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Preferences for Permitted and Protected Left-Turn Signal Displays

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ABSTRACT

Twenty-two different signal displays for permitted and protected left turns were evaluated from a driver comprehension perspective. The objective was to identify which alternate signal displays used to convey the same left-turn message to the driver are better comprehended and therefore recommended for use in the field. Protected displays compliant with the Manual on Uniform Traffic Control Devices were found to be better comprehended than certain noncompliant displays; however, some noncompliant permitted displays were found to outperform their compliant counterparts. Regional comprehension biases are nonexistent for the most part, regardless of display compliance with the Manual on Uniform Traffic Control Devices. Permitted left-turn signals using indications other than a steady green ball were found to enhance driver comprehension. The ''Left Turn Must Yield on Green Ball'' sign used with a ''doghouse'' display is beneficial during the permitted phase, but confusing when displayed during the protected left-and-through phase. Other supplemental signs used with various left-turn displays were also evaluated.

INTRODUCTION

Left-turn signal displays are used to convey a variety of messages to drivers intending to turn left at signalized intersections. For example, a left-turn green arrow indicates that the driver has the right-of-way over any other intersection movement, whereas a green ball indicates that the driver can complete a left turn without stopping, if there is an adequate gap in the opposing traffic [working simplifications of the definitions in the 1971 and 1988 editions of the Manual on Uniform Traffic Control Devices (MUTCD)].

It has been previously shown (Drakopoulos and Lyles 1997) that significant differences exist in the comprehension of leftturn signal displays, based on both signal message and driver age. A general decline in comprehension with age was identified, a finding in agreement with an investigation limited to permitted and protected displays (Bonneson and McCoy 1993). Left-turn signal comprehension data collected in a laboratory setting [Federal Highway Administration (FHWA) 1988] were analyzed in terms of correct answers, ‘‘minor’’ errors (answers indicating that subjects erroneously believed that they did not have the right-of-way), and ‘‘serious’’ errors (answers indicating that subjects erroneously believed they had the right-of-way, when, in fact, they did not).

Although the earlier work (Drakopoulos and Lyles 1997) was focused on overall comprehension of various signal messages, the current effort is a closer examination of the displays used to convey permitted and protected left-turn messages. The objective is to identify which alternate signal display(s) used to convey the same left-turn message to the driver is (are) better comprehended and therefore recommended for use in the field.

DESCRIPTION OF EXPERIMENT

The test population consisted of 191 paid subjects recruited through newspaper advertisements in Philadelphia, Pa., Seattle, Wash., Dallas, Tex., and Lansing, Mich. (FHWA 1988). Displays similar to the one presented in Fig. 1 were projected on a screen, reproducing 81 left-turn sign/illuminated signal lense combinations using 17 roadway/signal face configuration backgrounds. Signal indications were reproduced in color and flashing indications were depicted realistically with the use of two coordinated slide projectors. Subjects were told to imagine that they were approaching the intersection from the bottom of Fig. 1 and were positioned in the left-turn lane, intending to turn left. Adequate time was given to subjects to respond to the questions about each display. For each display, the subjects were to answer ‘‘yes’’ or ‘‘no’’ to each of the following five options for action:

1. Turn left without stopping for opposing or cross street traffic because you have the right-of-way.
2. Turn left without stopping unless you must wait for a large enough gap in the opposing traffic.
3. Stop; then turn left when there is a large enough gap in the opposing traffic.
4. Stop; then turn left when there is a large enough gap in the cross street traffic.
5. Stop; do not turn left until the signal changes to indicate that you may proceed.

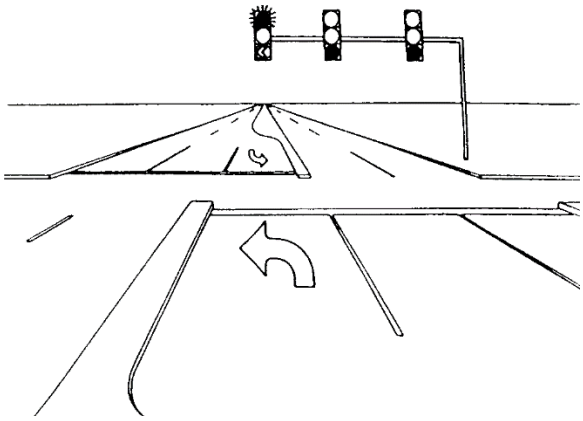

FIG. 1. Typical Laboratory Experiment Display (FHWA 1988)

For example, the correct answer for a display with a flashing red ball on the left-turn signal face and a flashing yellow ball on the through signal face is as follows: no, no, yes, no, no.

The original report (FHWA 1988) dealt with comparisons between pairs of displays and regional comprehension effects for one display at a time. Comprehension relations with driver age were analyzed for each display. No attempt was made to analyze how older driver comprehension relates to display message or display attributes; no conclusions were derived for groups of displays used to convey the same message (e.g., permitted left turn) and/or exhibiting similar attributes (e.g., same type of illuminated signal lenses). The present analysis focuses mainly in the examination of groups of displays exhibiting traits that are thought to influence driver comprehension, and emphasis has been placed in analyzing driver age effects on comprehension. Four age groups (16–30, 31–45, 46–60, and 60+ years of age) were used, and special attention was given to the findings for the 60+ group consisting of 42 individuals.

The following presentation is organized in a section on displays used in permitted left-turn phasing and a section on displays used in protected left-turn phasing. Each section and subsection concentrates, in turn, to findings for all subjects and those for older subjects. Age group limits were determined on the basis of including an adequate number of individuals in each group for statistical inferences.

COMPREHENSION ANALYSIS

The earlier work (Drakopoulos and Lyles 1997) indicated that significant comprehension differences exist among groups of displays used to convey distinct left-turn signal messages (e.g., permitted turn versus protected turn message versus flashing operations message). It is reasonable to expect that some, among a group of displays used to convey the same message (alternate displays), will be comprehended better than others. The present work concentrates on separate comparisons among permitted displays and among protected displays with the purpose of identifying best- and worst-comprehended displays within each group of alternate displays.

