in the simulator as opposed to the static evaluation ($p = < 0.001$).

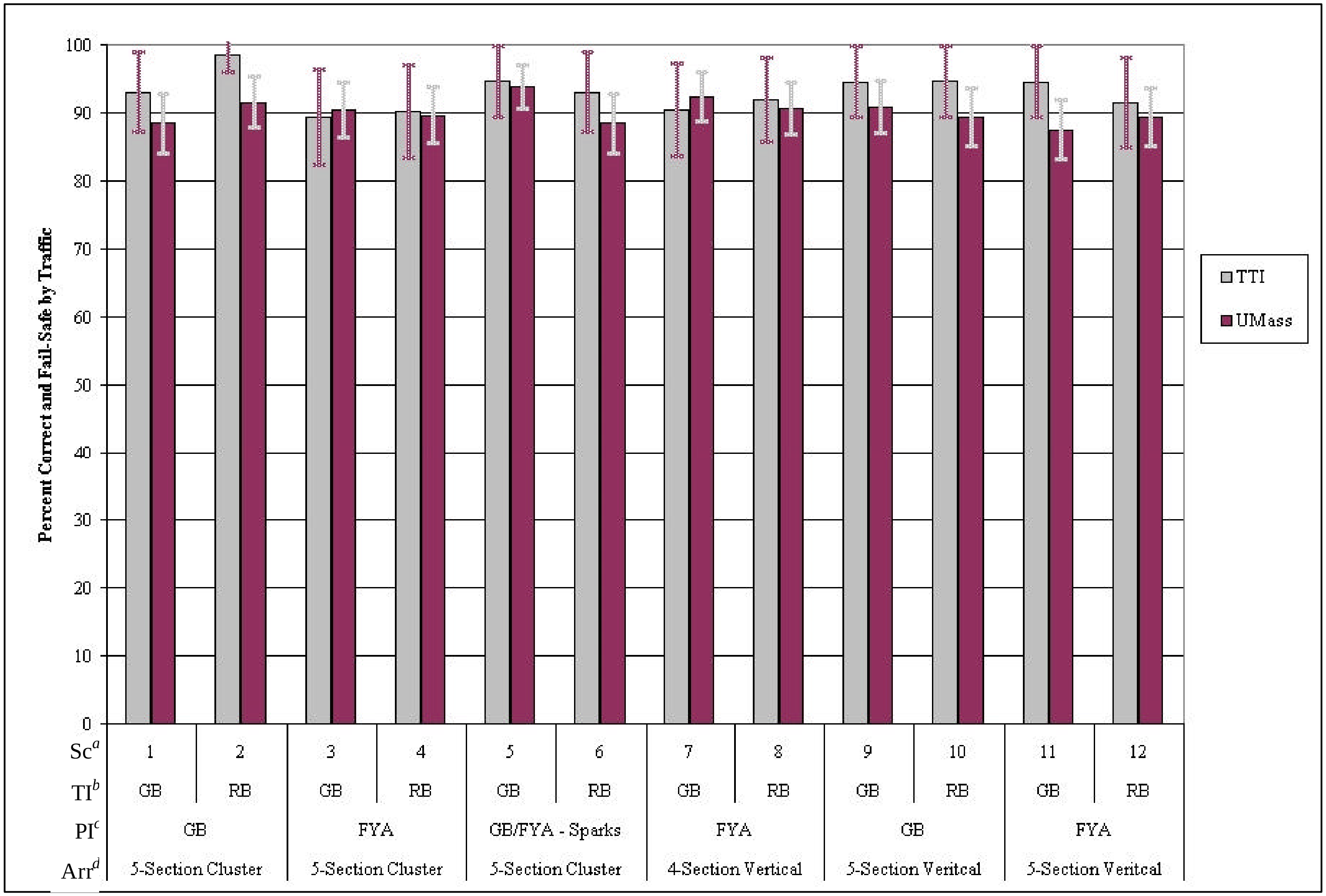
Analysis of Incorrect Responses

The incorrect responses were classified as either fail-safe or fail-critical. In the event that multiple incorrect actions were made, all were noted, and the result was classified by the most serious infraction. In total, fail-safe responses accounted for approximately two percent of all responses in the simulator and six percent of all responses in the static evaluation. Further emphasis was placed on the analysis of fail-critical responses for evaluation purposes, based on the premise that these errors are the most serious and are directly related to driver comprehension of a particular PPLT signal display. Figure 7 presents all responses classified as fail-critical responses from each methodology. Overall, the static evaluation resulted in significantly more fail-critical responses than the driving simulator experiment. For three of the 12 experimental displays, the difference was statistically significant ($p = <0.001$ for each).

