DEPARTMENT OF TRANSPORTATION

Driver Comprehension of Flashing Yellow Arrows

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December 2023

Research Project
Final Report 2023-42

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In 2009, the FHWA's *Manual on Uniform Traffic Control Devices* (MUTCD) introduced the flashing yellow arrow (FYA) traffic signal as an alternative to circular green (CG) to indicate permitted left turns. The FYA is arguably a more intuitive indication that left turns are permitted but not protected and, in addition, the FYA signal heads can support time-of-day changes between protective and permissive left -turn phasing. In 2019, a Research Needs Statement stated that "Research is needed to examine driver comprehension of flashing yellow arrows in different light arrangements and the role of signage." Our objective in this project was to assess drivers' understanding of FYA signal indications and to see if the presence or absence of "Left Turn Yield" signs affect gap acceptance. This was accomplished by conducting an online survey of drivers regarding their understanding of FYA signals and by carrying out a field study of drivers' gap acceptance at a set of Twin Cities intersections.

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Driver Comprehension of Flashing Yellow Arrows

Final Report

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Executive Summary

In 2009, the FHWA's *Manual on Uniform Traffic Control Devices* (MUTCD) introduced the flashing yellow arrow (FYA) traffic signal as an alternative to circular green (CG) to indicate permitted left turns. The FYA is considered a more intuitive indication that left turns are permitted but not protected, and, in addition, FYA signal heads can support time-of-day changes between protective and permissive left-turn phasing. In 2019, a Minnesota Research Needs Statement noted that "Research is needed to examine driver comprehension of flashing yellow arrows in different light arrangements and the role of signage." Our objective in this project was to assess drivers' understanding of FYA signal indications, and to see if the presence or absence of "Left Turn Yield" signs affects comprehension and gap acceptance. This was accomplished by conducting an online survey of drivers regarding their understanding of FYA signals, and by carrying out a field study of drivers' gap acceptance at a set of Twin Cities intersections.

Our survey found that more than 90% of the drivers who responded understood that FYA indicated a permitted, not protected, left turn, and there was little difference between when the "Left Turn Yield" sign was present versus when it was absent. For the small number of drivers who, when the sign was absent, interpreted a FYA as indicating a protected left turn, some, but not all, corrected this error when the yield sign was present. In our field study, the critical gaps at sites with 30 mph opposing speed limits were, on average, significantly longer when the "Left Turn Yield" sign was present, for both FYA and CG. At the 40 mph sites with a FYA, critical gaps were significantly longer when the sign was present compared to absent, but this pattern was reversed for the CG sites.

Chapter 1: Introduction

In 2009, the FHWA's *Manual on Uniform Traffic Control Devices* (MUTCD) introduced the flashing yellow arrow (FYA) traffic signal as an alternative to circular green (CG) to indicate permitted left turns. The FYA is considered a more intuitive indication. Additionally, FYA signal heads can support time-of-day changes between protective and permissive left-turn phasing. FYA signals have been deployed for at least 10 years in Minnesota, and as of December 2011, the Minnesota MUTCD (MNMUTCD) stated, "If a separate left-turn signal face is being operated in a protected/permissive left-turn model, a CIRCULAR GREEN signal indication shall not be used in that face." The MNMUTCD also specifies how FYA should be implemented as an alternative. Figure 1.1 (Figure 4D-12 from the MNMUTCD) illustrates typical signal configurations using FYA.

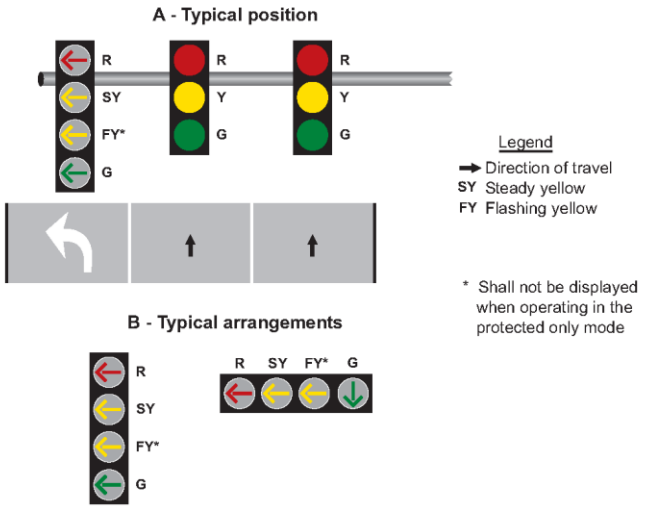

Figure 4D-12. Typical Position and Arrangements of Separate Signal Faces with Flashing Yellow Arrow for Protected/Permissive Mode and Protected Only Mode Left Turns

Figure 1.1 Typical Flashing Yellow Signal Arrangements from the MNMUTCD.

As noted above, since 2011 the MNMUTCD allowed use of FYA to indicate permitted left turns. As these were being deployed, however, articles in the Minnesota press (Harlow 2017; Divine 2018) have suggested some concern about the appropriate use of FYA signals. In 2019, Minnesota Research Needs Statement 583 noted, "Research is needed to examine driver comprehension of flashing yellow arrows in different light arrangements and the role of signage."

1.1 Literature Summary

Prior to adoption of the flashing yellow arrow (FYA) signal indications in the 2009 MUTCD, the National Cooperative Highway Research Program (NCHRP) sponsored "extensive research efforts to identify the 'best' traffic signal display for protected/permissive left-turn (PPLT) control" (Brehmer et al. 2003). A driver simulator component of this study found "a high level of comprehension and no variation

between the different PPLT displays tested." A field study component, where approximately 20 intersection approaches were observed for between 8 and 26 hours before and after FYA installation, found no discernible differences in conflict rates. In a follow-up study Noyce et al. (2007) investigated crash frequencies before and after installation of a FYA. Overall, crashes tended to decrease after the FYA replaced a circular green (CG) indication for the permitted phase in protected/permitted treatments but, not surprisingly, crashes tended to increase when FYA permitted phasing replaced protected-only phasing. A small field study at a single intersection in St. Louis, MO, (Lin et al. 2008) indicated that "90% of the drivers understood the meaning of the FYA."

Regarding safety effects, after inclusion of FYA in the MUTCD, a more extensive safety evaluation became possible. In an empirical Bayes before/after study of changes in left-turn signalization (Srinivasan et al. 2011), a 36% reduction in left-turn crashes was reported when FYA replaced CG for the permissive left-turn phase, but an increase in left-turn crashes when protected phasing was replaced by protected/permissive phasing was indicated by FYA. This general trend was confirmed by later work (King et al. 2018; Medina et al. 2018; Schattler et al. 2017; Srinivasan et al. 2018), and in Minnesota, by Storm et al. (2020).

As noted above, FYA signal faces, such as those shown in Figure 1.1, can allow for switching between protective and permissive left-turn phasing during the course of a day. The idea is to use protective (green arrow) phasing during those times when a shortage of safe, acceptable, gaps in opposing traffic streams can lead to delays and riskier gap acceptance on the part of left-turning drivers, and use permissive phasing when the opposing traffic conditions provide suitable gaps. The question then is to identify traffic conditions where use of FYA is most beneficial. Davis et al. (2015) developed statistical models that predicted how the relative change in left-turn crash risk varies as a function of hourly traffic flows, as well as a method for imputing missing traffic flows from partial turning movement counts. These tools were implemented in an Excel spreadsheet. Cunningham et al. (2020) computed updated estimates of crash modification factors (CMF) associated with conversion from protected-only to protected/permitted left-turn treatments in North Carolina. These were then included in a spreadsheet tool that also imputed hourly traffic flows to predict safety and operational outcomes of time-of-day changes in left-turn treatments.

Regarding driver comprehension of FYA, Hajbabaie et al. (2018) surveyed drivers who had encountered time-of-day (TOD) implementation of permissive LT treatments via FYA and reported that "half of the drivers who had encountered intersections with a left-turn control mode variable by TOD felt confused by that phasing strategy." Knodler et al. (2018) investigated different methods for implementing change/clearance intervals between protected LTs and permitted LTs indicated by FYA. Their survey respondents tended to correctly anticipate that solid red indications would follow solid yellow indications, but that other sequences (e.g., green arrow-solid yellow arrow-FYA) were more difficult to anticipate.

Finally, a related issue concerns left-turning drivers' gap acceptance when a vehicle also occupies an opposing left-turn lane. This issue is moot when protected-only left-turn phasing is used, but when

opposing left-turn lanes have negative offset, there can be a reduction in sight distance that can, in turn, affect gap acceptance (McCoy et al. 1992). In gap selection, the critical gap is often defined as the gap duration where a driver is equally likely to accept or reject a gap. Using video data from a single intersection, Yan and Radwan (2008) reported an estimated critical gap of 5.6 seconds when an opposing left-turn lane was unoccupied but a critical gap of 7.7 seconds when the opposing lane was occupied. Using data from the Naturalistic Driving Study (NDS), Hutton et al. (2015) found that for left-turning drivers, the estimated critical gap increased from 6.4 seconds when the opposing left-turn lane was not occupied to 7.5 seconds when the opposing left-turn lane was occupied.

Our objective in this project was to assess drivers' understanding of FYA signal indications, and to see if the presence or absence of "Left Turn Yield" signs affect gap acceptance. Chapter 2 describes an online survey designed to assess drivers' understanding of traffic signal indications, including FYA with and without "Left Turn Yield" signs. Chapter 3 describes a field study, where video data of drivers' gap selection decisions was collected at nine intersections having different combinations of signal type (FYA vs CG), presence or absence of "Left Turn Yield" signs, and speed limit for opposing vehicles (30 mph vs 40 mph). Chapter 4 describes analyses of the data collected in the field study, and Chapter 5 summarizes our findings.

Chapter 2: Driver Survey

Our survey was developed to examine drivers' understanding of different signal face arrangements, and to see if the addition of a "Left Turn Yield on Flashing Yellow Arrow" sign had any significant impact on the respondents' choice of actions when presented with a signal display scenario including a Flashing Yellow Arrow (FYA).

The survey was originally modeled after a survey conducted by Knodler et al. (2018). Knodler et al. explored drivers' anticipatory responses when presented with a signal sequence including an FYA. Figure 2.1 shows a screen capture from their original survey.

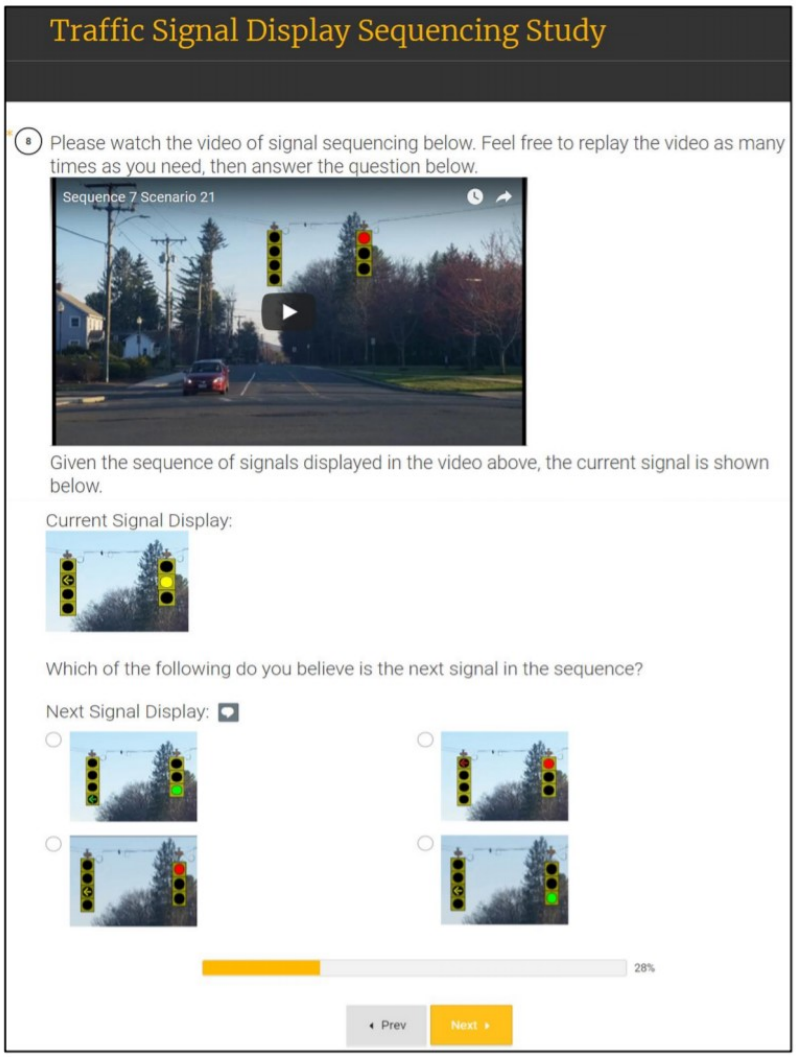

Figure 2.1 Image from Knodler et al. 2018 Survey.

The objective of our survey was different in that we sought to understand what effects, if any, were present in different signal face arrangements and the addition of a “Left Turn Yield on Flashing Yellow Arrow” sign.

Modeling our survey after Knodler et al. (2018), it originally consisted of video clips of 7-15 seconds in length displaying a series of signals to respondents before asking them to consider only the last signal shown. The last signal shown was replicated as a still image or animation of FYA and shown underneath the video.

With feedback from the TAP and volunteer testers, the videos were removed and instead respondents were presented only with the final signal display shown in the sequence. This decision was made due to respondent confusion and complaints of length and difficulty playing the videos, especially on mobile devices. Because the survey was designed to look at signed cases versus unsigned, rather than the impact of preceding signals, this not only streamlined the survey-taking experience but also removed some potentially confounding factors, allowing the research team to isolate the impact of the sign being present.

Extensive testing by the TAP and volunteer survey takers further refined the images shown, including removing the vehicle in the background. An additional answer choice, “wait, because the signal is about to turn red”, was also added based on feedback from test respondents (Figure 2.3).

Six pairs of identical signal displays were created, one version signed and one version unsigned. Both four-head (separate) and doghouse (shared) signal configurations were generated and displayed because both are common in Minnesota.

Respondents were presented with all 12 questions in a random order determined by the survey programming. The signals displayed are listed in Figures 2.4 and 2.5.

In response to user confusion, a progress bar and dynamic heading of “Question X of 12” was added to clarify that respondents were not seeing repeated images, though they may have appeared similar. The team decided not to show a “score” at the end of the survey to alleviate respondents taking the survey multiple times to “improve” their scores. Additionally, an open-ended question asking for any comments or concerns with flashing yellow arrows in Minnesota was added to allow respondents to voice their opinions.