The notion of mental task complexity required to interpret a signal display message (e.g., permitted or protected left-turn right-of-way rules) is employed here to explain observed comprehension differences among displays. Signal displays of higher complexity (i.e., signal displays requiring more involved mental processing for a correct interpretation of their message) are expected to be less well comprehended by drivers. Driver comprehension of a particular display is measured in terms of correct/minor error/serious error rates, where answer rate is the percentage of answers that fall within the corresponding answer category.

Display complexity, as described above, was previously used (Drakopoulos and Lyles 1997) to explain, for example, why (more complex) flashing operations displays were less well comprehended than (simpler) protected displays. Drivers turning left and faced with red flashing ball indications on both the left-turn and

through signals have to take both signal indications into account in order to follow the proper right-ofway rules—the left-turn signal indicates they have to stop before proceeding, and the through signal indicates that they have to give the right-of-way to both opposing and cross street traffic. Drivers facing a left-turn green arrow indication can conclude that they can proceed with the turn (they have the right-of-way) and do not need to consult the through signal— the mental processing required to arrive at a correct display interpretation is much less involved.

Furthermore, it was observed that permitted left-turn displays using a green ball indication require drivers to differentiate left-turn right-of-way rules from those applying to through traffic facing an identical signal face with an identical illuminated lens. Although drivers need only consult one signal face in this situation, the use of identical indications to convey drastically different messages, depending only on driver intention, results in a higher mental task complexity for these permitted turns than for protected turns associated with the single-purpose green arrow indication.

Complexity discussion in the present work focuses around two main signal display traits: (1) Concurrence/discordance of illuminated signal lens colors; and (2) the presence of a supplemental sign. Concurrence exists, for example, in a display where a green left-turn arrow and a green ball are illuminated on the left-turn signal face, and a green ball is illuminated on the through signal face. An example of discordance is a display where a red ball and a left-turn green arrow are illuminated on the left-turn signal face, and a red ball is illuminated on the through signal face.

Although it is concurrence in the above example that may reasonably be expected to simplify the required message interpretation mental processing task, concurrence may be a detriment under different circumstances. For example, a permitted left-turn green ball concurrent with a through green ball indication may lead to more serious errors, since the burden to differentiate the message of the left-turn indication (yield to oncoming traffic) from that of the through indication (proceed, you have the right-of-way) is placed on the driver. In contrast to the previous paragraph, discordant left-turn and through signal indications (e.g., flashing left-turn red ball—used in Michigan—with steady through green ball) may automatically warn drivers that right-of-way rules are different for through and left-turn maneuvers. In that sense, discordant lens colors conveying discordant left-turn and through right-of-way rules simplify the required driver decision processing. Thus, although discordant protected displays may increase display complexity, discordant permitted displays may be less complex than their concurrent counterparts.

Although a supplemental sign increases the amount of information a driver has to process (resulting in a more complex display), it may enhance driver comprehension if the sign message reinforces the message of the illuminated lens(es). On the other hand, a sign may be very helpful during a particular phase, but irrelevant, or even confusing, during another phase. Other investigators, for example, identified that the presence of sign message ‘‘Left Turn Yield on Green Ball’’ led to a comprehension deterioration during the protected phase, but improved comprehension during the permitted phase (Hummer et al. 1989; Bonneson and McCoy 1993).

The above discussion illustrates how the same complexity trait (e.g., concurrence of illuminated lenses) may have opposite effects on comprehension depending on display message. Furthermore, certain complexity traits may be applicable to one message (e.g., protected turns) but not to another (e.g., permitted turns). Thus, signal complexity trait analyses are undertaken separately for each group of displays used to convey a given message. Analyzing permitted and protected displays in the present work, provides an opportunity to offer practical recommendations for displays used in permitted/protected phasing. Not only should the best comprehended display traits be used for each phase, but traits useful for one phase but detrimental for the other should be avoided. The analysis is based on the fundamental hypothesis that increasing display complexity will adversely affect driver comprehension.

Non-MUTCD-compliant displays included in the original study (FHWA 1988) are analyzed here for overall and also regional comprehension effects, because it is important to determine whether such displays, in use by individual states at the time of the study, were well comprehended by drivers in other parts of the country.

Multiple-response analysis of variance models (Barcikowski 1983) using percent answers falling within a given correctness category (e.g., correct answer rate) as the dependent variable are used to analyze the effects of subject age, study location, and various display complexity traits. Supplemental sign presence is examined using Cochran's Q statistic for multiple responses (Conover 1999). All responses and older-subject responses are analyzed separately in order to allow a better understanding of issues particular to the older driver.

Null H_0 and alternate H_1 hypotheses tested throughout this work could generally be stated as

- H_0—There are no statistically significant signal display comprehension differences based on subject age, study location, or complexity trait.
- H_1—There are significant display comprehension differences based on subject age, study location, or complexity trait

Permitted Displays

Eight displays used for the permitted interval analysis are shown in Fig. 2. Two displays are examined with and without supplemental signs. Left-turn and through signal face configuration (e.g., stacked-three-section, dog house, stacked-fivesection), color mode (steady or flashing), illuminated signal lenses, and presence of any supplemental signs are indicated for each display.

Display complexity traits investigated for permitted displays were the concurrence or discordance of illuminated signal lens colors on the left-turn and through signals and the presence or not of supplemental signs. Concurrent lens colors were expected to be associated with lower comprehension, and the presence of a supplemental sign emphasizing dissimilarity from the through signal message was expected to improve driver comprehension based on the preceding discussion.

Permitted display comprehension analysis is presented both in terms of serious error and correct answer rates. All subjects and older subjects were analyzed separately.

Repeated measures analysis methods using serious error rate as the dependent variable yielded the results discussed below. Numerical results are presented in Tables 1–4.