Direct Comparison of Driving Simulator and Static Evaluation Results

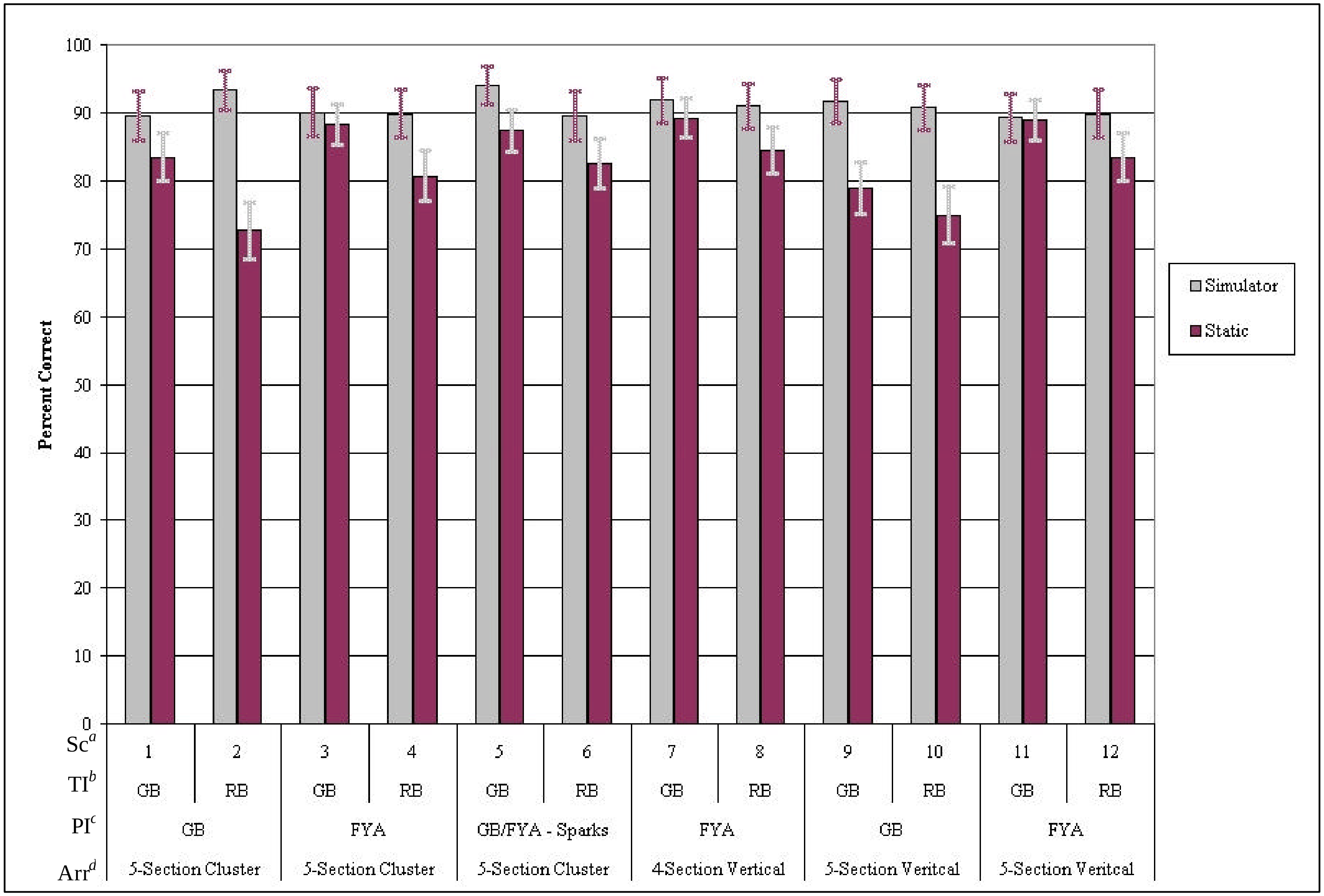
A direct comparison of responses in the simulator and static evaluations was completed by cross-analyzing individual driver's responses in each methodology. The analysis was focused on those drivers who failed critical in the static evaluation. The query was undertaken to determine if drivers' comprehension from the static evaluation was consistent with each driver's action in the dynamic simulation.