For accessibility purposes, a question asking if the respondent was using a screen reader was added that led respondents to an alternative version of the survey using text to describe the signal display rather than the image or animation. Out of nearly 500 responses, only 16 respondents indicated they were using a screen reader. For this analysis, these 16 responses were not included to avoid potential issues of respondent interpretation of the text as compared to the presentation of the image.

Standard demographic questions were asked along with the question “Are you a transportation professional?” in order to assess potential bias in the responses.

Please watch the video of signal sequencing. Feel free to replay the video as many times as you need, then answer the question below.

You are in the left turn lane waiting to turn left for the duration of the light displayed in the video. Based on the final signal in the sequence (image below), you should...

wait until the signal changes to a green arrow and then make your turn.

wait until there is a sufficient gap in opposing traffic and then make your turn.

make your turn, because opposing traffic should stop.

Figure 2.2 First draft of survey question including both video and still.

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Question 1 of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.

wait until there is a sufficient gap in oncoming traffic and then make your turn.

wait, because the signal is about to turn red.

make your turn, because oncoming traffic should stop.

Figure 2.3 Example question from the survey distributed to drivers May 2021.

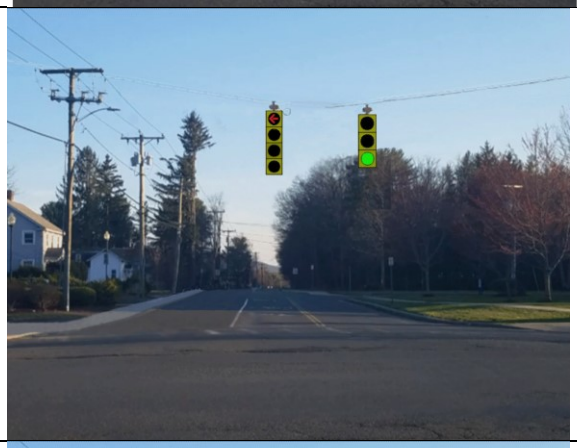
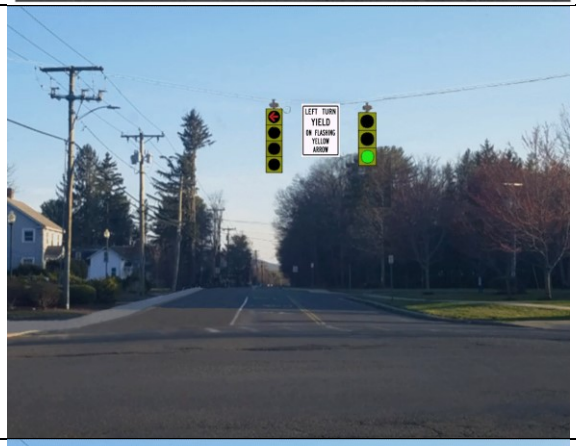
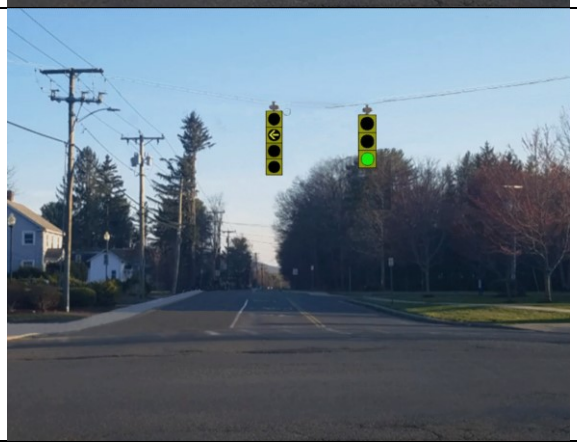
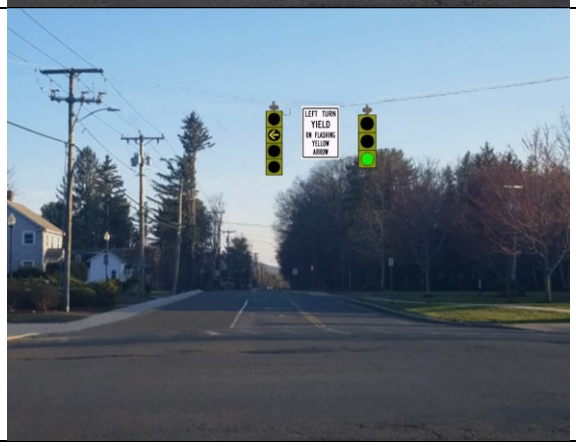
Signal Display	Unsigned Image	Signed Image
Flashing yellow arrow, green ball (animated)		
Solid red arrow, green ball		
Solid yellow arrow, green ball		

Figure 2.4 Four-head configuration signal displays, signed and unsigned

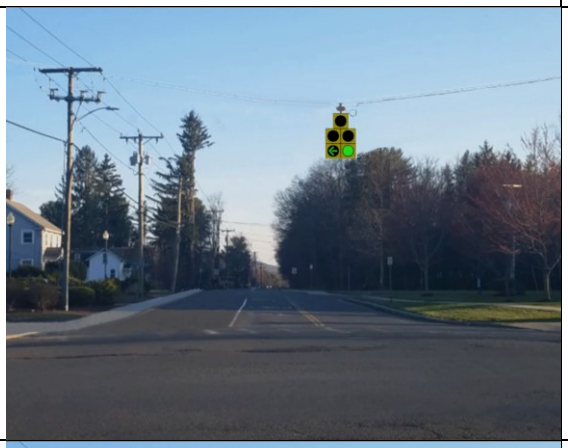
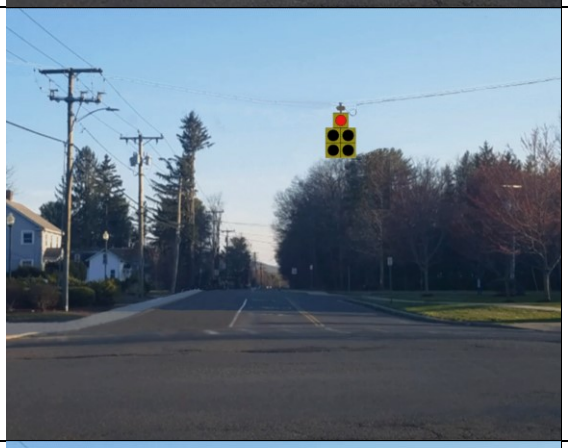
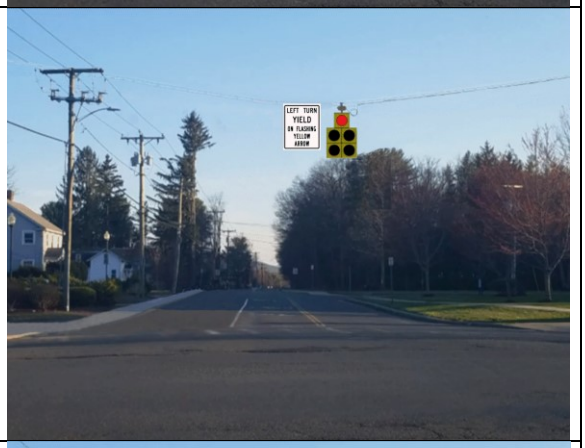
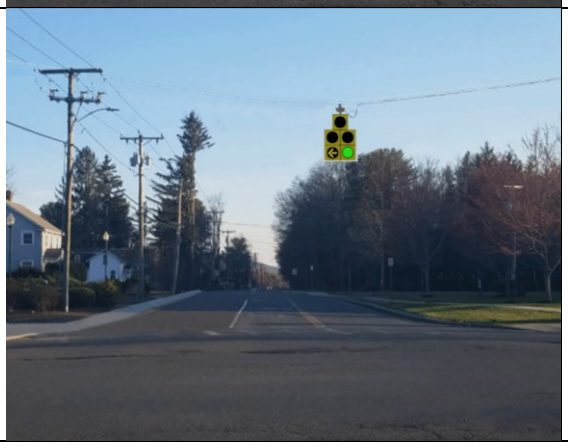
Signal Display	Unsigned Image	Signed Image
Solid green arrow, green ball		
No arrow, red ball		
Flashing yellow arrow, green ball		

Figure 2.5 Dog house configuration signal displays, signed and unsigned

2.1 Survey Results

The survey was distributed during May 2021 through various personal and professional networks. Specific organizations contacted for distribution included:

- Humphrey School of Public Affairs, Urban Planning program
- St. Paul District Councils
- Driving for Safe Communities Coalition
- St. Louis County Employees
- UMD Student Transportation Association and Civil Engineering Department
- Minnesota County Engineers Association
- Washington County social media channels

A total of 480 partial and complete responses were received.

Respondents were asked several demographic questions in order to better understand any potential biases in responses. Respondents were asked about their primary form of transportation (Figure 2.6). 451 (94%) indicated that driving a car was their primary mode of transportation.

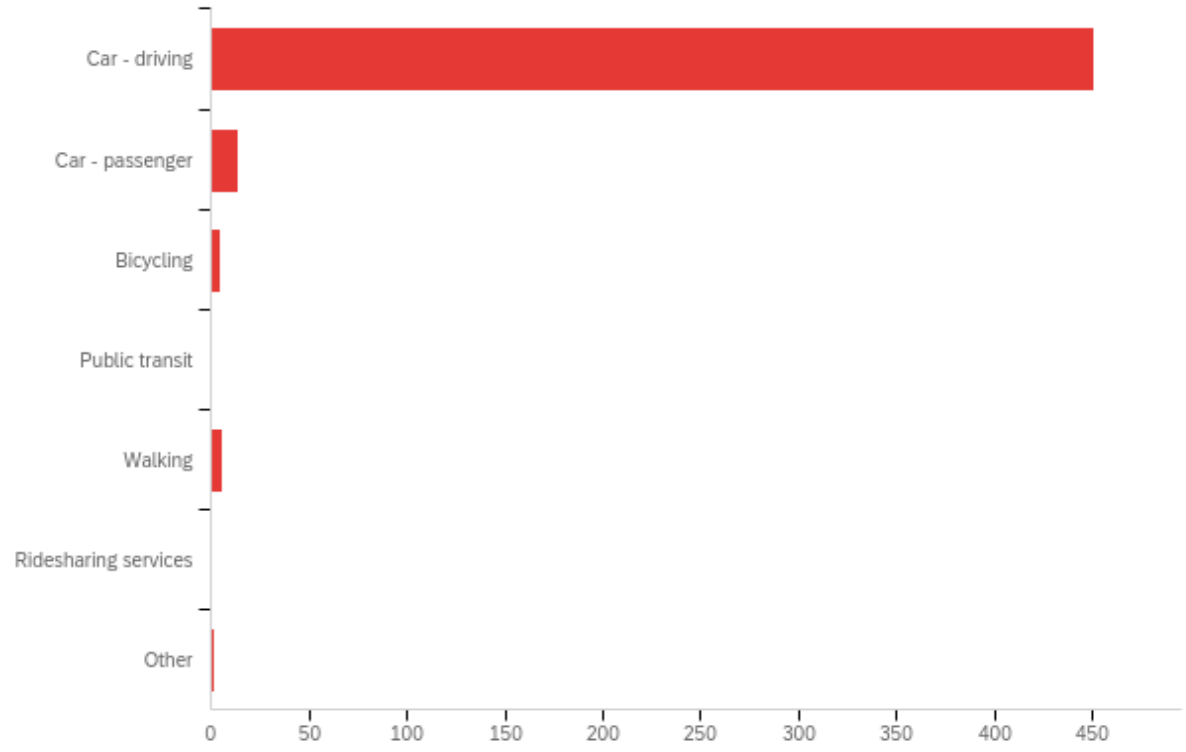


Figure 2.6 What is your primary form of transportation? (n=480)

Respondents were also asked about identified gender (Figure 2.7) and age (Table 2.1). Among our respondents, 61% identified as female which is both higher than the state of MN (50.2% according to 2019 Census data) and the subset of licensed drivers within the state of MN (49.8%, 2015 FHWA).

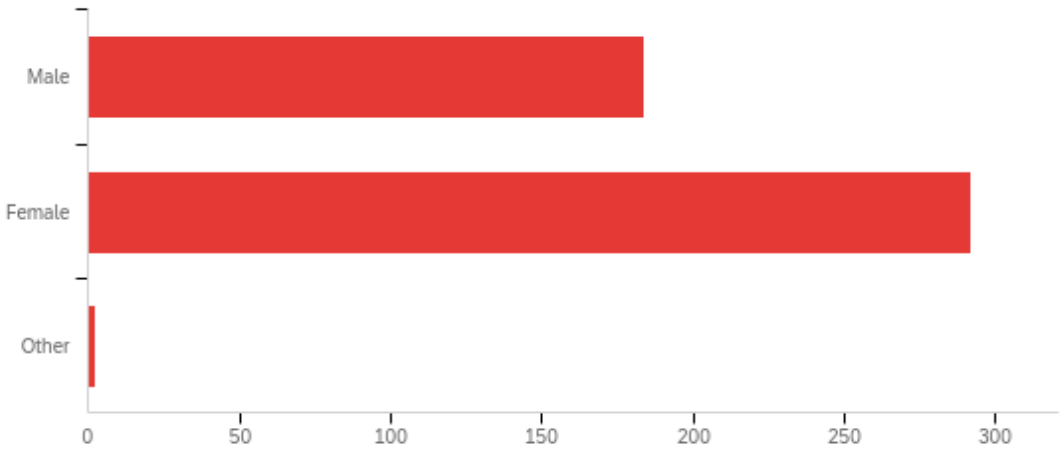


Figure 2.7 What is your identified gender? (n=478)

As seen in Table 2.1, our survey underrepresented younger drivers (<24 years old) and overrepresented older drivers (>55 years old) as compared to 2018 FHWA data specific to licensed drivers.

Table 2.1 Age of FHWA 2018 licensed driver age groups compared to survey respondents

Age Group	FHWA 2018, Licensed Drivers	UMN Survey (n=480)
18-24	13.49%	2.29%
25-34	19.27%	19.58%
35-44	22.11%	23.75%
45-54	18.90%	20.42%
55-64	11.89%	17.29%
65+	14.34%	16.67%
Total	100.00%	100%

Respondents were also asked how many years of driving experience they had (Figure 2.8). As expected with the underrepresentation of younger drivers and overrepresentation of older drivers, the majority (50.4%) of our respondents had more than 30 years of driving experience.

