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Analysis and Modeling of Drivers' Responses at Urban Signalized Intersections

Brian T. W. Lin, Te-Ping Kang,
Paul Green, and Heejin Jeong

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DRIVER INTERFACE

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16. Abstract

This study provided baseline data on how subjects approached intersections to support a follow-on study of augmented reality crash warnings. Twenty-four licensed drivers (12 ages 18-30, 12 greater than age 65) drove through 71 urban, signalized intersections in a fixed-base driving simulator while following a lead vehicle. Five types of conflicts were simulated at 10 intersections, straight crossing path (SCP), left turn across path – opposite direction (LTAP/OD), left turn across path – lateral direction (LTAP/LD), left turn into path (LTIP), and right turn into path (RTIP).

The probability of stopping at yellow light was = $e^x/(1+e^x)$, where x = -5.84 - 0.01*gap to stop line + 1.49*yellow light timing - 2.93*pedal position + 0.29*age + 0.15*gender, accounting for 19% of the variance because of individual differences.

Subject vehicle approach speed to the intersection varied by conflict type and traffic light color and timing. When approaching a green light, 21% of subjects slowed down for LTAP/OD conflicts and 27% slowed down for RTIP. For yellow lights, when subjects chose to run light, they never slowed down for LTAP/OD.

The approach speed to an intersection was = 13.70 - 0.17*gap to stop line - 5.38*run or not + 0.07*conflict or not + 3.21*yellow light timing 2.8 s - 0.18*yellow light timing 3.5 s - 1.58*age, with an R^2 of 0.74.

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Analysis, Models, and Prediction of Drivers' Responses at Urban Signalized Intersections

UMTRI Technical Report 2016-13, September 2015

Brian T.W. Lin, Te-Ping Kang, Paul Green, and Heejin Jeong

University of Michigan Transportation Research Institute Ann Arbor, Michigan, USA

1 Questions

1. How often did crashes occur for each scenario of interest?

2. How did drivers respond to traffic signals?

3. How did the probability each subject stopped for an intersection vary as a function of speed and/or gap to stop line, yellow-light timing, throttle and brake pedal positions, and subject age/gender, when the light just changed to yellow?

4. What was the speed vs. distance profile for approaching each intersection? (Note: Going through and departing are of secondary interest as they are post-decision. However, they are included in the appendix.)

5. How does speed approaching an intersection vary as a function of gap to stop line, yellow-light timing, other traffic maneuver, and subject age/gender?

6. How did longitudinal acceleration and jerk vary as the driver approached each intersection and was it indicative of any crash related behavior?

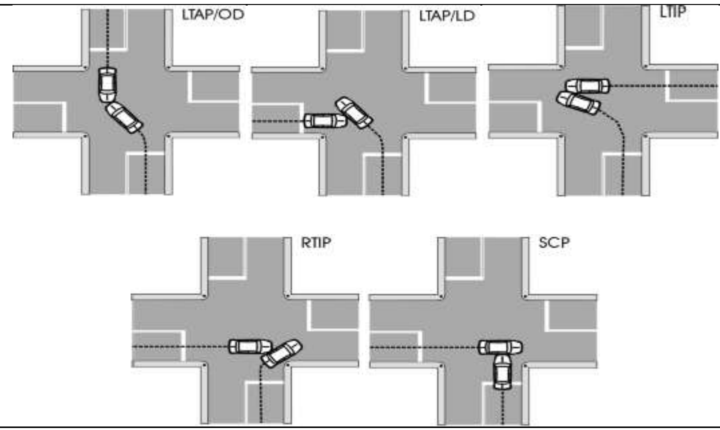
2 Methods

Typical Road Scene

NADS MiniSim-based driving simulator with steering wheel and foot pedals

#	Task	Time (min)
1	Introduction to experiment (check driver's license, describe experiment to subject, complete consent form (Appendix B), and complete biographical form (Appendix C)	10
2	Check vision (far, near, color)	5-10
3	Introduction to simulator	5
4	Practice driving	5-15
	Collect data for test block 1	25
	Take a break and save data, load in next test block	2
	Collect data for test block 2	25
	Take a break and save data, load in next test block	2
	Collect data for test block 3	35
5	Collect post test (Appendix D) and pay subject (data saved after subject leaves)	10
	Total	**129-139**

Crossing Path Crash Scenarios

Code	**Scenario**	**Illustration**
LTAP/OD	Left Turn Across Path – Opposite Direction	
LTAP/LD	Left Turn Across Path – Lateral Direction	
LTIP	Left Turn Into Path	
RTIP	Right Turn Into Path	
SCP	Straight Crossing Path	