There were 353 fail-critical responses from the UMass portion of the static evaluation for which a direct comparison with the driver's response in the simulator were available. Of the 353 fail-critical responses from the static evaluation, drivers had responded correctly in the simulator environment 79 percent of the time. Only 19 percent of the 353 pairs resulted in fail-critical responses in both the simulator and static evaluation. Figure 8 presents the number of drivers with fail-critical responses for each of the 12 PPLT signal displays in the static evaluation, and the number of those drivers with fail-critical responses at the same display in the simulator.



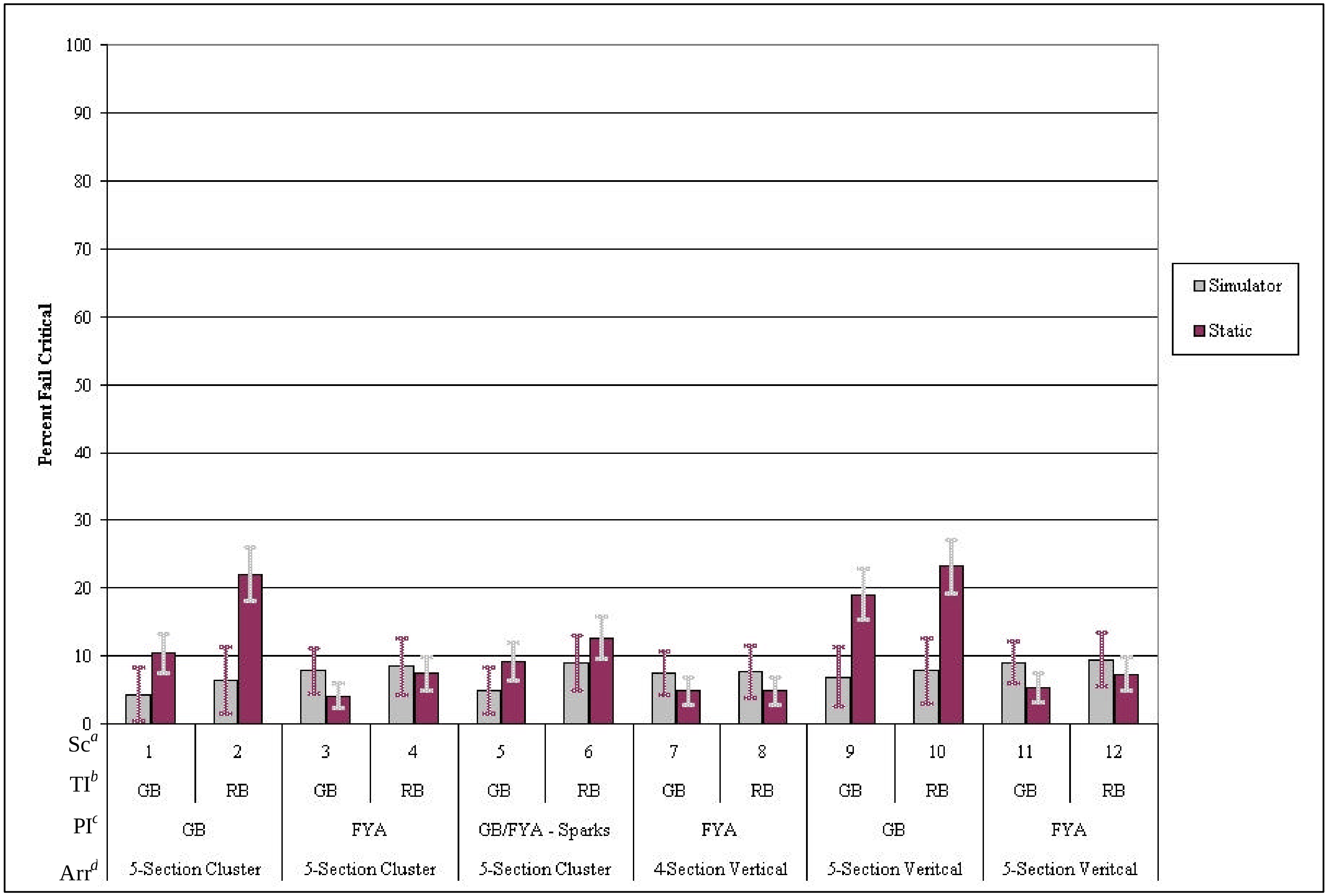
[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green ball; RB = circular red ball)
[c] Left-turn permissive indication (GB = circular green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