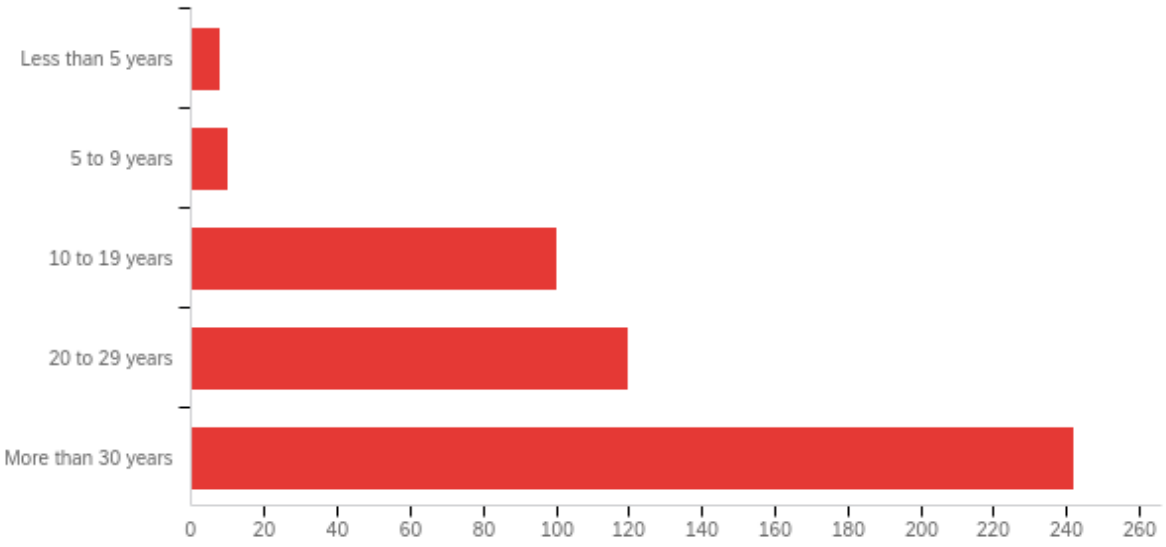


Figure 2.8 How many years of driving experience do you have? (n=480)

Respondents were asked if they work in the transportation field, in order to account for potential bias in the responses. “Yes” responses to this question (85 responses) were set aside during the analysis of responses for safety implications, as it is assumed a transportation professional has more experience with FYAs than the average driver.

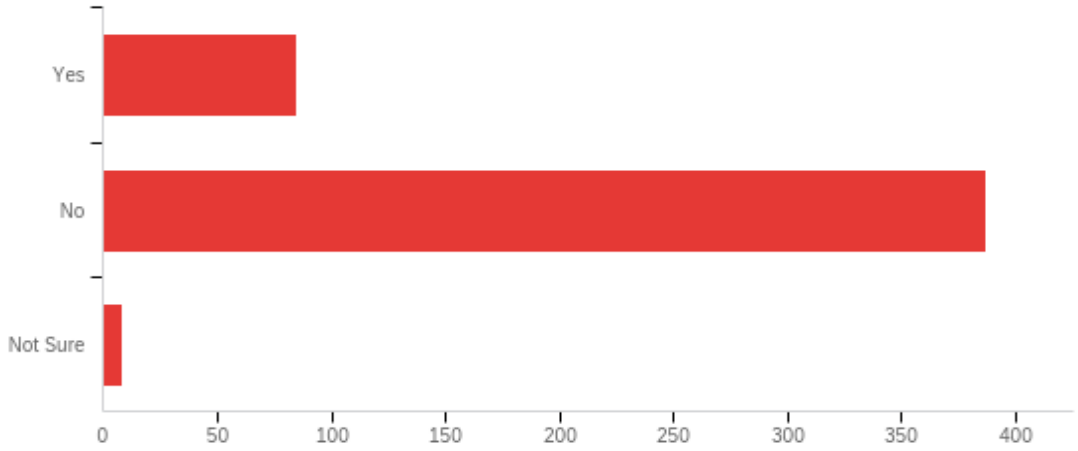


Figure 2.9 Are you a transportation professional in any capacity? (n= 480)

2.1.1 Driver Comprehension Results

Each pair of signed and unsigned signals accompanied by the distribution of responses is shown below. The full survey is included as Appendix B. Please note the “question numbers” on the survey were not shown to respondents as they are generated by Qualtrics, the survey program, and used for internal purposes only

Figure 2.10 Four-head, Flashing Yellow Arrow and Green Ball (n=390)

The vast majority of drivers correctly indicated that in the case of an FYA and CG, they should "wait until there is a sufficient gap in oncoming traffic and then make [their] turn, both with (95.6%) and without (93.7%) the sign being present. Further exploration of the sign's potential effects with this signal display can be found in the "Safety Implications" section.

Figure 2.11 Four-Head, Solid Red Arrow and Circular Green (n= 386)

Nearly all respondents chose the correct response ("wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn") both with (97.7%) and without (98.2%) the sign being present.

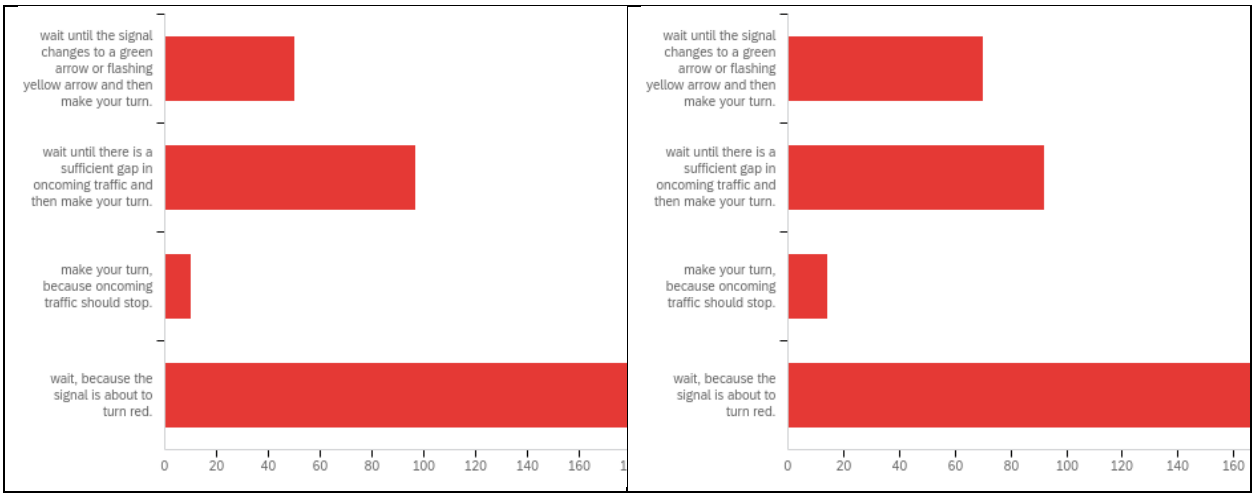


Figure 2.12 Four-Head, Solid Yellow Arrow and Circular Green (n=389)

This signal display could be interpreted in multiple ways, so although “wait, because the signal is about to turn red” is the most correct answer, “wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn” as well as “wait until there is a sufficient gap in oncoming traffic and then make your turn” are also legal maneuvers in this case. This is a limitation of showing a still rather than a video including oncoming traffic conditions. 94.4% of drivers with the sign and 97.4% without the sign chose correctly.

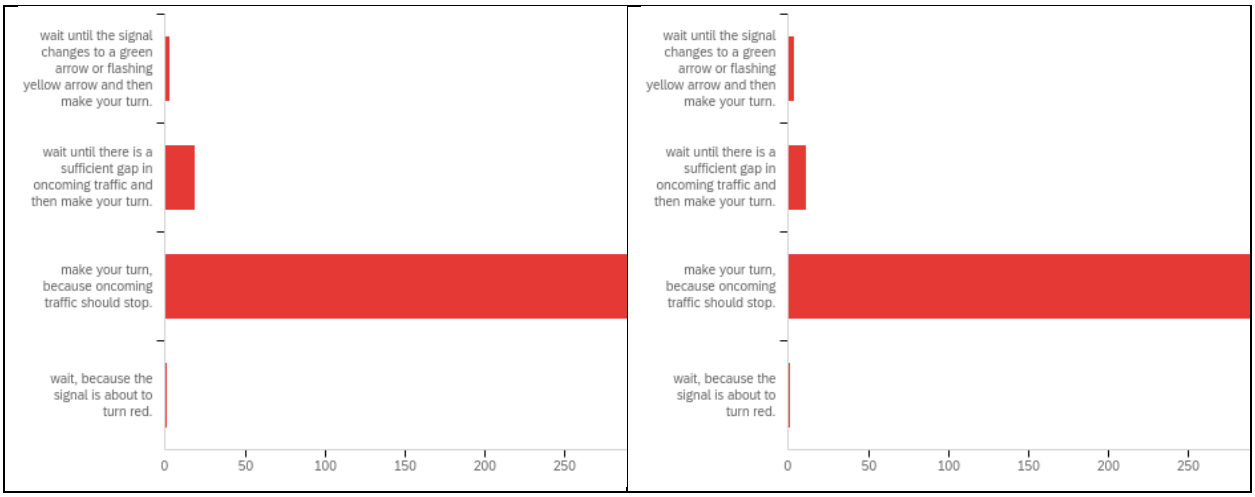


Figure 2.13 Doghouse, Solid Green Arrow and Circular Green (n=393)

Nearly all drivers answered this question correctly (94.2% without sign, and 95.9% with sign).

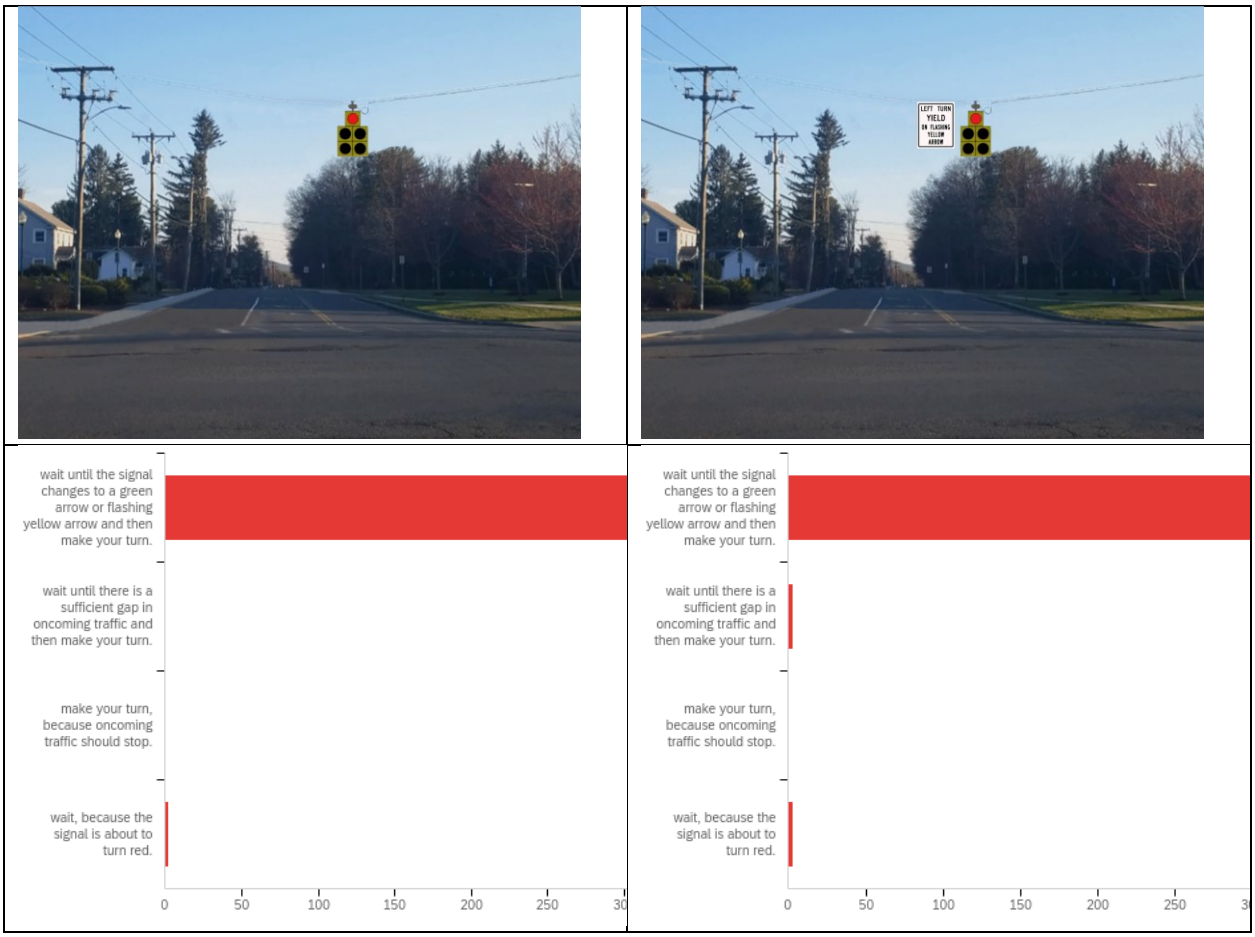


Figure 2.14 Doghouse, No Arrow Solid Red (n= 389)

This signal display was the most unambiguous presented to respondents, and responses reflect that: 99.5% of respondents answered correctly to wait for a signal change without the sign present, and 98.5% with the sign present.