Maneuver Combinations Explored

Variable		**Condition** (*C* = Conflict; *V* = Violation)	**Description**
Vehicle maneuver	Left	go straight	green light for left vehicle and it went straight
		stop	red light for the left vehicle and it stopped
		signal left	red light for the left vehicle and it stopped with left turning signal on, waiting until the traffic changed to green
		turn right	red light for the left vehicle and it turned right
		turn left *(C, V)*	red light for the left vehicle, but it turned left into subject’s driving path when the subject is just entering the intersection
		go *(C, V)*	red light for the left vehicle, but it ran the red light and went straight
	Right	go straight	green light for right vehicle and it went straight
		stop	red light for the right vehicle and it stopped
		signal left	red light for the right vehicle and it stopped with left turning signal on, waiting until the traffic changed to green
		signal right	red light for the right vehicle and it stopped with right turning signal on, waiting until subject’s vehicle passed
		turn left *(C, V)*	red light for the right vehicle, but it turned left into opposing vehicle’s driving path, crossing subject’s driving path
		turn right *(C)*	red light for the right vehicle, but it turned right into subject’s driving path
		go *(C, V)*	red light for the right vehicle, but it ran the red

Variable		Condition (*C* = Conflict; *V* = Violation)	Description
			light and went straight
	Opposing	go straight	green or yellow light for the opposing vehicle and it went straight
		slow to avoid crash	green or yellow light for the opposing vehicle, but it slowed down if the left/right vehicle turned into its driving path or ran the red light
		signal left	green light for the opposing vehicle and it stopped with left turning signal on, waiting until subject's vehicle passed
		turn right	green or yellow light for the opposing vehicle and it turned right
		turn left *(C, V)*	green light for the opposing vehicle and it stopped with left turning signal on, but turned left in between lead and subject's vehicle

Event Numbers Used to Code Data

Vehicle maneuver			Traffic light state					Conflict type
Left vehicle	Opposing vehicle	Right vehicle	Green	Red	Yellow			
					4.2 s	3.5 s	2.8 s	
go straight	slow down	go straight	-	1-7	-	-	-	
stop	go straight (run yellow light if there)	stop	8-21	-	22-23	24-25	26-27	
Maneuver by vehicle from left								
go straight (run red light)	go straight (run yellow light)	stop	-	-	-	28	-	SCP
stop, left-turn signal on	go straight (run yellow light if there)	stop	29	-	30	31	32	
turn left (run red light)	go straight (run yellow light)	stop	-	-	-	33	-	LTIP
turn right	go straight	stop	34	-	35	36	37	
Maneuver by vehicle from opposing direction								
stop	stop, left-turn signal on	stop	38	-	39	40	41	
stop	turn left	stop	42	-	43	44	45	LTAP

	(run yellow light if there)							/OD
stop	turn right	stop	46	-	47	48	49	
Maneuver by vehicle from right								
stop	go straight (run yellow light)	go straight (run red)	-	-	-	50	-	SCP
stop	go straight (run yellow light if there)	stop, left-turn signal on	51	-	52	53	54	
stop	go straight (run yellow light)	turn left (run red)	-	-	-	55	-	LTAP/LD
stop	go straight	stop, right-turn signal on	56	-	57	58	59	
stop	go straight (run yellow light if there)	turn right	60	-	-	61	-	RTIP

. Event Numbers Used to Code Data

Vehicle maneuver			Traffic light state					Conflict type
Left vehicle	Opposing vehicle	Right vehicle	Green	Red	Yellow			
					4.2 s	3.5 s	2.8 s	
go straight	slow down	go straight	-	1-7	-	-	-	
stop	go straight (run yellow light if there is)	stop	8-21	-	22-23	24-25	26-27	
Maneuver by vehicle from left								
go straight (run red light)	go straight (run yellow light)	stop	-	-	-	28	-	SCP
stop, left-turn signal on	go straight (run yellow light if there is)	stop	29	-	30	31	32	
turn left (run red light)	go straight (run yellow light)	stop	-	-	-	33	-	LTIP
turn right	go straight	stop	34	-	35	36	37	
Maneuver by vehicle from opposing direction								
stop	stop, left-turn signal on	stop	38	-	39	40	41	
stop	turn left (run yellow light if there is)	stop	42	-	43	44	45	LTAP/OD
stop	turn right	stop	46	-	47	48	49	
Maneuver by vehicle from right								
stop	go straight (run yellow light)	go straight (run red light)	-	-	-	50	-	SCP
stop	go straight (run yellow light if there is)	stop, left-turn signal on	51	-	52	53	54	
stop	go straight (run yellow light)	turn left (run red light)	-	-	-	55	-	LTAP/LD
stop	go straight	stop, right-turn signal on	56	-	57	58	59	
stop	go straight (run yellow light if there is)	turn right	60	-	-	61	-	RTIP