FIGURE 5 Percent Correct for each PPLT Signal Display by Study Location (with 95% C.I.).



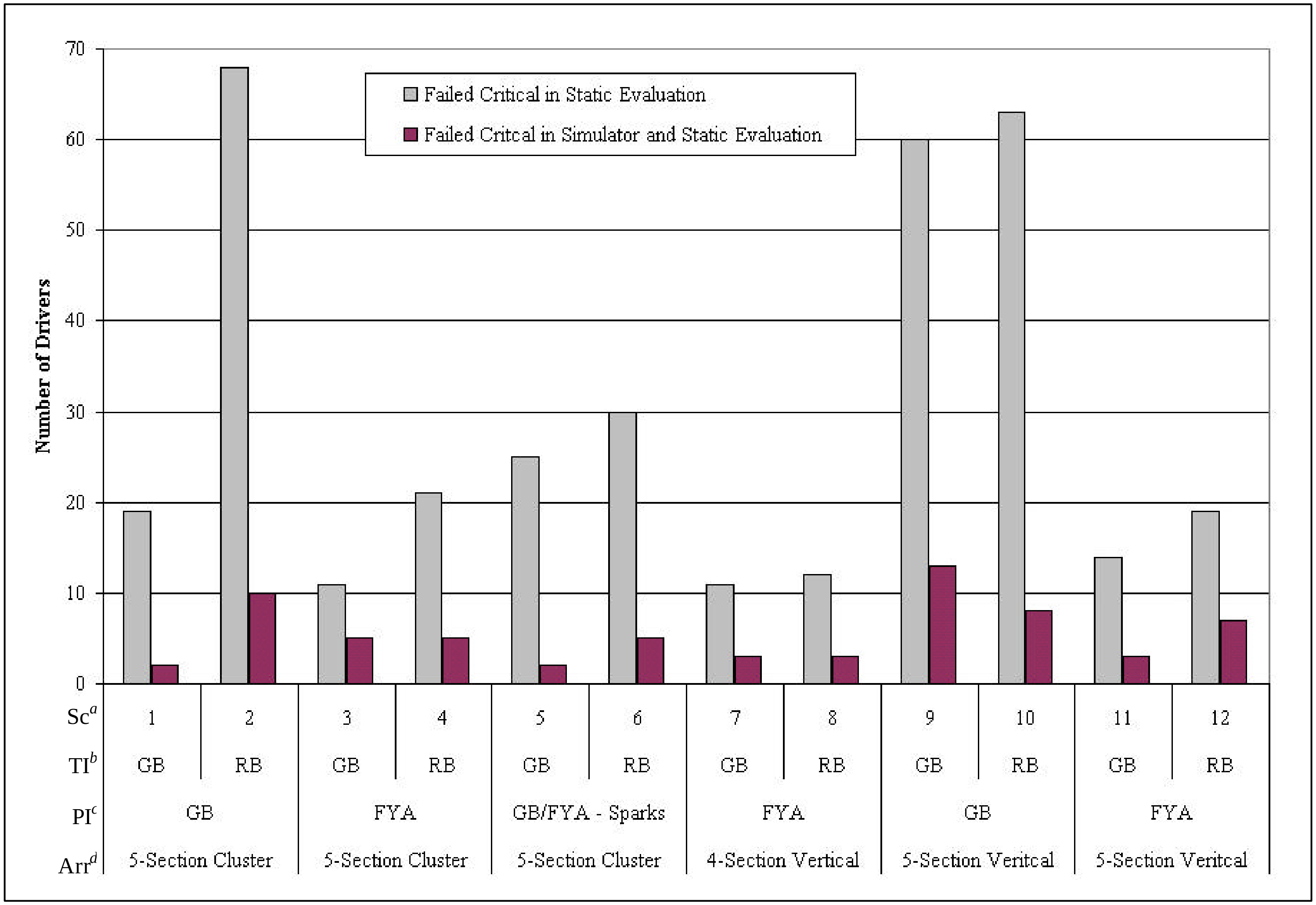
[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green ball; RB = circular red ball)
[c] Left-turn permissive indication (GB = circular green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