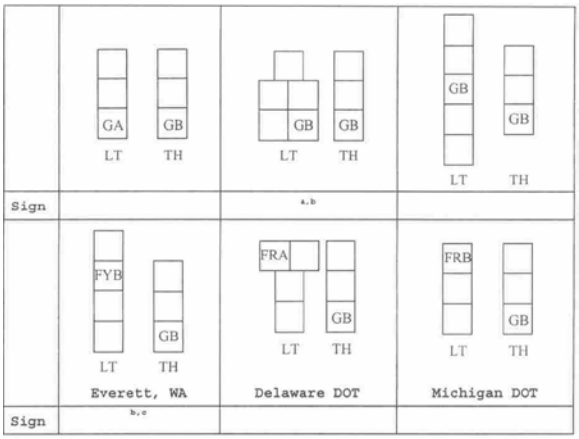

FIG. 2. Permitted Interval Study Displays

Left-Turn Signal Concurrence/Discordance with Through Signal

Statistically significant serious error rate differences exist between concurrent and discordant displays—p = 0.000 [Table 1(a)]. The mean serious error rate [Table 2] is 13.2% for concurrent displays and 1.4% for discordant displays. However, no significant differences exist among age groups (p = 0.207), and no significant concurrence/discordance interactions exist with age (p = 0.431). Results for older subjects (60+), parallel findings for all subjects. In particular, a repeated measures ANOVA model revealed significant comprehension differences based on concurrence/discordance [Table 1(b)]: Serious error rates for concurrent displays were 17.8%, those for discordant displays were 1.8% (Table 2). These findings indicate that use of discordant displays for permitted left turns can be expected to reduce serious error rates for all age groups, because no significant differences exist between age groups

MUTCD Compliance

Several of the concurrent displays [those displaying a left-turn green indication (Fig. 2)] are in compliance with the MUTCD. Discordant displays (those not using a green ball indication)—the Everett, Wash., flashing yellow ball, the flashing red arrow used by the Delaware DOT, and the flashing red ball used by the Michigan DOT—are non-MUTCD-compliant.

There is a natural concern about how well noncompliant displays are comprehended by drivers in parts of the country where they are not being used—an ideal display should be universally well comprehended, regardless of how widely it is used. Conversely, some displays may not be well comprehended regardless of how widespread their use is.

A multiple-response ANOVA model used to investigate the effects of MUTCD compliance and regional effects on comprehension indicated that, although statistically significant comprehension differences exist between compliant and noncompliant displays, comprehension does not differ between study locations, and no significant interactions exist between display compliance and study location [Table 1(c)]. Noncompliant displays were better comprehended (lower serious error rates) in all study locations [Table 3(a)]. Findings for drivers 60+ paralleled overall findings; noncompliant displays significantly outperformed compliant displays [Table 1(d)], with a serious error rate of 1.8% versus 19.7% [Table 3(b)]. The display consisting of a doghouse signal face and the supplemental sign ‘‘Left Turn Must Yield on Green Ball’’ was excluded from this analysis because it fell in a hybrid category by itself. The doghouse signal face arrangement was included in the 1971 MUTCD edition, but the supplemental sign was not included in the MUTCD until its 1988 edition, thus, it was thought best to restrict comparisons among the remaining displays.

TABLE 1. Permitted Displays Repeated Measures Analysis of Variance Serious Error Rates

				F Statistic	
Source of variation (1)	Sum of squares (2)	Degrees of freedom (3)	Mean squares (4)	Value (5)	*P* (6)
(a) Age and Concurrence/Discordance with Through Signal Indication—All Subjects					
Age	0.15	3	0.05	1.53	0.207
Error (age)	5.82	183	0.03	—	—
Concurrence	1.33	1	1.33	44.61	0.000[b]
Age/concurrence	0.08	3	0.03	0.92	0.431
Error[a]	5.47	183	0.03	—	—
b) Concurrence/Discordance with Through Signal Indication—Subjects 60+					
Concurrence	0.54	1	0.54	15.23	0.000[b]
Error[c]	1.45	41	0.04	—	—

(c) Location and MUTCD Compliance—All Subjects					
Location	0.15	3	0.05	1.40	0.246
Error (location)	6.60	182	0.04	—	—
Compliance	1.64	1	1.64	47.71	0.000[b]
Location/compliance	0.10	3	0.03	0.97	0.407
Error[d]	6.24	182	0.003	—	—
(d) MUTCD Compliance—Subjects 60+					
Compliance	0.67	1	0.67	17.19	0.000[b]
Error[e]	1.60	41	0.04	—	—

[a]Age/concurrence/subject (age).

[b]Statistically significant at the 0.05 level of significance.

[c]Concurrence.

[d]Location/compliance/subject (location).

[e]Compliance.

TABLE 2. Permitted Displays: Mean Serious Error Rates—All Subjects

Age (1)	Concurrent[a] (2)	Discordant[a] (3)
16 to 30	0.080	0.005
31 to 45	0.137	0.015
46 to 60	0.140	0.018
60+	0.178	0.018
All ages	0.132	0.014

[a]With through signal indication.

TABLE 3. Permitted Displays: Mean Serious Error Rates

Location (1)	Compliant[a] (2)	Noncompliant[a] (3)
(a) All Subjects		
Philadelphia	0.127	0.011
Dallas	0.105	0.009
Seattle	0.159	0.019
Lansing	0.200	0.018
All locations	0.145	0.014
(b) Subjects 60+		
All locations	0.197	0.018

[a]With MUTCD.

TABLE 4. Permitted Interval-Sign Presence and Message Effects Frequencies (%)

Sign (1)	Serious error (2)	Other (3)	Correct (4)	Other (5)
(a) Doghouse Displays—All Subjects[a]				
No sign	14 (8)	157 (92)	70 (41)	101 (59)
Sign[b]	7 (4)	164 (96)	77 (45)	94 (55)
(b) Doghouse Displays—Subjects 60+[c]				
No sign	3 (8)	33 (92)	15 (42)	21 (58)
Sign[b]	2 (3)	34 (97)	13 (36)	23 (64)
(c) Everett Displays—All Subjects[d]				
No sign	0 (0)	164 (100)	84 (51)	80 (49)
Sign[e]	0 (0)	164 (100)	63 (38)	101 (62)
(d) Everett Displays—Subjects 60+[f]				
No sign	0 (0)	32 (100)	10 (31)	22 (69)
Sign[e]	0 (0)	32 (100)	7 (22)	25 (78)

[a]Serious errors. ‘‘Sign’’ significantly better, Cochran’s Q significance = 0.052. Correct, no significant difference, Cochran’s Q significance = 0.345.
[b]‘‘Left Turn Yield on Green Ball.’’
[c]Serious errors. Frequencies are inadequate for statistics. Correct, no significant difference, Cochran’s Q significance = 0.527.
[d]No serious errors for either display. Correct, ‘‘no sign’’ significantly better, Cochran’s Q significance = 0.001.[e] ‘‘Left Turn Must Yield on Flashing Yellow.’’
[f]No serious errors for either display. Correct, no significant difference from other, Cochran’s Q significance = 0.257.