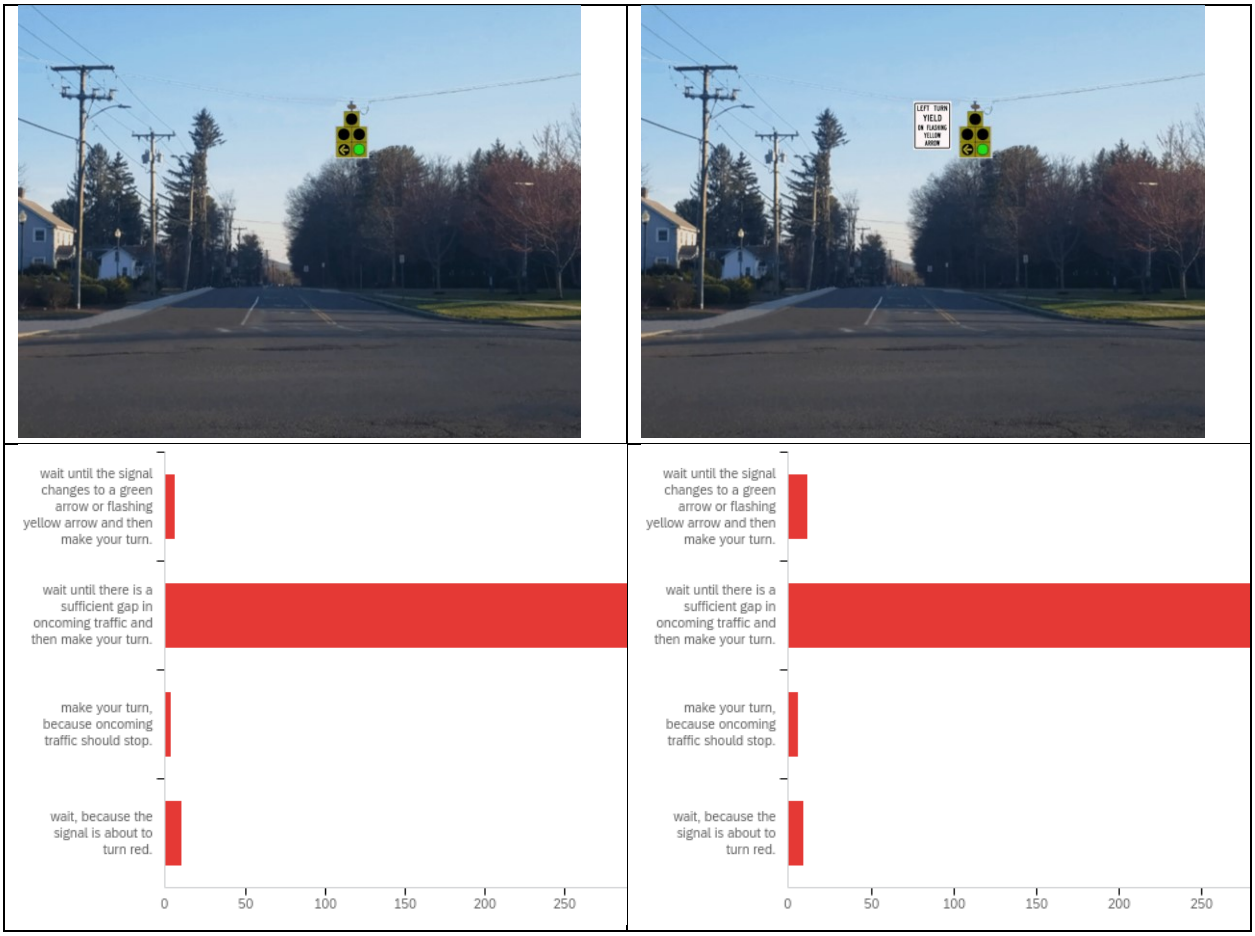


Figure 2.15 Doghouse, Flashing Yellow Arrow and Circular Green (n=386)

In the case of the doghouse configuration FYA, 94.9% of drivers answered correctly without the sign present and 93.0% with the sign present. Further exploration of the sign's potential effect is explored in the "Safety Implications" section.

2.1.2 Open-Ended Responses

Of the open-ended responses that directly addressed FYAs, 18 were positive and 19 were negative. The positives included keeping traffic flowing and avoiding wasting time as well as being a useful accessibility tool for those with colorblindness. Concerns included driver confusion and the need for education, confusion with both separated and shared signal faces, and general complaints about changing from "traditional" three-head signals. Some salient responses, including one highlighting a lack of driver education about signal displays, are included here:

> "A flashing yellow arrow should ALWAYS be accompanied by a sign indicating "yield to oncoming traffic on flashing yellow arrow" so that there's no question about the intended meaning of the flashing yellow arrow. I question the usefulness of flashing yellow arrows, because the rule "left turns always yield to oncoming traffic except when making a protected left turn (green arrow) takes precedence. Unless and until ALL semaphore controlled intersections have flashing yellow arrows, flashing yellow arrows appear to create the potential for confusion for drivers making left turns at semaphores. Until then, stick with the left turn yield rule that all drivers should already know by heart"

> "Much prefer the 4 vertical flashing light rather than the cluster it is less confusing. Also, many communities do not have the clusters but have some form of the vertical flashing light therefore it may cause confusion and lead to accidents."

> "Do not have a green ball (which to me means ALL turns are a 'GO') with a red left turn arrow!!"

> "The signs explaining the lights helped when taking this survey."

2.2 Safety Implications

As noted in Chapter 1, following inclusion of FYA in the MUTCD, safety-related evaluations became possible. In an empirical Bayes before/after study of changes in left-turn signalization Srinivasan et al. (2011) reported a 36% reduction in left-turn crashes when FYA replaced green ball for the permissive left turn phase, but a significant increase in left turn crashes when protected phasing was replaced by protected/permissive phasing indicated by FYA. This general trend has been confirmed by later work (Medina et al. 2018; King et al. 2018; Srinivasan et al. 2018; Schattler et al. 2017; Storm et al. 2020). One possibility is that at least part of the crash increase might be due driver confusion about the meaning of FYA rather than due solely to gap selection errors and, if this is the case, then placing a supplementary sign might at least partially mitigate the crash increase. As noted earlier almost all respondents to our survey correctly identified FYA as indicating a permitted left turn, but a small number interpreted FYA as indicating a protected left turn. Here we look at whether or not the survey offers evidence that supplementary signs might mitigate this.

Questions 10 and 12 of the survey compare responses to FYA scenarios with and without supplementary signs. Figure 2.16 shows the scenario addressed in Question 10 while Figure 2.17 shows the scenario for Question 12. In both scenarios the yellow arrow was flashing.

Figure 2.16 Question 10 - Four-Head Flashing Yellow Arrow with Sign. The image was animated to show flashing.

Figure 2.17 Question 12 - Four-Head Flashing Yellow Arrow without Sign. The image was animated to show flashing.

The wording for both Question 10 and 12 was as follows:

> You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...
>
> wait until the signal changes to a green arrow and then make your turn. (1)
> wait until there is a sufficient gap in oncoming traffic and then make your turn. (2)
> wait, because the signal is about to turn red. (4)
> make your turn, because oncoming traffic should stop. (3)

For both questions the correct response code was (2), wait until there is a sufficient gap. Of particular interest here is response code (3), which interpreted the flashing yellow arrow as indicating a protected left turn.

Table 2.2 shows cross-tabulations of responses to questions 10 and 12 for those respondents who did not identify themselves as transportation professionals. Of the 264 respondents who answered both questions, 238 (90.2%) responded correctly to both questions 10 and 12. 245 of these (92.8%) responded correctly when the sign was absent and 249 (94.3%) responded correctly when the sign was present. Of particular interest here was response code (3), which interprets FYA as indicating a protected left turn. Three respondents gave this response to Question 12 (no sign). Of those two gave a correct response when the sign was present and one gave response code (3) in both scenarios. One respondent gave a correct response when the sign was absent but gave response (3) when the sign was present.

Table 2.2 Cross-Tabulation of Question 10 vs Question 12 for Respondents Not Identifying as Transportation Professionals

		Response Code to Question 10 (sign)					
		1	**2**	**3**	**4**	**No Response**	**Total**
Response Code to Question 12 (no sign)	**1**	2	6	0	0	2	8
	2	5	238	1	1	45	245
	3	0	**2**	**1**	0	0	3
	4	0	3	0	5	1	8
	No response	0	47	1	0	22	*
	Total	7	249	2	6	*	264

For questions 48 and 50 the signal head had a “doghouse” arrangement instead of the parallel vertical arrangement shown in questions 10 and 12. Figure 2.18 shows the configuration where the sign was present (Question 50).

Figure 2.18 Doghouse signal head used in Questions 48 and 50. The yellow arrow was flashing, and the sign was not present for Question 48.

Table 2.3 Cross-Tabulation of Question 48 vs Question 50 for Respondents Not Identifying as Transportation Professionals

		Response Code to Question 50 (sign)					
		1	**2**	**3**	**4**	**No Response**	**Total**
Response Code to Question 48 (no sign)	**1**	1	3	1	0	0	5
	2	6	230	1	4	48	241
	3	0	1	2	0	1	3
	4	0	6	0	3	0	9
	No Response	3	44	2	1	25	*
	Total	7	240	4	7	*	258

As with the vertical arrangements, most respondents (230 out of 241, or 95.4%) gave the correct answer (2) whether or not the sign was present. Three respondents indicated that FYA without the sign meant a protected left turn and of those one gave a correct response when the sign was present. One respondent gave a correct answer when the sign was absent but gave response (3) when the sign was present.

The most safety-relevant response was (3), which misinterprets FYA as indicating a protected left turn. The number of respondents making this choice was small, and at least some of those giving the incorrect response when the "Left Turn Yield" sign was absent gave a correct response when the sign was present. However, the relevant sample sizes were too small for statistical significance testing.

Chapter 3: Field Study Design and Data Collection

The main object of the field study was to measure differences in drivers' tendencies to accept or reject gaps when they face a flashing yellow arrow (FYA) versus a circular green (CG) indication, and also to measure differences in gap acceptance when "Left Turn Yield" signs are present versus absent. Before proceeding to our study design, however, it might be helpful to briefly discuss methods for describing drivers' gap acceptance.

One key feature in intersection design is the sight distance available to drivers who need to make gap acceptance decisions. A commonly-used summary measure of gap acceptance in a population of drivers is their critical gap, defined as the gap duration where the probability of acceptance equals the probability of rejection, 0.5 (Garber and Hoel, 2015). Beginning in 2004, the guidance provided in AASHTO's *Policy on Geometric Design of Highways and Streets* has been based on field observations of drivers' critical gaps. In particular, for permitted left turns against opposing main road traffic, AASHTO recommends that sight distance for drivers of passenger cars be based on a gap of 5.5 seconds for single-lane opposing approaches, with 0.5 seconds being added for each additional opposing lane. This recommendation was developed from estimated critical gaps of 4.6 seconds and 5.2 seconds, computed from logistic regression models fit to data from two intersections (Harwood et al. 1996, p. 80; Fitzpatrick 1991). For the simplest case, where gap acceptance/rejection depends only the gap's duration, a logistic regression, or logit, model describing the probability of a gap's being accepted takes the form

$$P[accept|t] = \frac{\exp(\beta_0 + \beta_1 t)}{1 + \exp(\beta_0 + \beta_1 t)}$$

Here t denotes the duration of the gap in question and β_0, β_1 are parameters to be estimated from data. Given estimates for the parameters the estimated critical gap is found by solving the equation

$$ln\left(\frac{P[accept|t]}{1 - P[accept|t]}\right) = \beta_0 + \beta_1 t = 0$$

where ln(.) denotes the natural logarithm. Approximate confidence intervals and hypothesis test for estimated critical gaps can then be based on the estimates of the parameters, along with their covariance matrix.

3.1 Selecting Field Data Collection Sites

The Minnesota Traffic Observatory (MTO) maintains portable, pole-mounted, video equipment that can be left unattended to record traffic activity for one week or more. Figure 3.1 shows the MTO's pole-anchored camera while Figure 3.2 shows the MTO's portable trailer.

Figure 3.1 MTO's Pole-Anchored Camera at Our Louisiana/Franklin Site.

Figure 3.2 MTO's Trailer-Mounted Camera at Our Valley Creek/Bielenberg Site.

To identify sites for collecting gap data, we began by reviewing a list prepared in an earlier project (Davis et al. 2015), containing state-managed intersections during the years 2013-2014. Since then, however, FYA signals have been deployed widely, and the initial list contained no information about the presence/absence of signs, so it appeared that without extensive field checking the list was too limited to be helpful. The project's PI then initiated a field review of locations in the western Twin Cities suburbs. Generally, finding locations with FYA and the "Left Turn Yield" sign was straightforward, even with opposing speed limits up to 50 mph. Finding CG signals, both with and without signs, was also possible as long as opposing speed limts were not greater than 40 mph. Finding sites with FYA but no "Left Turn Yield" signs turned out to be difficult, but after feedback from the project's TAP it was possible to locate some such sites in the eastern Twin Cities metro area. Our final list, after field visits to check for camera placements and other issues, is shown in Table 3.1.

Table 3.1 Sites Used for Video Study

	Sign		**No sign**	
	30 mph	**40 mph**	**30 mph**	**40 mph**
FYA	Winnetka/Golden Valley Road	Xenium/Carlson Parkway	Valley Creek and Weir	Valley Creek and Bielenberg
CG	Boone/Golden Valley Road & Louisiana/28th	Xenium/West Medicine Lake Road	Louisiana/Franklin	Xenium/Sunset Trail

Collection of video began on June 11, 2021 and ended on December 1, 2021. At each site at least one week of video was recorded, and scheduling of data collection depended on coordination with other projects using the MTO's equipment.

Table 3.2 Dates for Video Collection at Our Nine Sites

Site	**Start Date**	**End Date**
Winnetka & Golden Valley Road	6/11/2021	6/22/2021
Boone & Golden Valley Road	6/22/2021	6/30/2021
Louisiana & Franklin	9/15/2021	9/24/2021
Louisiana & 28th	9/15/2021	9/24/2021
Xenium & Carlson Parkway	10/6/2021	11/1/2021
Xenium & Medicine Lake	10/7/2021	11/1/2021
Xenium & Sunset Trail	10/6/2021	10/21/2021
Valley Creek Road & Bielenberg	11/18/2021	12/1/2021
Valley Creek Road & Weir	11/18/2021	12/1/2021

Figure 3.3-Figure 3.11 show the views obtained at each of our camera placements.

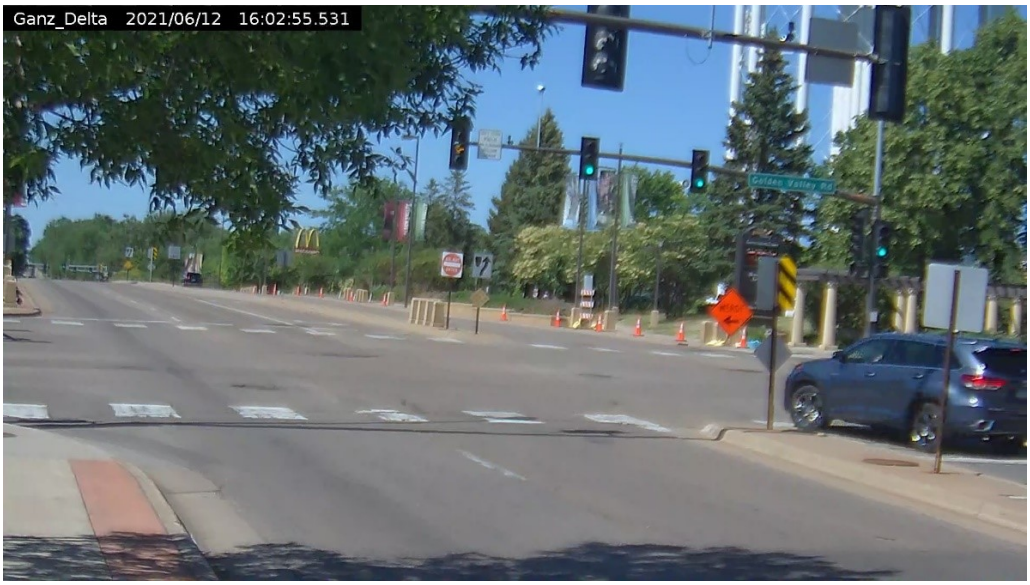


Figure 3.3 Camera View at Winnetka and Golden Valley Road.