FIGURE 6 Percent Correct for each PPLT Signal Display by Study Methodology(with 95% C.I.).



[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green ball; RB = circular red ball)
[c] Left-turn permissive indication (GB = circular green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

FIGURE 7 Percent Fail Critical for each PPLT Signal Display by Study Methodology(with 95% C.I.).



[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green ball; RB = circular red ball)
[c] Left-turn permissive indication (GB = circular green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

FIGURE 8 Comparison of Fail-Critical Responses in the Simulator and Static Evaluations at UMass by Driver

CONCLUSIONS

The results of the simulator and static evaluations carried out at UMass and TTI identified statistically significant differences in driver responses between methodologies. Specifically, drivers responded correct in the simulator significantly more so than in the video-based static evaluation. This idea is believed to support the idea that simulator results are more consistent with the actual driving experiment than static based measures given the consistency with real world observed crash frequencies. The additional cues provided to the driver in the simulator environment had an impact on driver comprehension of the tested PPLT signal displays. Additionally, the results of the simulator study and static evaluation indicate evidence to suggest that the PPLT indication is only one of many elements that the driver takes into account when making left-turn decisions. The direct comparison of individual driver's responses to specific displays in the simulator and following in the static evaluation indicate that what drivers say they will do and what they actually do in the driving environment are not always consistent.

Overall, the application of driving simulator technology is well-suited for driver behavior and comprehension analysis of traffic signal displays. Although it is preferred to evaluate driver comprehension in an environment that is as close to real world as possible, there is the potential for additional driving cues to influence the pure driver comprehension analysis of the display. As a result, the combination of the driving simulator experiment (more realistic with actually driving environment) with the static evaluation (where the variables are more readily isolated) allows for a more comprehensive analysis. In this evaluation the lack of significant findings in the simulator study is in itself a significant finding, and coupled with the statistically significant differences in comprehension identified with the static evaluation the analysis provided a comprehensive evaluation of the 12 PPLT scenarios evaluated. Additionally, it should be noted that the use of simulator technology requires the constant monitoring of simulator subjects for instances of simulator sickness.

ACKNOWLEDGEMENTS

This research was conducted as a component of NCHRP 3-54(2) contracted by Kittelson & Associates, Inc. The authors would like to acknowledge Ray Derr of the Transportation Research Board and Wayne Kittelson and Christopher Brehmer of Kittelson & Associates, Inc.

REFERENCES

1. *Manual on Uniform Traffic Control Devices.* Millennium Edition. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2000.

2. Noyce, D.A. Development of a Uniform Traffic Signal Display for Protected/Permissive Left-Turn Signal Displays. Ph.D. Dissertation, Texas A&M University, College Station, TX, 1998.

3. Staplin, L. and A.D. Fisk. A Cognitive Engineering Approach to Improving Signalized Left Turn Intersections. Human Factors, 33, pp. 559-571.

4. Noyce, D.A. and C.R. Smith. Using of Driving Simulator to Evaluate Novel Traffic Control Devices: Protected/Permissive Left-Turn Signal Displays Analysis. In Conference Proceedings, 2003 Annual Meeting of the Transportation Research Board (CD-ROM), Washington D.C., January 2003.

5. Potential Factors Associated with Simulator Sickness in Virtual Environments, http://www.cyberedge.com, Accessed May 26, 2000.

6. Mourant, R.R. and T.R. Thattacheny. Simulator Sickness in Virtual Environments http://www1.coe.neu.edu/~mourant/pubs/simSickIEA2000. Accessed June 28, 2003.

7. *Highway Capacity Manual.* Transportation Research Board, National Research Council, Washington DC, 2000.