Supplemental Sign Presence and Message

Two separate evaluations of the comprehension effects of supplemental signs were possible based on comparisons of identical signal face arrangements. The first comparison was among two doghouse displays, one with no supplemental sign and one using the sign ‘‘Left Turn Must Yield on Green Ball.’’ Based on a dichotomous examination of serious error versus other (minor error 1 correct) responses, Cochran’s Q statistic for multiple responses indicated nonstatistically significant differences (just above the 5% significance threshold) in serious error rates among the displays [Table 4(a)]. The addition of the supplemental sign leads to better comprehension and a serious error rate of 4%. For the 60+ age group it was not possible to evaluate comprehension effects of the presence of the supplemental sign ‘‘Left Turn Must Yield on Green Ball’’ for doghouse displays due to lack of adequate serious error observations [Table 4(b)].

In the second comparison, the Everett special displays with and without the sign ‘‘Left Turn Must Yield on Flashing Yellow’’ were found to perform equally (exceptionally) well [Table 3(c)] with 0% serious errors. Naturally, the Everett displays had 0% serious errors in the 60+ age group.

Results based on repeated measures analysis methods using correct answer rate as the dependent variable are discussed below. Numerical results can be found in Tables 4–7.

Concurrence/Discordance with Through Signal Indication

Significant correct answer rate differences were identified between age groups [Table 5(a)], but no significant effects of concurrence/discordance or interactions were identified for any subject group. Correct answer rate declines with subject age from a high of 69.2% for the youngest age group to a low of 34.6% for drivers 60+ (Table 6). Concurrence/discordance had no statistically significant comprehension effect among drivers 60+ [Table 5(b)].

MUTCD Compliance

Significant correct answer rate differences were identified based on study location but not MUTCD compliance. However, interactions between the two factors were found to be significant [Table 5(c)]. Location and interaction effects are mainly due to an unusually high correct answer rate for compliant displays among Dallas subjects (Table 7). Dallas is the only study location where compliant displays have higher correct answer rates than noncompliant displays. In all other study locations, noncompliant displays slightly outperform compliant displays. For drivers 60+, MUTCD compliance was also not statistically significant [Table 5(d)]. Notwithstanding the lack of significance, noncompliant displays here again have a higher correct answer rate than compliant ones [Table 7(b)]. Thus, compliance results for correct answer rates parallel those for serious errors (with the noted Dallas exception)—noncompliant displays outperform compliant ones.

Supplemental Sign Presence and Message

No significant comprehension differences were identified based on the presence of the sign ‘‘Left Turn Must Yield on Green Ball’’ used with doghouse displays for the all subjects group as well as the older subject group

[Table 4(a and b)]. The Everett display with no supplemental sign was found to be comprehended significantly better (51% correct) than the same display complemented with the sign ''Left Turn Must Yield on Flashing Yellow'' (38%) for all drivers [Table 4(c)]. Although sign presence affected older subject comprehension in a similar manner, findings were not statistically significant [Table 4(d)].

TABLE 5. Permitted Displays Repeated Measures Analysis of Variance Correct Answer Rates

				F Statistic	
Source of variation (1)	Sum of squares (2)	Degrees of freedom (3)	Mean squares (4)	Value (5)	P (6)
(a) Age and Concurrence/Discordance with Through Signal Indication—All Subjects					
Age	4.04	3	1.35	7.95	0.000[b]
Error (age)	30.98	183	0.17	—	—
Concurrence	0.02	1	0.02	0.41	0.524
Age/concurrence	0.47	3	0.16	2.60	0.053
Error[a]	11.00	183	0.06	—	—
(b) Concurrence/Discordance with Through Signal Indication—Subjects 60+					
Concurrence	0.22	1	0.22	3.18	0.082
Error[c]	2.83	41	0.07	—	—
(c) Location and MUTCD Compliance—All Subjects					
Location	2.79	3	0.93	5.34	0.002[b]
Error (location)	31.75	182	0.17	—	—
Compliance	0.04	1	0.04	0.61	0.437
Location/compliance	0.84	3	0.28	4.33	0.006[b]
Error[d]	11.78	182	0.06	—	—
(d) MUTCD Compliance—Subjects 60+					
Compliance	0.19	1	0.19	2.49	0.122
Error[c]	3.16	41	0.08	—	—

[a] Age/concurrence/subject (age).
[b] Statistically significant at the 0.05 level of significance.
[c] Concurrence.
[d] Location/compliance/subject (location).
[e] Compliance

TABLE 6. Permitted Displays: Mean Correct Answer Rates—All Subjects

Age (1)	Concurrent[a] (2)	Discordant[a] (3)
16 to 30	0.692	0.643
31 to 45	0.672	0.578
46 to 60	0.519	0.495
60+	0.346	0.448
All ages	0.566	0.545

[a]With through signal indication.

TABLE 7. Permitted Displays: Mean Correct Answer Rates

Location (1)	Compliant[a] (2)	Noncompliant[a] (3)
(a) All Subjects		
Philadelphia	0.413	0.440
Dallas	0.716	0.539

Seattle	0.638	0.663
Lansing	0.526	0.569
All locations	0.577	0.548
(b) Subjects 60+		
All locations	0.353	0.448

[a]With MUTCD.

Conclusions and Discussion

Permitted phase displays were previously found to have the lowest correct answer rates (54.8%) and highest serious error rates (10.0%) among normal, nonflashing operations, signal displays (Drakopoulos and Lyles 1997). These findings were especially important in light of the popularity of permitted phasing. Given that the permitted phase commonly uses a large fraction of the available green time, ample opportunity for right-of-way rule violations exists among drivers misinterpreting its message. The significant differences identified between concurrent and discordant displays lead to the conclusion that a reduction in serious errors can be expected if discordant indications are displayed on the left-turn and through signals, and, because no serious error rate differences exist among age groups, comprehension benefits can be expected for all driver ages. In addition to a reduction in serious error rates, use of discordant displays can be expected to have no adverse effects on correct answer rates, based on the finding that correct answers are only related to subject age, not concurrence/discordance of left-turn and through signal indications. Thus, the main expected comprehension effect from the use of discordant displays would be a shift from serious errors to minor errors (i.e., from drivers violating the right-of-way of opposing traffic to drivers stopping before completing a left turn) possibly leading to a decrease in head-on collisions, an increase in rear-end collisions, and a deterioration in left-turn capacity.