Figure 3.4 Camera View at Boone and Golden Valley Road.

Figure 3.5 Camera View at Louisiana and Franklin.

Figure 3.6 Camera View at Louisiana and 28th.

Figure 3.7 Camera View at Xenium and Carlson Parkway.

Figure 3.8 Camera View at Xenium and West Medicine Lake Drive.

Figure 3.9 Camera View at Xenium and Sunset Trail.

Figure 3.10 Camera View at Valley Creek Road and Bielenberg.

Figure 3.11 Camera View at Valley Creek Road and Weir.

Chapter 4: Field Study Data Reduction and Analyses

As noted above, the structure of our data collection plan was as a factorial study with three binary factors: circular green (CG) vs flashing yellow arrow (FYA) to indicate permitted left turns, 30 mph vs 40 mph as speed limits for opposing vehicles, and presence vs absence of a "Left Turn Yield" sign. Table 4.1 lists the sites where video data was collected.

Table 4.1 Sites Used for Video Study

	Sign		**No sign**	
	30 mph	**40 mph**	**30 mph**	**40 mph**
FYA	Winnetka/Golden Valley Road	Xenium/Carlson Parkway	Valley Creek/ Weir	Valley Creek/ Bielenberg
CG	Boone/Golden Valley Road & Louisiana/28th	CSAH 61/ Medicine Lake Rd	Louisiana/Franklin	Xenium/ Sunset Trail

Following completion of video data collection, we began reviewing the video to identify events where left-turning drivers were faced with gap selection decisions. When a gap selection event was identified we made a copy of the relevant video clip for later analysis, our goal being to obtain samples showing at least 30 accepted gaps for each site. We also attempted to hire student workers to help reduce the video and measure the durations of rejected and accepted gaps, but with limited success. During our initial effort at measuring gap durations from the video we found that many of the gap selection events identified in our initial review were not usable because of ambiguities regarding when a gap began or ended. In order to reach our desired sample sizes it was necessary then to go back to the original video and identify additional video clips.

Gaps were measured by viewing the video and recording the times opposing vehicles crossed a designated conflict point. These conflict points and our data reduction instructions can be found in Appendix A. Once gap data had been extracted from the video from each site data files for statistical analyses were prepared. For our analyses we focused on situations where the left-turning vehicle was a sedan, van, pickup truck, or SUV (commercial trucks and buses were removed) and where it was possible to estimate the durations of the accepted gaps. That is, situations where the permitted left-turn phase or video clip ended before an opposing vehicle arrived to define the end of a gap were also removed.

Table 4.2 shows summary statistics for the gap data at each of our sites, while Figure 4.1 shows boxplots summarizing the gap distributions at each site.

Table 4.2 Summary Statistics for Gap Data at Each Site

		Site								
Variable		**vcw**	**bgv**	**c61ml**	**xst**	**xcp**	**l28**	**lf**	**wgv**	**vcb**
Approach Direction of LT Vehicles		SB	NB	SWB	NB	SB	SB	NB	NB	EB
Speed Limit for Opposing Vehicles		30 mph	30 mph	40 mph	40 mph	40 mph	30 mph	30 mph	30 mph	40 mph
LT Signal Face (FYA or CG)		FYA	CG	CG	CG	FYA	CG	CG	FYA	FYA
LT Yield Sign ("Y"-present or "N"-absent)		N	Y	Y	N	Y	Y	N	Y	N
Total # Gaps in Sample		145	119	204	126	99	164	139	162	130
Total # Accepted Gaps		37	33	29	28	26	32	29	32	31
Accepted Gaps	**median**	6.833	15.13	7	7.8975	8.3	9.75	8.934	12.402	8.6
	min	2.466	5.4	3.466	5.533	4	4.667	5	3.455	4.06
	max	16.034	36.2	20.3	37.8	48.79	32.866	24.867	33.467	48.46
Rejected Gaps	**median**	1.648	2.4	1.333	2.5505	2.07	2.067	2.333	2.3835	1.6
	min	0.134	0.333	0.067	0.168	0.27	0.333	0.134	0.067	0.14
	max	7.267	8.137	8.4	6.271	9.07	4.733	8.071	6.634	5.27
% Stopped Opposing LT vehicle present		9.66%	21.01%	0%	2.38%	5.05%	0%	0%	32.10%	13.85%

Codes used for study sites and plotting positions in Figure 4.1**.**

bgv - Boone Ave & Golden Valley Rd (1)
c61ml - Northwest Blvd (CSAH 61) & Medicine Lake Dr (2)
l28 - Louisiana Ave & 28th St (3)
lf - Louisiana Ave & Franklin Ave (4)
vcb - Valley Creek Road & Bielenberg (5)
vcw - Valley Creek Rd & Weir (6)
wgv - Winnetka Ave & Golden Valley Rd (7)
xcp - Xenium Ln (CSAH 61) & Carlson Pkwy (8)
xst - Xenium Ln (CSAH 61) & Sunset Trail (9)

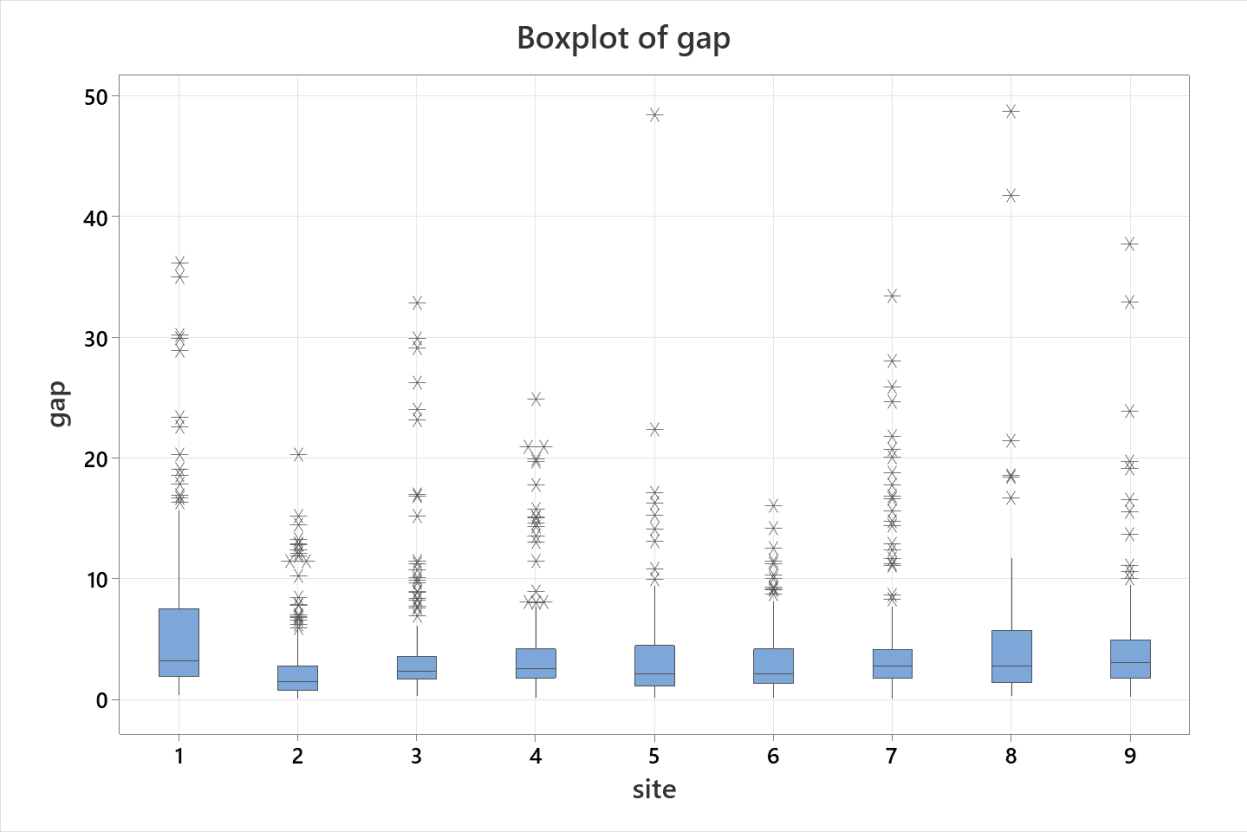


Figure 4.1 Boxplots Summarizing the Distributions of Observed Gaps at Each of the 9 Study Sites.

Our next goal was to use logistic regression analyses in order to assess the effects of flashing yellow arrow signals and the presence/absence of "Left Turn Yield" signs on drivers' gap acceptances, using logistic regression (logit) analysis. Logit models have the form

$$P[accept|x_1, \ldots, x_n] = \frac{exp(\beta_0 + \sum_{i=1}^{n} \beta_i x_i)}{1 + exp(\beta_0 + \sum_{i=1}^{n} \beta_i x_i)}$$

where $x_1,\ldots,x_n$ denote measured features of a gap selection situation, such as the duration of a gap or an indicator for the presence of a sign, while $\beta_0,\beta_1,\ldots,\beta_n$ denote coefficients to be estimated from the data. Again, our study design can be viewed as a factorial study where each combination of signal type (FYA vs CG), sign (present vs absent) and opposing speed limit (30 mph vs 40 mph) was represented in our sample. In addition, since other researchers have observed that the presence of an opposing vehicle waiting to turn left can influence drivers' gap selections and since, as Table 4.1 shows, our sites differ as to the frequencies of opposing left turns, this feature was included as a possible confounding variable. Finally, we looked at whether or not the turning movement of the opposing vehicle (through vs right turn) also had an effect on gap acceptance. The glm routine in R was used to compute maximum likelihood estimates of our logit models' parameters. Our initial analyses included comparing the measured gap versus the logarithm of the gap to predict whether a gap is accepted or rejected, and comparing an aggregated analysis, where data from all sites was compiled to fit one logit model, to

analyses where a separate logit models are fit to individual sites. Overall, we found that the natural logarithm of a gap was a better predictor than was the raw gap, that the two analysis approaches (individual site vs aggregated) gave largely similar results, but that the individual site analysis was somewhat easier to interpret. Table 4.3 displays statistical summaries of the individual models, showing all predictors whose β-coefficients were significantly different from zero at the 0.05 level. Note that the two sites with circular green signals, 30 mph opposing speed limits, and yield signs (bgv and l28) were combined.

Table 4.3 Summaries of Gap Acceptance Models Fit to Study Sites

FYA	Sign	PSL40	Site(s)	Logistic Regression Model Coefficients				
				Predictor	Estimate	Std. Error	z value	Pr(>|z|)
0	0	0	lf	(Intercept)	-30.253	12.991	-2.329	0.0199
				ln(gap)	18.864	8	2.358	0.0184
				oprt	-7.518	3.672	-2.047	0.0406
0	1	0	bgv + l28	(Intercept)	-13.942	2.698	-5.167	2.38E-07
				ln(gap)	8.033	1.592	5.046	4.52E-07
0	0	1	xst	(Intercept)	-39.31	15.982	-2.46	0.0139
				ln(gap)	22.889	9.233	2.479	0.0132
0	1	1	c61ml	(Intercept)	-10.074	2.241	-4.495	6.95E-06
				ln(gap)	6.429	1.474	4.363	1.28E-05
1	0	0	vcw	(Intercept)	-7.1805	1.3021	-5.514	3.50E-08
				ln(gap)	5.0333	0.9432	5.337	9.47E-08
1	1	0	wgv	(Intercept)	-12.737	3.063	-4.158	3.21E-05
				ln(gap)	7.765	1.963	3.955	7.64E-05
				stpoplt	-3.394	1.565	-2.168	3.01E-02
1	0	1	vcb	(Intercept)	-14.843	4.352	-3.41	6.48E-04
				ln(gap)	9.325	2.782	3.352	8.01E-04
1	1	1	xcp	(Intercept)	-10.601	2.643	-4.012	6.03E-05
				ln(gap)	6.282	1.577	3.983	6.82E-05

Here
ln(gap) = natural logarithm of the observed gap
stopolt = 1 if opposing left turn lane is occupied, 0 otherwise
oprt = 1, if opposing vehicle made right turn, 0 if opposing vehicle continued through
FYA = 1 if FYA site, 0 if CG site
Sign = 1, if "Left Turn Yield" sign present, 0 if sign absent
PSL40 = 1, if posted speed limit for opposing traffic was 40 mph, 0 if posted limit was 30 mph

A positive value for a coefficient means that, other things being equal, an increase in the corresponding predictor increases the probability that a gap is accepted, while a negative value for a coefficient means that an increase in the predictor decreases the probability a gap is accepted. For example, the positive

value for the coefficient associated with 'ln(gap)' means that, other things equal, longer gaps are more likely to be accepted. The negative values for the coefficient associated with 'stpoplt' means that, when an opposing left-turn lane is occupied, a given gap is less likely to be accepted.

As noted above, for all our sites the natural logarithm of the gap was the better predictor of gap acceptance. For one site (Lousiana/Franklin) left-turning drivers were noticeably less likely to accept a gap when the opposing vehicle made a right turn, and at one site (Winnetka/Golden Valley Road) left-turn drivers were less likely to accept a gap when the opposing left-turn lane was occupied.