Comprehension benefits can be expected for doghouse displays showing a green ball if the sign ‘‘Left Turn Must Yield on Green Ball’’ is present. Sign presence reduces serious error rates and has no significant effect on correct answer rates.

However, improved comprehension can be expected if the Everett display is used without the sign ‘‘Left Turn Yield on Yellow,’’ because the sign was shown to reduce correct answer rates from 51% (no sign present) to 38%. When the sign is present, dissimilarity from the through signal message is present in two synergistic ways: (1) Discordant illuminated left-turn and through signal lenses; and (2) the presence of the sign itself. Given that there are no serious errors regardless of sign presence, the conclusion is reached that this outstanding comprehension is due to the use of discordant leftturn and through illuminated lenses and that the addition of the sign has no detrimental effect in terms of serious errors. Apparently, the sign has the effect of overemphasizing the dissimilarity between through and left-turn right-of-way rules and many subjects think they have to stop before completing the turn. The evaluated signs use similar wording; however, more subjects think they have to stop for a flashing yellow than for a steady green ball—this seems to be related to the illuminated lens type, rather than the supplemental sign message.

Protected Displays

Fourteen displays used to convey the message of a protected left turn were included in the analysis and are shown in Fig. 3 (two displays are examined with and without supplemental signs). Responses to protected displays were classified either as correct or minor errors (if subjects indicated that they would yield to opposing traffic or stop and wait for the signal indication to change, respectively). In earlier work (Drakopoulos and Lyles 1997), protected displays were found to lag behind red and change interval displays in terms of correct answers despite the unambiguous and unique message of a left-turn green arrow. In the present effort, an attempt is made to explain this originally puzzling finding by incorporating complexity traits particular to protected displays. Although a steady left-turn green arrow is present in all displays except one, a number of protected displays include two illuminated left-turn signal lenses, a condition that may introduce confusion among drivers.

The sole exception to the steady arrow is the display from Vancouver, British Columbia, using a fast flashing green arrow. Simultaneously illuminated left-turn signal lenses may cause drivers to mistakenly think that the message of a green arrow is modified in some way.

Concurrent/discordant left-turn and through signal indications may also have an effect in confusing drivers. Effects of simultaneously illuminated signal lenses on driver comprehension were analyzed with the use of variable ‘‘colors’’ which placed each display in one of four categories (Fig. 3): (1) Concurrent (green) left-turn signal face indications, with red through signal face indication; (2) discordant left-turn signal face indications (red ball and green arrow) with red through signal face indication; (3) concurrent left-turn signal face indications with green through signal face indication; and (4) special left-turn signal displays. The latter category consists of the Vancouver fast flashing green arrow and the Dallas special display, the only display where an illuminated red ball indication is not used to prohibit a movement in the direction it is facing. It was expected that, for protected displays, driver comprehension would be higher when the ‘‘go-ahead’’ message is emphasized; i.e., it is higher when all indications on the left-turn signal face are green, but lower when a red indication is present, because it may make drivers hesitant to complete the turn.

Comprehension effects of the sign message ‘‘Left Turn Signal’’ were evaluated for standard stacked-three-section left-turn signal faces. Effects of the sign message ‘‘Left Turn Must Yield on Green Ball’’ were evaluated for doghouse left-turn signal faces.

Since no serious errors are possible for protected displays, this part of the analysis is focused on minor error rates.

The repeated measures analyses using minor error rate as the dependent variable are described below. Numerical results and statistics are provided in Tables 8–11.

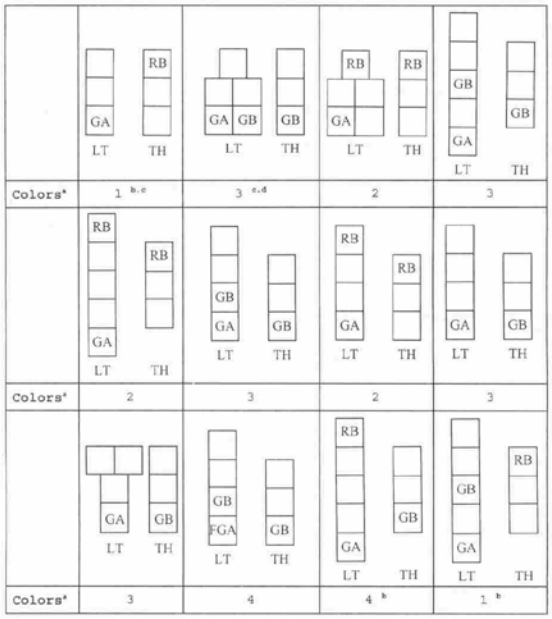

FIG. 3. Protected Interval Study Displays

TABLE 8. Protected Displays Repeated Measures Analysis of Variance Minor Error Rates

Source of variation (1)	Sum of squares (2)	Degrees of freedom (3)	Mean squares (4)	F Statistic Value (5)	P (6)
(a) Age and Colors—All Subjects					
Age	6.51	3	2.17	5.97	0.001[b]
Error (age)	66.94	184	0.36	—	—
Colors	14.34	3	4.78	90.17	0.000[b]
Age/colors	0.45	9	0.05	0.95	0.483
Error[a]	29.27	552	0.05	—	—
(b) Colors—Subjects 60+					
Colors	4.14	3	1.38	23.64	0.000[b]
Error[c]	7.01	120	0.06	—	—
(c) Location and MUTCD Compliance—All Subjects					
Location	2.80	3	0.93	4.56	0.004[b]
Error (location)	37.73	184	0.21	—	—
Compliance	6.21	1	6.21	129.35	0.000[b]
Location/compliance	0.18	3	0.06	1.22	0.304
Error[d]	8.84	184	0.05	—	—
(d) MUTCD Compliance—Subjects 60+					
Compliance	1.90	1	1.90	44.27	0.000[b]
Error[e]	1.72	40	0.04	—	—

[a] Age/colors/subject (age).
[b] Statistically significant at the 0.05 level of significance.
[c] Location/compliance/subject (location).
[d] Colors.
[e] Compliance.

TABLE 9. Protected Displays: Mean Minor Error Rates—All Subjects

Age (1)	Colors = 1[a] (2)	Colors = 2[b] (3)	Colors = 3[c] (4)	Colors = 4[d] (5)
16 to 30	0.147	0.256	0.200	0.473
31 to 45	0.212	0.436	0.315	0.588
46 to 60	0.250	0.503	0.330	0.597
60+	0.353	0.587	0.432	0.768
All ages	0.235	0.438	0.314	0.599

[a] Left-turn green arrow or green arrow 1 green ball with through red ball.
[b] Left-turn green arrow 1 red ball with through red ball.
[c] Left-turn green arrow or green arrow 1 green ball with through green ball.
[d] Special displays (Vancouver and Dallas) (Fig. 3).

TABLE 10. Protected Displays: Mean Minor Error Rates

Location (1)	Compliant[a] (2)	Noncompliant[a] (3)
(a) All Subjects		
Philadelphia	0.361	0.609
Dallas	0.230	0.425
Seattle	0.301	0.610
Lansing	0.416	0.698
All locations	0.325	0.580
(b) Subjects 60+		

All locations	0.452	0.756

[a]With MUTCD.

TABLE 11. Protected Interval-Sign Presence and Message Effects Frequencies (%)

Sign (1)	Correct (2)	Minor error (3)
(a) Stacked-Three-Section Displays—All Subjects[a]		
No sign Sign[b]	137 (74) 146 (79)	47 (26) 38 (21)
(b) Stacked-Three-Section Displays—Subjects 60+[b]		
No sign Sign[c]	22 (59) 26 (70)	15 (41) 11 (30)
(c) Doghouse Displays—All Subjects[d]		
No sign Sign[e]	120 (68) 64 (36)	56 (32) 112 (64)
(d) Doghouse Displays—Subjects 60+[f]		
No sign Sign[e]	23 (61) 8 (22)	14 (39) 29 (78)

[a] Cochran's Q significance = 0.072. Displays perform comparably.
[b] Cochran's Q significance = 0.102. Displays perform comparably.
[c] ''Left Turn Signal.''
[d] Cochran's Q significance = 0.000. Display with sign performs worse.
[e] ''Left Turn Yield on Green Ball.''
[f] Cochran's Q significance = 0.000. Display with sign performs worse.

Simultaneously Illuminated Lenses

Statistically significant differences were identified between age groups and colors categories, with insignificant interactions [Table 8(a)]. Comprehension consistently deteriorates with age across all colors categories (Table 9). Best understood (least minor errors) are displays with one or more green left-turn signal indications illuminated concurrently with a circular red through signal indication (colors = 1). Listed in order of diminishing comprehension are (1) Displays with green left-turn signal indication(s) illuminated concurrently with a circular green through signal indication (colors = 3); (2) those with discordant left-turn signal indications (colors = 2); and (3) special left-turn displays (colors = 4). Findings about the significant effects of colors for older (60+) subjects' comprehension [Table 8(b)] parallel those stated for all subjects; their comprehension is the lowest within each protected display type (Table 9).

MUTCD Compliance

Statistically significant comprehension differences were identified based on MUTCD compliance and study location, however, their interactions were nonstatistically significant [Table 8(c)]. Compliance explains most of the variance in the data. Noncompliant displays are less well comprehended in every study location (Table 10). Compliance is significant for older subjects as well, with comprehension differences in the same direction as for all drivers [Tables 8(d) and 10(b)].

Supplemental Sign Presence and Message

Based on a dichotomous examination of minor error versus correct answer rate for standard stacked-three-section displays, Cochran's Q statistic for multiple responses was applied to both all subjects and older subjects, and the results indicated nonstatistically significant comprehension differences when the sign ''Left Turn Signal'' is present compared to when no sign is present [Tables 11(a and b)]. However, statistically significant differences were identified for doghouse displays based on presence or absence of the supplemental sign ''Left Turn Must

Yield on Green Ball'' for all subjects and older subjects [Tables 11(c and d)]. Displays without that sign were found to be better comprehended.

Conclusions and Discussion

Significant comprehension differences were identified among subject age groups—subject comprehension deteriorates with age across all examined color combination categories for protected left-turn displays. The presence or absence of the sign ''Left Turn Signal'' has virtually no effect on any age group for standard stacked-three-section signal faces. However, its use may be beneficial in situations where it is necessary to identify the left-turn signal because of signal positioning problems in the field, provided it does not prove to be confusing during other signal phases. One important finding is that the presence of the ''Left Turn Must Yield on Green Ball'' sign in doghouse displays is confusing to all subjects, particularly those in the 60+ age group. The reason for the distinctly poor comprehension of this particular display may be the fact that when a green ball and a green arrow are simultaneously illuminated on the left-turn signal face, drivers may become confused by the conflicting messages conveyed by the green arrow (go ahead with the left turn) and the sign message (yield to other traffic) which is applicable during this phase, since the green ball is also illuminated.

Concurrent illuminated left-turn signal lenses (green indications) are better comprehended than discordant (green arrow and circular red lenses), perhaps because the presence of a circular red indication on the left-turn signal contradicts the message of the green arrow and might be interpreted as a modifier of the go-ahead green arrow message, confusing the driver. The special Vancouver and Dallas displays exhibit unique traits that may confuse drivers not familiar with them. Indeed, the Dallas display is much better understood by Dallas subjects (33.3% minor errors), than it is by subjects in Philadelphia (45.5%), Seattle (71.8%), or Lansing (73.8%). Thus, the display performed as well as other displays used in the left-turn and through phase (colors = 3), who have an average minor error rate of 31.4% (Table 9) among familiar drivers. However, the fast flashing green arrow used in Vancouver for the same phase (not used in any of the study sites) performed worse than the colors = 3 displays. Error rates ranged from a low of 49.1% in Dallas to a high of 73.9% in Philadelphia. Results on special displays do not necessarily imply that such displays should be avoided. It is possible that, if drivers across the country were to become familiar with the Dallas or Vancouver displays, their comprehension of these displays could become comparable to, or better than, that of MUTCD displays. The question, however, would remain of how currently unfamiliar and/or poorly understood displays can be introduced nationwide in driver education programs and, subsequently, in the field without detrimental comprehension effects on (part of) the driving population.