The different values for the parameter estimates shown in Table 4.3 suggest that gap acceptance might differ across the sites. For example, at the Valley Creek/Weir site the probability of accepting a 5-second gap would be

$$P[accept|t = 5] = \frac{\exp(-7.1805 + (5.0333)\ln(5))}{1 + \exp(-7.1805 + (5.0333)\ln(5))} = 0.72$$

while the probability accepting a 5-second gap at the Winnetka/Golden Valley Road site, when the opposing left-turn lane is unoccupied, would be

$$P[accept|t = 5] = \frac{\exp(-12.737 + (7.765)\ln(5))}{1 + \exp(-12.737 + (7.765)\ln(5))} = 0.44$$

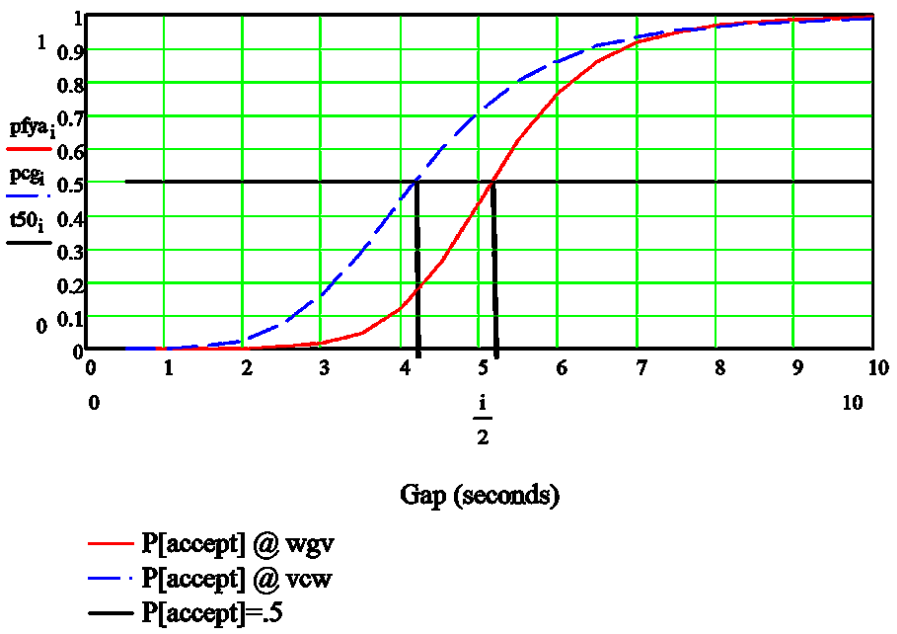


Figure 4.2 Probability of Gap Acceptance versus Gap for the Winnetka/Golden Valley Road and Valley Creek/Weir Sites.

To help interpret the results summarized in Table 4.3 we can use the sites' critical gaps as summary measures. Figure 4.2 plots the probability of gap acceptance versus gap for the above two sites along with a horizontal line corresponding to P[accept|gap=t]=0.5. The gap where an acceptance curve intersects the 0.5 line is called that curve's critical gap, denoted by t_{50}. Estimated critical gaps are readily computed from the estimated coefficients shown in Table 4.3. For example, the critical gap for the Winnetka/Golden Valley Road (wgv) curve shown in Figure 4.2 is

$$t_{50} = exp\left(\frac{12.737}{7.765}\right) = 5.2\ seconds$$

while the critical gap for the Valley Creek/Weir (vcw) curve is

$$t_{50} = exp\left(\frac{7.1805}{5.0333}\right) = 4.2\ seconds$$

Generally, the longer the critical gap the more conservative drivers are when selecting gaps, and we can use estimated critical gaps along with their associated confidence intervals to give a more intuitive summary of our results. These are tabulated in Table 4.4, and displayed graphically in Figure 4.3 and Figure 4.4.

Table 4.4 Estimated Critical Gaps and 90% Confidence Intervals. Opposing Left-Turn Lane Unoccupied, Opposing Vehicle Movement is Through

Opposing Speed Limit = 30 mph		
	No Sign	**Sign**
FYA	4.2 (3.7, 4.7)	5.2 (4.5, 5.9)
CG	5.0 (4.6, 5.3)	5.7 (5.2, 6.2)
Opposing Speed Limit = 40 mph		
	No Sign	**Sign**
FYA	4.9 (4.4, 5.4)	5.4 (4.8, 6.1)
CG	5.6 (5.3, 5.9)	4.8 (4.3, 5.4)

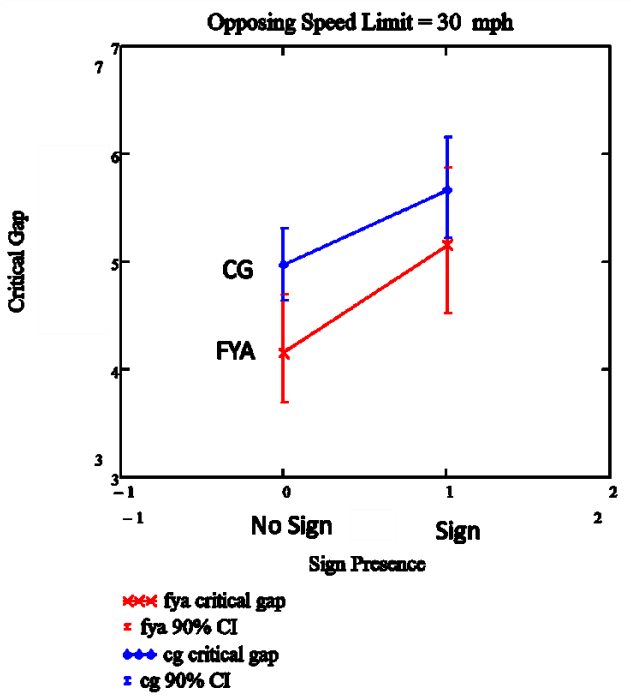


Figure 4.3 Estimated Critical Gaps and Associated 90% Confidence Intervals for Sites with 30 mph Opposing Speed Limits.

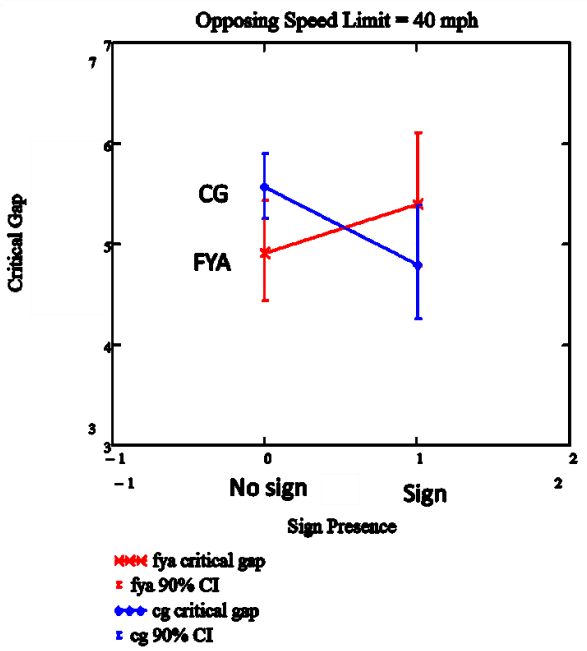


Figure 4.4 Estimated Critical Gaps and Associated 90% Confidence Intervals for Sites with 40 mph Opposing Speed Limits.

Looking at Figure 4.3 and Figure 4.4 several comparisons stand out:

(1) At the 30 mph sites, when the "Left Turn Yield" sign was not present, the critical gap at the FYA site was significantly shorter than that at the CG sites ($z=-2.13$, $p < .05$), while when the sign was present the difference between the FYA site and CG site was not significantly different from zero ($z=-1.10$, $p > 0.1$).

(2) At the 30 mph sites, the critical gaps when the sign was present were significantly longer than when the sign was absent, for both the FYA and the CG sites ($z=2.033$, $p < .05$ for CG; $z=1.982$, $p < .05$ for FYA).

(3) At the 40 mph site without the yield sign the critical gap for the FYA site tended to be shorter than that for the CG site ($z=-1.76$, $p < 0.1$) When the sign was present, however, the difference between the FYA and CG was not statistically significant ($z=-1.18$, $p > 0.1$).

(4) At the 40 mph sites with CG, the critical gap without the sign was significantly longer than that with the sign ($z=1.89$, $p < 0.1$).

4.1 Impact of Sight Distance Obstructions

As noted above, prior studies (Yan and Radwan 2008; Hutton et al. 2015) have reported that critical gaps for left-turning drivers tend to be longer when their sight distance is obstructed by the presence of vehicles in the opposing left-turn lane. In our study only one site, Winnetaka/Golden Valley Rd, showed an obstruction effect in its gap selection model. At this site the northbound/southbound left-turn lanes have a negative offset of about 9.5 feet and left-turns from the northbound approach are on an upgrade, which tends to exacerbate the sight distance obstructions. Figure 4.5 shows our camera's view for this site.

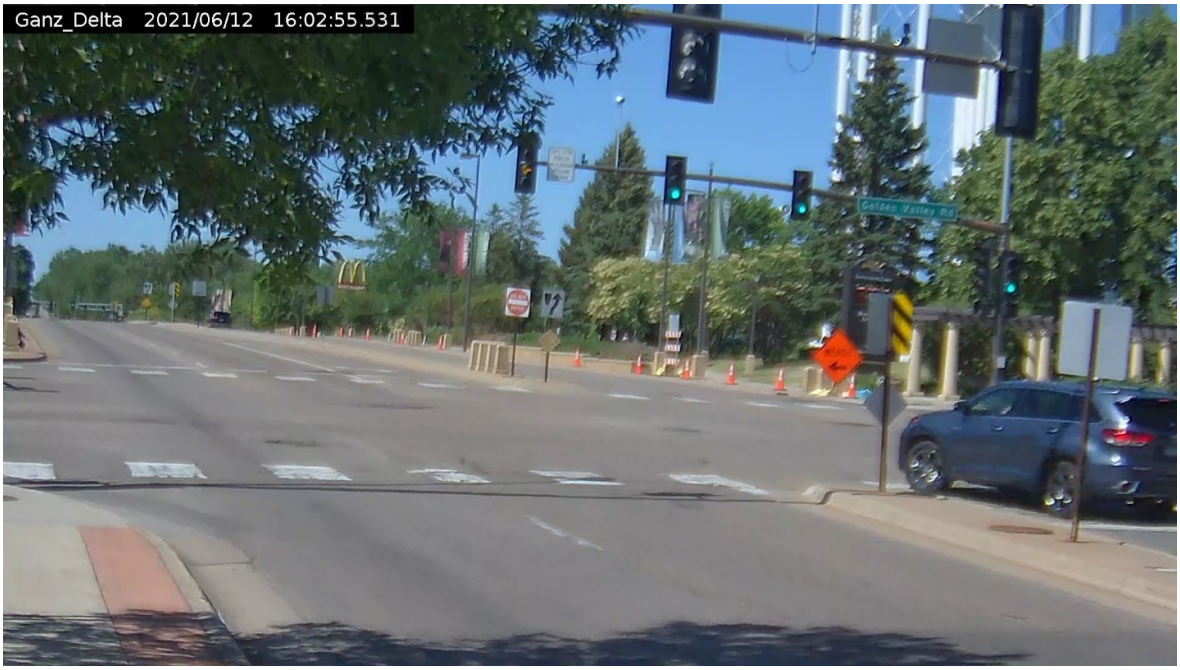


Figure 4.5 Camera View Looking Northbound at Winnetka and Golden Valley Rd.

Table 4.5 below compares the estimated critical gaps for unobstructed and obstructed left turns from our study and from two previous studies. (The study by Yan and Radwan did not report confidence intervals for its critical gap estimates.) Overall, our estimated critical gap for obstructed left turns is consistent with what others have reported. Our estimate for unobstructed left turns is similar to that reported by Yan and Radwan, but is somewhat shorter than that reported by Hutton et al.

Table 4.5 Estimated Left Turn Critical Gaps for Unobstructed and Obstructed Conditions

	Critical Gap (95% Confidence Interval)	
Study	Sight Distance Not Obstructed	Sight Distance Obstructed
Yan & Radwan (2008)	5.6	7.7
Hutton et al. (2015)	6.4 (6.0,6.9)	7.5 (6.6, 8.5)
This Study (Winnetka/Golden Valley Rd)	5.2 (4.4, 6.0)	8.0 (5.8, 10.9)

Chapter 5: Summary and Conclusions

As noted in Chapter 1, Minnesota has widely deployed flashing yellow arrow signals that allow for time-of-day changes between protective and permissive left-turn phases. However, there have been anecdotal reports of driver confusion regarding how FYA signals are to be interpreted, along with debate regarding the value of "Left Turn Yield" signs. Our goal in this project was to collect and analyze data relevant to these issues, and toward that end, we conducted an online survey to assess drivers' understanding of FYA signals and a field study of drivers' gap acceptances when facing FYA signals.

Regarding our survey:

(a) 96% of our respondents interpreted the FYA signal correctly when the "Let Turn Yield" sign was present and 94% interpreted FYA correctly when the sign was absent. Results were similar for four-lens and dog-house arrangements.

(b) 90% of the respondents who did not identify as transportation professionals interpreted the FYA signal correctly for both sign present and sign absent presentations.

(c) When the "Left Turn Yield" sign was absent, 3 respondents who did not identify as transportation officials interpreted the FYA signal as indicating a protected left turn, and of those, two correctly interpreted the FYA signal when the sign was present.

Overall, almost all respondents appeared to understand that FYA indicates permitted left turns. A small number of respondents (3) interpreted FYA as indicating protected left turns when the sign was absent and some of those gave correct responses when the sign was present. This suggests that "Left Turn Yield" signs might be helpful for these cases.

Regarding our field study:

(a) Critical gaps tended to be, but were not always, shorter at FYA sites compared to CG sites.

(b) Critical gaps tended to be, but were not always, longer when the "Left Turn Yield" was present compared to when it is absent.

(c) When the "Left Turn Yield" sign was present, critical gaps at FYA sites tended to be more similar to those at CG sites.

(d) At the one site where the offset of the opposing left-turn lane created a potential sight-distance issue, critical gaps tended to be longer when the opposing left-turn lane was occupied.

In summary, using $p < 0.1$ as our significance level, the critical gaps at the the 30 mph sites were, on average, significantly longer when the "Left Turn Yield" sign was present, for both FYA and CG. At the 40 mph site with FYA, critical gaps were significantly longer at the site when the sign was present compared to absent, but this pattern was reversed for the CG sites.

References

Brehmer, C., Kacir, K., Noyce, D., & Manser, M. (2001). *Evaluation of traffic signal displays for protected/permissive left-turn control* (NCHRP Report 493). Washington, DC: NCHRP.

Cunningham, C., Rouphail, N., Lee, T., & Kearns, B. (2020). *Guidelines for left-turn phasing options by time-of-day: A safety and operational stud*y (Report NCDOT/NC/2018-22). Raleigh, NC: North Carolina Dept. of Transportation.

Davis, G., Hourdos, J., & Moshtagh, V. (2015). D*evelopment of guidelines for permitted left-turn phasing using flashing yellow arrows*. St. Paul, MN: MnDOT.

Divine, M. (2018). Concerned about confusion at yellow arrows, she fights for prominent signs, *Pioneer Press*, July 2, 2018.

Fitzpatrick, K. (1991). Gaps accepted at stop-controlled intersections. *Transportation Research Record*, *1303,* 103-112.

Hajbabaie, A., Sattarov, S., & Mohebifard, R. (2018). *Safety and operations assessment of various left-turn strategies*. Seattle, WA: Pacific Northwest University Transportation Center.

Harlow, T. (2017). The drive: Crash rate shows many drivers failing to yield on flashing yellow arrow, *Star Tribune*, April 16. 2017.