CONCLUSIONS AND RECOMMENDATIONS

A number of signal display factors that affect driver comprehension of permitted and protected left-turn messages have been identified. Comprehension may or may not be related to driver age, depending on the signal message and whether one is interested in how often drivers correctly interpret the signal message, or commit a minor or serious comprehension error. An ideal left-turn signal display would be correctly understood across all age groups, both during the permitted and the protected phases by the vast majority of drivers.

However, the results here show a situation that is not quite ideal; display traits that are associated with lower error rates (serious or minor) may also be associated with lower correct answer rates and vice versa. For example, the Everett permitted display has zero serious errors, but performs rather poorly in terms of correct answers when accompanied by the ''Left Turn Yield on Flashing Yellow'' sign. A trait that may be beneficial to the comprehension of one phase may be detrimental to the comprehension of another; e.g., the presence of the sign ''Left Turn Yield on Green Ball'' reduces serious errors for doghouse displays during the permitted phase, but is responsible for higher minor errors during the protected left-turn and through phase. The challenge to the

practitioner, then, is to carefully choose displays that will optimize the benefits and minimize adverse comprehension effects, a choice that may not always be clear-cut.

Conclusions are organized around discussions of factors whose effect on comprehension was analyzed in the previous sections. This section concludes with an examination of findings' agreement with other research efforts.

Subject Age

Findings based on all subjects are consistent with those for older subjects (where enough data for the latter are available). It is important that no significant differences across age groups exist for serious errors; however, correct answer differences exist across age groups both for permitted and protected displays. Notwithstanding the statistical significance of findings, comprehension was shown to deteriorate with subject age in terms of every analyzed comprehension measurement (serious errors, correct answers, and minor errors).

Concurrent/Discordant Illuminated Signal Lenses

Comprehension benefits can be expected for permitted displays if emphasis is placed on differentiating the message of the permitted left-turn indication from that of the through indication, leading drivers turning left to use caution when completing their maneuver. When steady circular green is indicated on both the left-turn and the through signal faces, drivers are expected to differentiate left-turn right-of-way rules (complete the turn without stopping if no opposing traffic is present) from those applying to through traffic (you have the right-ofway) on their own; i.e., the signal configuration does not actively convey a different message to the left-turning driver. Two factors that amplify differences between left-turn and through signal messages were examined: (1) Use of discordant left-turn and through signal indications (discussed here); (2) and supplemental signs (discussed later).

Use of discordant left-turn and through signal indications (e.g., the flashing yellow ball used in Everett, the flashing red arrow used by the Delaware DOT, or the flashing red ball used by the Michigan DOT) was found to be an efficient way to actively differentiate between the permitted left-turn and through signal messages.

It can be expected that, in the absence of serious error rate differences between age groups, measures to improve message discrimination between permitted left-turn and through signal messages, associated with lower serious error rates, will yield comprehension benefits (reduced serious error rates) across all ages. Furthermore, based on the lack of significant concurrence/discordance effects on correct answer rates both for all drivers and older drivers, use of discordant left-turn and through signal messages is not expected to decrease comprehension in terms of correct answer rates.

Contrary to permitted displays, improved comprehension of protected displays can be expected when emphasis is placed on avoidance of discordant, or unusual, information on the left-turn signal face (e.g., red ball, fast flashing green arrow) that might lead drivers turning left to hesitate in completing their maneuver.

It is possible that such discordant information is interpreted as a modifier of the unique and unambiguous green arrow message, leading to higher minor error rates. A red ball on the through signal face, however, enhances driver comprehension compared to a green ball, possibly because drivers anticipate a symmetric phasing plan, in which case opposing through traffic would also face a red ball. A through green ball—associated with a left-turn and through phase—may confuse left-turning drivers expecting a symmetric intersection phasing plan and may lead them to wonder whether opposing through traffic also faces a green ball, putting it in conflict with their path. Here again, discordance between the left-turn signal face indication(s) and through signal indication was found to enhance driver comprehension.

Sign Presence

The sign ‘‘Left Turn Must Yield on Green Ball’’ used in a doghouse display during the protected left-turn and through phase was found to contribute to comprehension deterioration, possibly because drivers receive conflicting messages from the green arrow (go ahead), and the green ball/sign combination (yield). Thus, they are not sure whether they should proceed with the turn or yield to opposing through traffic. However, the presence of the same sign improves driver comprehension of a doghouse display during the permitted phase during which only the green ball is illuminated and the sign is not in conflict with any signal indication. In fact, it provides an interpretation enhancement of the permitted circular green indication. Given the above discussion, a mechanism that would allow the message to be displayed only during the permitted phase should improve display comprehension (lower serious error rate during permitted phasing and lower minor error rate during protected phasing) during these two phases.

The sign message ‘‘Left Turn Signal’’ was found not to affect comprehension of protected displays using a standard stacked-three-section signal face. Its merits should be decided based on findings about its comprehension effects during other phases and/or other considerations.

The Everett display was better comprehended during the permitted phase when no sign was present (based on correct answers), however, final conclusions on the use of the sign ‘‘Left Turn Yield on Flashing Yellow’’ cannot be reached until its comprehension effects during other phases are evaluated.

MUTCD Compliance and Study Location

For tested permitted displays, noncompliance is associated with better comprehension (significantly lower serious errors and nonsignificantly higher correct answers). It is noteworthy to mention that, although noncompliant permitted displays are used by individual jurisdictions, even drivers from other parts of the country were shown to comprehend them better (lower serious errors) than the more common standard stacked-three-section display and stacked-five-section display.

Contrary to findings for permitted displays, among tested displays, it is compliant protected displays that are better comprehended (lower minor errors), than noncompliant ones. The two noncompliant protected displays included in the analysis, the Vancouver and Dallas displays, fared worse than compliant displays in terms of minor errors in study locations where subjects were unfamiliar with them.