Hutton, J., Bauer, K., Fees, C., & Smiley, A. (2015). Evaluation of left-turn lane offset using the naturalistic driving study data. *Journal of Safety Research*, *54*, 5-15.

Harwood, D., Mason, J., Brydia, R., Pietrucha, M., & Gittings, G. (1996). *Intersection sight distance* (Report 383). Washington, DC: National Cooperative Highway Research Program.

King, F., Appiah, J., Fontaine, M., & Cottrell, B. (2018). Safety and operations guidance for using time-of-day protected-permissive left-turn phasing using flashing yellow arrows (Report FHWA/VTRC 10-R10). Richmond, VA: Virginia DOT.

Knodler, M., Christofa, E., Tainter, F., Santiago-Chaparro, K., Bill, A., & Noyce, D. (2018). *A field and simulator evaluation of all-red clearance intervals for use in left-turn applications*. Iowa City, IA: Safer-Sim University Transportation Center.

Lin, P.-W., Thiagarajan, G., & Atie, D. (2008). Analysis of drivers' reaction to the flashing yellow arrow signal design form field observations. Paper presented at the *ITS America 2008 Annual Meeting and Exposition*, New York City, November 2008.

Medina, J., Shea, M., & Azra, N. (2018). *Safety effects of protected and protected/permissive left-turn phases* (Report UT-19.04). Salt Lake City: Utah DOT.

McCoy, P., Navarro, U., & Witt, W. (1992). Guidelines for offsetting opposing left-turn lanes on four-lane divided roadways. *Transportation Research Record*, *1356,* 28-36.

Noyce, D., Bergh, C., & Chapman, J. (2007). *Evaluation of the flashing yellow arrow permissive-only left turn indication field implementation* (NCHRP Report W123). Washington, DC: NCHRP.

Schattle, K., Anderson, E., & Hanson, T. (2017). Safety performance of flashing yellow arrow for protected-permissive left-turn signal control in central Illinois. *Transportation Research Record*, *2636,* 32-42.

Srinivasan R., Lan, B., Carter, D., Smith, S., & Signor, K. (2018). Crash modification factors for the flashing yellow arrow treatment at signalized intersection. *Transportation Research Record*, *2672,* 142-152.

Storm, R., O'Keefe, R., Srinivasan, R., lan, B., Klump, S., Herring, R., & Welle, B. (2020). *Flashing yellow arrow signal safety evaluation*. St. Paul, MN: MnDOT.

Yan, X., & Radwan, R. (2008). Influence of restricted sight-distance on permitted left-turn operation at signalized intersections. *ASCE Journal of Transportation Engineering*, *134*(2), 68-76.

Appendix A
Video Data Reduction Instructions

FYA Project Video Data Reduction

09/13/2022

Steps to Access Data and Data Reduction Template:

1. Log into your UMN account
2. Google Drive→Shared with Me→FYA→Gap Acceptance Video Clips
3. Google Drive → Shared with Me → FYA → "FYA Project Example Video Clip Information Template_220913.xlsx"

Steps to Extract Gap Acceptance Data from Video Clips:

Important note:

1. Gaps in the following conditions are supposed to be excluded from the analysis:
    1) Gaps involving motorcycles and bicycles (for both the LT and the opposing vehicles);
    2) Gaps where a pedestrian presented and interfered with either the LT or the opposing vehicles;
    3) Gaps where the LT vehicle is a semi-truck;
    4) Gaps during which signal changed from permitted to prohibited for either LT vehicle of interest or the corresponding opposing vehicles.
    5) Gaps involved in LTs performed with the presence of a leading vehicle.
2. At this time, for clips with a string of left-turn (LT) vehicles, gap acceptance data is extracted only for the 1st vehicle in the queue.
3. The video timestamp format is "HH:MM:SS.XXX". "HH" "MM" "SS.XXX" are supposed to be entered separately where time information is needed ("Gap Start Time" "Gap End Time").
4. Terms
    1) "Inside/Outside the Intersection" (LT vehicles)
        - If the LT vehicle's front bumper is behind or at the reference line (RL), then it is said to be outside the intersection;
        - If the LT vehicle's front bumper has crossed the RL, then it is said to be inside the intersection.

        ** See "reference line: LT vehicle's arrival" in the attached Figure 2-10.*
    2) "LT Vehicle's Arrival":
        i) If the LT vehicle came to a complete stop outside the intersection (i.e. the LT vehicle's stop location was outside the intersection) for a favorable gap to cross the intersection: the video timestamp when the LT came to a complete stop;
        ii) If the LT vehicle performed a rolling stop outside the intersection (i.e. the LT vehicle's slowest speed occurred when it was outside the intersection) for a favorable gap to cross the intersection: the video timestamp when the LT vehicle's speed was the slowest as it approached the intersection;
        iii) Cases other than i) & ii): the timestamp when the LT vehicle's front bumper crossed the RL.
    3) "Opposing conflicting vehicle's crossing at the conflict point" :
        i) If there's a crosswalk: the video timestamp when opposing conflicting vehicle's front bumper reached the near edge of the far crosswalk.
        ii) If there's no crosswalk: the video timestamp when opposing conflicting vehicle's front bumper reached the extended pavement edge.

        ** "near"/"far": relative to LT vehicle's stop location. Please see Figure 1.*

** See "reference line: Opposing conflicting vehicle's crossing at the conflict point" in the attached Figure 2-10.*

4) "Gap Acceptance"
   - A gap is said to be accepted by a LT vehicle if, within this gap, the LT vehicle passes the intersection point of the LT vehicle's trajectory and the opposing conflicting vehicle's trajectory before the opposing conflicting vehicle does.
   - Each LT has only 1 accepted gap (the last gap in the sequence of available gaps).

5) "Positioned LT": if the LT vehicle was inside the intersection when a gap was accepted, then this LT was said to be a positioned LT.

Entries are needed for:

1. **"Clip #"**
   Clip ID, which is consistent with the number in the file name of the clip.

2. **"Vehicle ID"**
   Vehicle ID (starting from "1" for each site), for differentiation among gap acceptance decisions made by different left-turn vehicles.

3. **"Vehicle Type"**
   Vehicle class for the LT vehicle of interest. Choose from *sedan*, *SUV*, *van*, *pick-up truck*, *bus*, and *single-body truck*.

4. **"Gap Start Time"**

1) If it is the 1st available gap after the LT vehicle's arrival:
   i) If LT was prohibited upon the LT vehicle's arrival (red light for LTs): the video timestamp when the traffic signal changes from prohibited LT phase to permitted LT phase (flashing yellow arrow for FYA sites and circular green for CG sites).
   ii) If LT was permitted upon the LT vehicle's arrival: the video timestamp of LT vehicle's arrival.
   ** For clips where it is difficult to determine whether a LT vehicle performed a complete or rolling stop outside the intersection due to camera angle (ex. Winnetka Ave & Golden Valley Rd), use the video timestamp when the LT vehicle's front bumper reached the RL.*
2) If it is the 1st available gap after a rejected gap by the LT vehicle:
   i) If LT was prohibited upon the opposing conflicting vehicle's (the vehicle generating the most recent rejected gap) crossing at the conflict point: the video timestamp when the traffic signal changed from prohibited left-turn phase to permitted left-turn phase.
   ii) If LT was permitted upon the opposing conflicting vehicle' (the vehicle generating the most recent rejected gap) crossing at the conflict point: the video timestamp when the opposing conflicting vehicle crossed the conflict point.

5. **"Gap End Time"**
   Video timestamp when the opposing conflicting vehicle crossed the conflict point.
   ** For sites with the opposing direction of road having more than one through lane, sometimes a right-turn (RT) vehicle and a crossing vehicle might arrive at the RL at approximately the same time. If so, treat those two vehicles as one vehicle.*

6. **"Gap Acceptance Decision"**
   See "*Gap Acceptance*" in "*4. Terms*" in the "*Important Note*" Section.
   "1", if a gap was accepted by the LT vehicle;
   "0", if a gap was rejected by the LT vehicle.

7. "Opposing Vehicle Maneuver"

"crossing", if the gap was ended by an opposing crossing vehicle;
"RT", if the gap was ended by an opposing RT vehicle.
** For sites with the opposing direction of road having more than one through lane, sometimes a right-turn (RT) vehicle and a crossing vehicle might arrive at the RL at approximately the same time. If so, treat those two vehicles as one vehicle, and enter "Crossing + RT" for Opposing Vehicle Maneuver.*

8. "Opposing Vehicle Travel Lane"

The lane where the opposing conflicting vehicle was traveling.

i) If the road has more than one through lane in the direction conflicting with LTs of interest: choose between "near lane" and "far lane" (relative to the LT vehicle's travel lane, see Figure 1).
***** If a right-turn (RT) vehicle and a crossing vehicle arrived at the RL at approximately the same time, treat those two vehicles as one vehicle, and enter "near+far" for "Opposing Vehicle Travel Lane".

ii) If the road has only one through lane in the direction conflicting with LTs of interest: enter "one through lane".

9. Positioned LT

See "*Positioned LT*" in "*4. Terms*" in the "*Important Note*" Section.
"1", if a gap was rejected or accepted by a LT vehicle that performed positioned LT;
"0", otherwise.

10. Notes

Note special features for the gap data (ex. opposing vehicle's lane-changing behavior near the reference line), if any.

11. *Special Case

If a clip contains any special conditions that are not covered in this instruction, please enter the case information into the "List of Video Clips with Information TBD.xlsx" spreadsheet in the "Video Clip Information" folder on the Shared Google Drive "FYA" and proceed to the next clip.

Steps to share data:

Go to "Google Drive" →"Shared with Me"→"FYA"→"Video Clip Information" and upload Excel spreadsheets containing gap acceptance data reduced from video clips to the corresponding site folder.

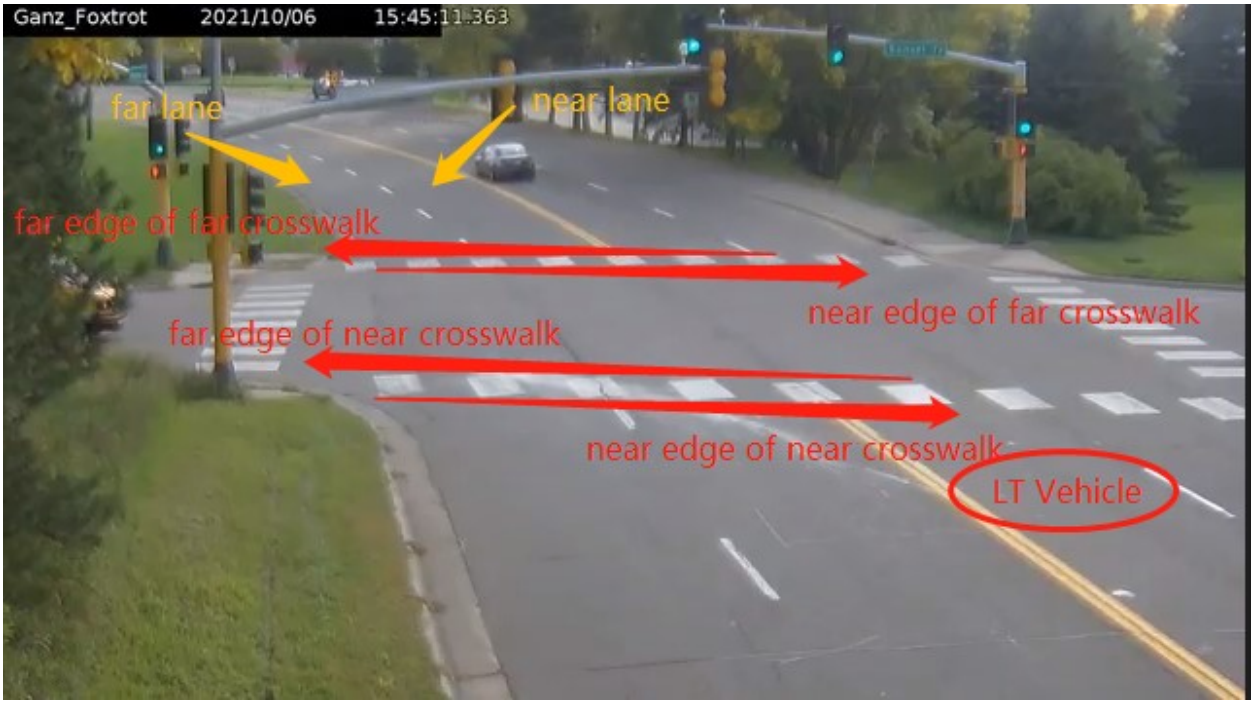


Figure 1 "Near" "Far" Terms

Figure 2 Valley Creek & Weir Site Video Data Reduction Reference

Figure 3 Valley Creek & Bielenberd Site Video Data Reduction Reference

Figure 4 Xenium & Sunset Trail Site Video Data Reduction Reference

Figure 5 Xenium & Medicine Lake Site Video Data Reduction Reference

Figure 6 Xenium & Carlson Parkway Site Video Data Reduction Reference

Figure 7 Louisiana & 28th Site Video Data Reduction Reference

Figure 8 Louisiana & Franklin Site Video Data Reduction Reference

Figure 9 Boone & Golden Valley Site Video Data Reduction Reference

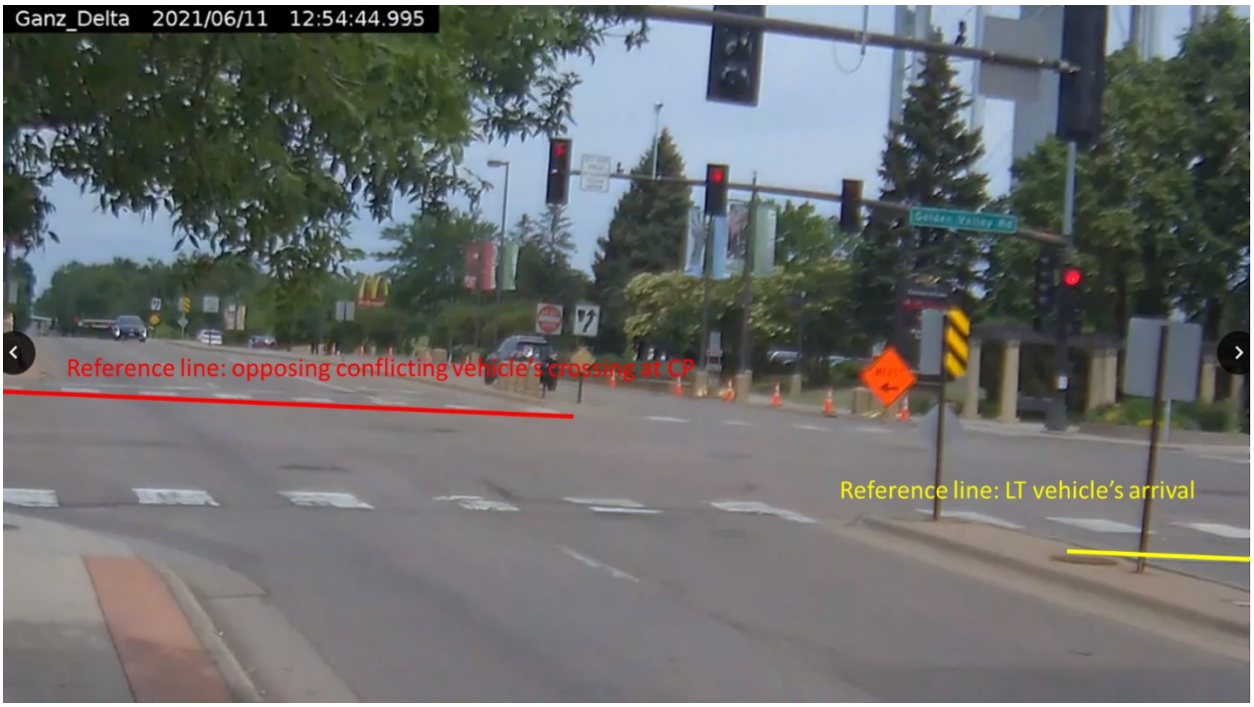


Figure 10 Winnetka & Golden Valley Site Video Data Reduction Reference

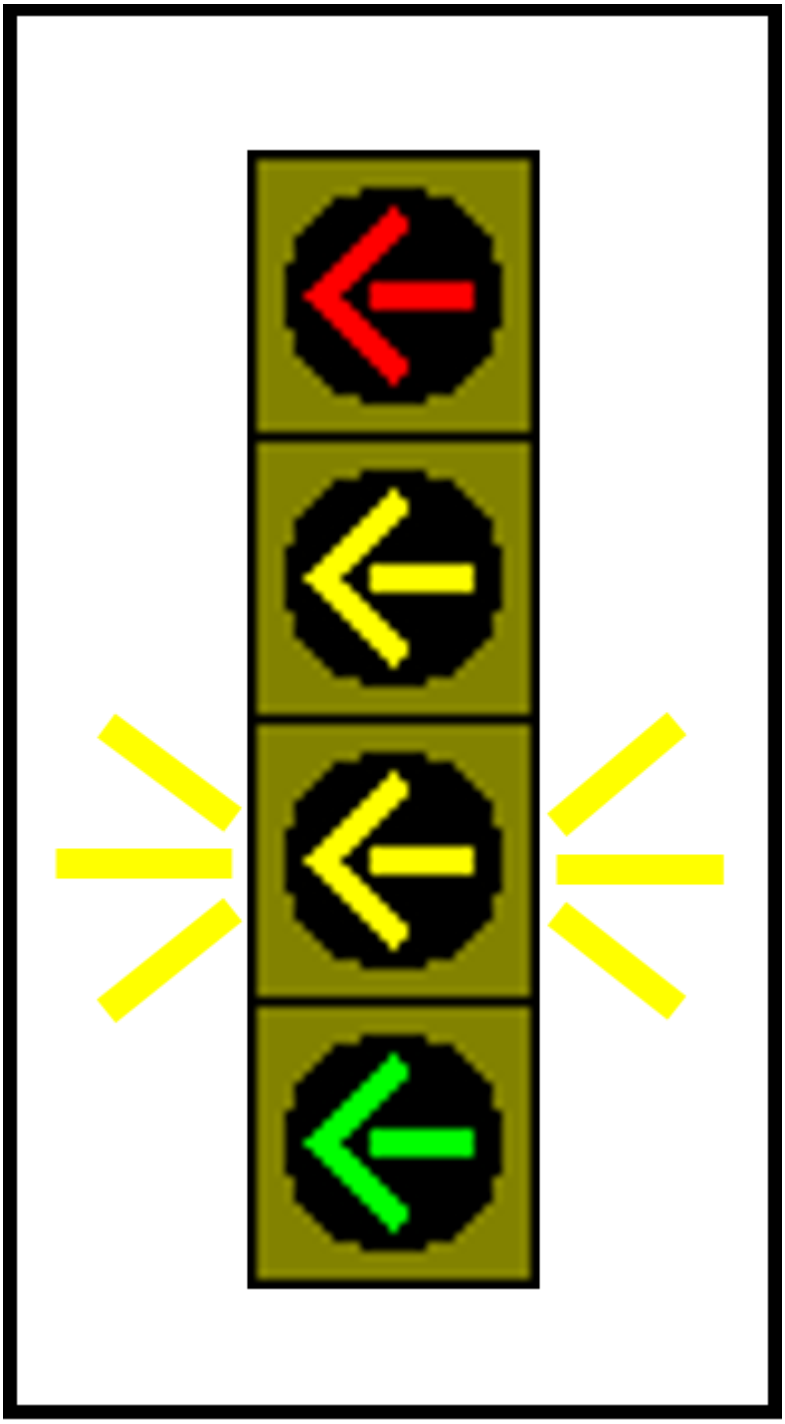
Appendix B
Printout of Survey

Introduction block

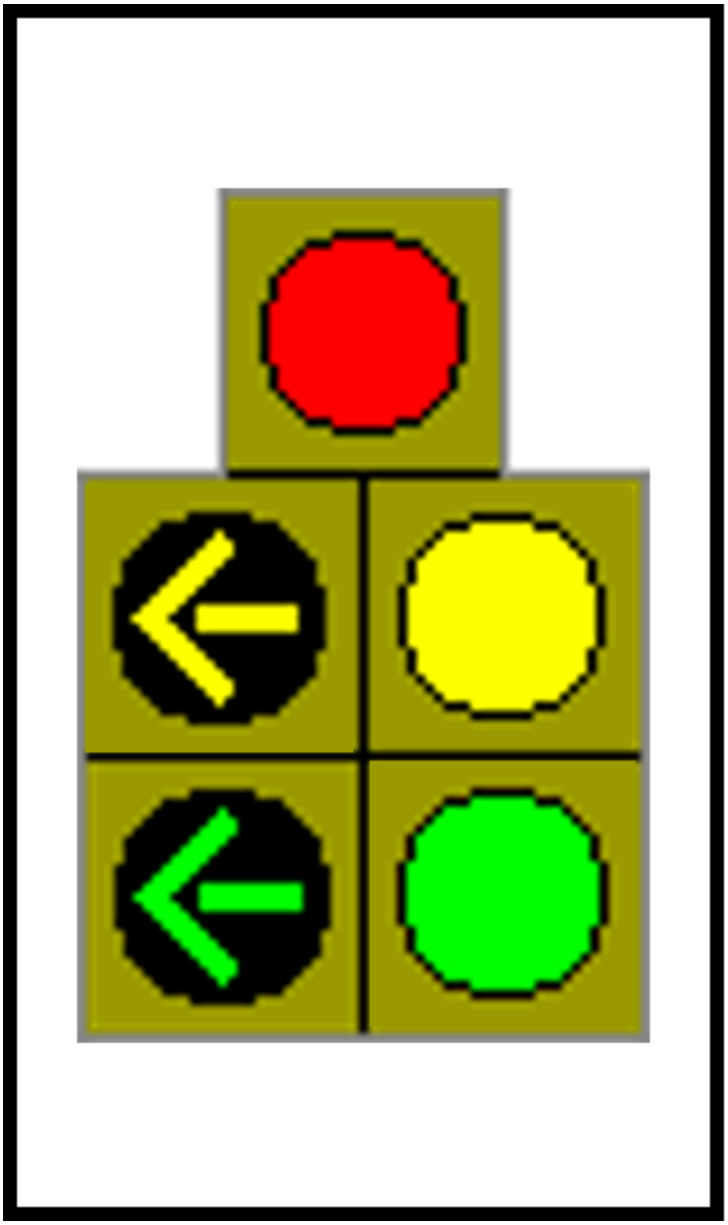
Thank you for agreeing to take this survey. The objective of this study is to evaluate the understanding of traffic signals during left turns at signalized intersections. While this survey is anonymous, you will be asked to provide some non-identifiable demographic information at the start of the survey. The responses collected from this survey will be reviewed and analyzed only by members of our research team. You will not be required to answer these questions.

During this survey, you will see 12 questions displaying traffic lights like the kinds below, including a flashing yellow arrow in some cases. You will be asked how you would respond to each scenario. Please click next to begin the survey.

Four-Head Traffic Signal



Cluster-Head "Doghouse" Traffic Signal



Demographics block

Are you using a screen reader or other visual assistance tool to access this survey? We will provide alternative questions easier for your screen reader to process. Please answer "yes" if you are using a screen reader.

- ○ Yes
- ○ No

Are you a transportation professional in any capacity? (Ex: transportation engineer, transportation planner, etc.)

- ○ Yes
- ○ No
- ○ Not Sure

What is your age group?

- ○ 18-24
- ○ 25-34
- ○ 35-44
- ○ 45-54
- ○ 55-64
- ○ 65+

What is your identified gender?

- ○ Male
- ○ Female
- ○ [ ] Other

How many years of driving experience do you have?

- ○ Less than 5 years
- ○ 5 to 9 years
- ○ 10 to 19 years
- ○ 20 to 29 years
- ○ More than 30 years

What is your primary form of transportation?

- ○ Car - driving
- ○ Car - passenger
- ○ Bicycling
- ○ Public transit
- ○ Walking
- ○ Ridesharing services
- ○ [ ] Other

What is your zip code?

[ ]

Block 1: Separate Signal Faces Sign FY G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

Content made on Kapwing

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and flashing yellow arrow on the left, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

Block 2: Separate Signal Faces No Sign FY G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

Content made on Kapwing

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and flashing yellow arrow on the left.)

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

Block 3: Separate Signal Faces No Sign SY G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and solid yellow arrow on the left.)

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- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 4: Separate Signal Faces Sign SY G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and solid yellow arrow on the left, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 5: Separate Signal Faces No Sign R G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and solid red arrow on the left.)

B-12

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 6: Separate Signal Faces Sign R G

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A separated four head signal head displays a continuous circular green on the right and solid red arrow on the left, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

Block 7 - "Doghouse" style configuration, SG CG sign

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A doghouse signal displays both a solid green arrow and circular green light, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 8 - "Doghouse" style configuration, SG CG no sign

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A doghouse signal displays both a solid green arrow and circular green light.)

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 11 - "Doghouse" style configuration, CR no sign

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A doghouse signal displays a circular red light.)

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.

- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Block 12 - "Doghouse" style configuration, CR sign

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

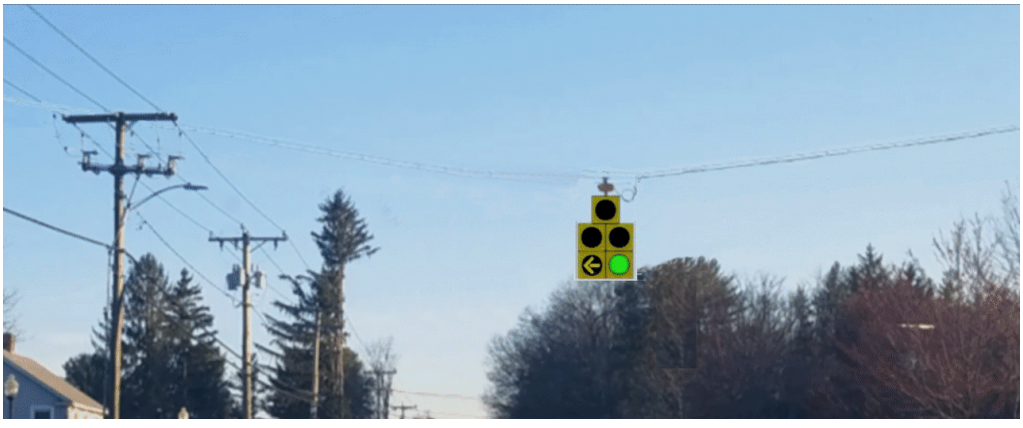
(Image: A doghouse signal displays a circular red light, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

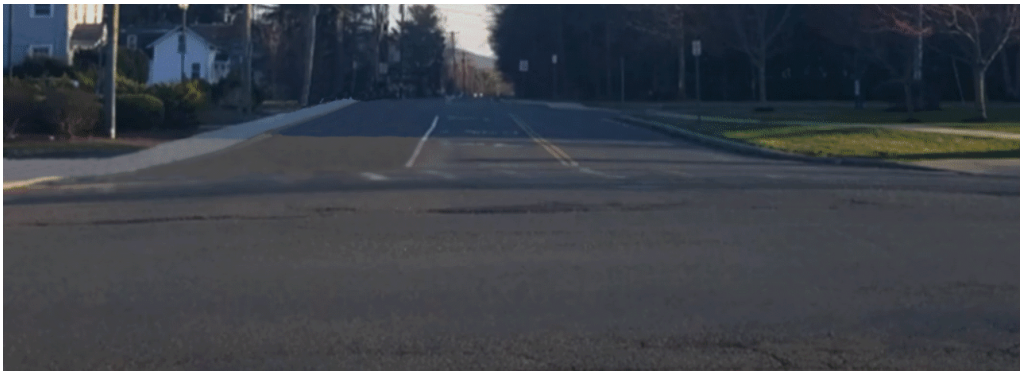
- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Doghouse FYA no sign

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...





Content made on Kapwing

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

You are in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A doghouse signal head displays a continuous circular green on the right and flashing yellow arrow on the left.)

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

Doghouse FYA signed

Question ${e://Field/counter} of 12

You are stopped in the left turn lane waiting to turn left. Based on the signal displayed below, you should...

Content made on Kapwing

- wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- wait until there is a sufficient gap in oncoming traffic and then make your turn.
- wait, because the signal is about to turn red.
- make your turn, because oncoming traffic should stop.

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You are stopped in the left turn lane waiting to turn left. Based on the signal described below, you should...

(Image: A doghouse signal head displays a continuous circular green on the right and flashing yellow arrow on the left, with a sign saying "Left Turn Yield on Flashing Yellow Arrow")

- ○ wait until the signal changes to a green arrow or flashing yellow arrow and then make your turn.
- ○ wait until there is a sufficient gap in oncoming traffic and then make your turn.
- ○ wait, because the signal is about to turn red.
- ○ make your turn, because oncoming traffic should stop.

End block: Thank you!

Thank you for completing this survey! If you have any comments regarding Flashing Yellow Arrows and their use in the Twin Cities Metro Area, please include them in the text box below.