Comparing the findings about noncompliant permitted displays and protected displays, it is evident that compliance— and thus, wider display use and driver familiarity with a display—does not guarantee better driver comprehension. Indeed, noncompliant permitted displays were found to be better comprehended despite driver unfamiliarity, but noncompliant protected displays were shown to be less well comprehended by unfamiliar subjects. Thus, it appears that it is not driver familiarity that drives comprehension, but rather, the effective or ineffective use of display traits.

Noncompliant permitted displays do not introduce new concepts; drivers are familiar with flashing red and yellow ball or arrow indications, normally present on flashing beacons and during nighttime operation, compelling drivers to stop or proceed with caution, respectively. It is the application of these familiar concepts that is new (on left turns during normal signal operations)—and, according to the findings, also appropriate—leading to enhanced driver comprehension. The uniformly better comprehension of such displays across study locations indicates that adoption of such displays by other states can be expected to lead to better, not worse, comprehension, despite driver unfamiliarity. Furthermore, the Everett and Michigan displays use existing signal face configurations, virtually eliminating hardware conversion concerns.

Analyzed noncompliant protected displays also use new combinations of familiar lens types; however, their combined messages were found to confuse drivers—the Vancouver display uses a fast flashing green arrow, an unfamiliar mode for the green arrow, and the Dallas display uses a red indication not intended to prohibit a movement, an unfamiliar use for such an indication. The display also employs discordant leftturn signal lenses (least well comprehended among tested protected displays).

Agreement with Other Research Efforts

Bonneson and Hummer have addressed the issue of driver comprehension of left turn displays (Bonneson and McCoy 1993; Hummer et al. 1990). The former concentrated on three signal head arrangements of interest to the Nebraska DOT. Data was collected through a survey form at various Nebraska Department of Motor Vehicle offices. The latter was also based on a survey form depicting eight signal displays, based on those developed for the original study (FHWA 1988). Although direct comparisons are not possible with these efforts due to differences in the examined displays, survey instruments, and definitions of erroneous answers, an attempt will be made to address whether fundamental agreement exists with the present study.

Findings about the sign ‘‘Left Turn Yield on Green Ball’’ for the doghouse display are in agreement with Hummer and Bonneson; both investigators find enhanced comprehension during the permitted phase and significant comprehension deterioration during the protected phase, compared to the no sign condition.

Improved protected left-turn display comprehension for concurrent left-turn signal face indications during the red through phase identified in Bonneson’s study agrees with findings here. It should be kept in mind, however, that his findings are based on MUTCD displays m., n., and s. with only the green arrow illuminated. The present study is based on combined findings on MUTCD displays c. (only green arrow illuminated), and m. (green ball and green arrow illuminated) —see colors = 1 (Fig. 3).

Findings here about the influence of through signal indication on comprehension of protected displays using concurrent left-turn signal face lenses are in agreement with Hummer et al. (1990)—a red through signal indication (colors = 1 in Fig. 3) enhances comprehension; a green through signal indication (colors = 3 in Fig. 3) adversely affects comprehension.

Comprehension is only one of many factors that affect safety at signalized intersections. Its accident contribution potential is difficult, if not impossible, to quantify. Use of better comprehended displays, however, can be expected to improve signalized intersection safety. Differences in driver comprehension of left-turn signal displays found in the above analysis warrant a more extensive research effort, with a focus on signal display characteristics associated with driver comprehension and based on comparisons among a larger number of displays that will allow a more thorough analysis of various display traits. Comprehension differences between age groups have been hypothesized herein to be due to display complexity leading to driver confusion; however, no direct verification of this hypothesis is possible based on the available information. The confused driver hypothesis could be further investigated with the addition of variables that will allow an evaluation of a wider variety of comprehension contributing factors (e.g., driver education history, multitasking ability, cognition, and dementia measurements).

A larger subject sample is necessary, especially if factors affecting older drivers are a main focus. The artificial age limit of 60 years of age used here includes many individuals in the older category who are virtually indistinguishable in terms of mental capacity from younger subjects. A laboratory, rather than field setup, is recommended. The laboratory can be much more focused on driver comprehension by avoiding the introduction of factors that may affect driver performance in the field [e.g., visual and auditory cues from other drivers and vehicles, glare and illumination problems (signal and background related), pavement markings, traffic volumes, and pedestrian presence] that may vary between locations or even within any given location.

The above findings could translate into a few practical measures in the field that should improve driver comprehension:

• Use of any of the analyzed permitted displays with discordant left-turn and through indications, instead of a typical stacked-three-section, doghouse, or stacked-five-section permitted displays (green ball illuminated)
• Elimination of simultaneous red ball and green arrow on the same signal face during protected phasing
• Use of the ''Left Turn Must Yield on Green Ball'' sign with doghouse displays, under the conditions that the message is visible when only the green ball is illuminated, and the message is not visible when the left-turn green arrow and green ball lenses are simultaneously illuminated
• Use of the Everett permitted display without the supplemental sign ''Left Turn Yield on Yellow Arrow''

REFERENCES

Barcikowski, R. S. (1983). Computer packages and research design: With annotations of input and output from the BMDP, SAS, SPSS, and SPSSX statistical packages. University Press of America, Lanham, Md.

Bonneson, J. A., and McCoy, P. T. (1993). ''Evaluation of protected/ permitted left-turn traffic signal displays.'' Res. Rep. TRP-02-27-92, Nebraska Department of Roads, Lincoln, Neb.

Conover, W. J. (1999). Practical nonparametric statistics, 3rd Ed., Wiley, New York.

Drakopoulos, A., and Lyles, R. W. (1997). ''Driver age as a factor in comprehension of left-turn signals.'' Transp. Res. Rec. 1573, Transportation Research Board, Washington, D.C., 76–85.

Federal Highway Administration (FHWA). (1988). ''Signal displays for left turn control—Final report.'' Contract FHWA DTFH61-85-C00164, Washington, D.C.

Hummer, J. E., Montgomery, R. E., and Sinha, K. C. (1989). ''An evaluation of leading versus lagging left turn signal phasing.'' Joint Hwy. Res. Proj. FHWA/IN/JHRP-89/17, Purdue University, West Lafayette, Ind.

Hummer, J. E., Montgomery, R. E., and Sinha, K. C. (1990). ''Motorist understanding of and preferences for left-turn signals.'' Transp. Res. Rec. 1281, Transportation Research Board, Washington, D.C., 136– 147.