Vehicle from Right Turns (LTAP/LD) in Front of Subject at Yellow Light

Vehicle from Left Turns (LTIP) in Front of Subject at Green Light

16 Subjects

Age	Men	Women
18-30	4	4
>65	4	4

3 Results and Conclusions

1. How often did crashes occur for each scenario of interest?

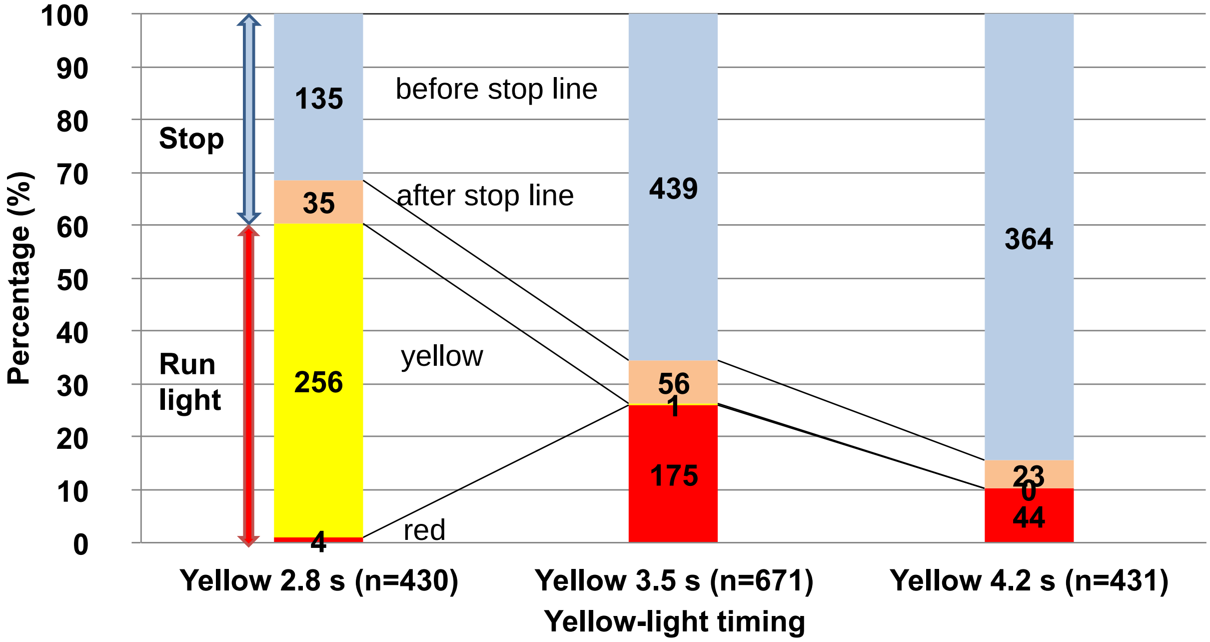
Subject	Intersection	Traffic light	Conflict	Crash with
Young male	39	yellow	n/a	vehicle behind
Young male	62	green	LTAP/OD	vehicle opposing
Old female	24	yellow	n/a	vehicle behind
Old female	39	yellow	n/a	vehicle behind

Conclusion: Consider some changes to increase the number of crashes to make the effectiveness of crash warning systems easier to detect.

2. How did drivers respond to traffic signals?

Number of Encounters of This Experiment

Light State	With conflict	Without conflict	Total	Probability of stopping
Green	96	960	1056	-
Yellow 2.8 s - run	25	235	260	0.40
Yellow 2.8 s - stop	22	148	170	
Yellow 3.5 s - run	68	108	176	0.74
Yellow 3.5 s - stop	186	309	495	
Yellow 4.2 s - run	2	42	44	0.90
Yellow 4.2 s - stop	46	341	387	
Total	445	2143	2588	-
Red			336	
TOTAL		2924		



Subjects’ Behavior to Stop/Run Light under Three Yellow Light Durations

Note: 3 subjects, all older, stopped at every yellow light.

Conclusion: Consider changes to reduce the probability of stopping as when they run the yellow and encounter a conflict is of interest.

Conclusion: Age had a major effect on the probability of stopping.

3. How did the probability each subject stopped for an intersection vary as a function of speed and/or gap to stop line, yellow-light timing, throttle and brake pedal positions, and subject age/gender, when the light just changed to yellow?

$$P(stop) = \frac{e^x}{1 + e^x}$$

where:

$$x = -5.84 - 0.01 \times gap\ to\ stop\ line + 1.49 \times yellow\ light\ timing - 2.93 \times pedal\ position + 0.29 \times age + 0.15 \times gender$$

and:

gap to stop line [ft; negative value = location before stop line];
yellow light timing = 2.8, 3.5, or 4.2 [s].
pedal position is between ±1;
age = 0 for younger, 1 for older;
gender = 0 for males, 1 for females;

4. What was the speed vs. distance profile for approaching each intersection? (Note: Going through and departing are of secondary interest as they are post-decision. However, they are included in the appendix.)

Condition – Approaching a…	**Action**
green light with conflict	10/48 slightly slowing down for LTAP/OD 13/48 obviously slowing down for RTIP
run yellow light with conflict	no slowing down for LTAP/OD 2-3 slowing down for SCP, LTIP, LTAP/LD, & RTIP
run yellow light without conflict	constant speed or speeding up prior to passing the intersection
stop for yellow light	brake was applied more aggressively with time after subject began to apply the brake

5. How does speed approaching an intersection vary as a function of distance to stop line, yellow-light timing, other traffic maneuver, and subject age/gender?

$$Speed = 13.70 - 0.17 \times gap\ to\ stop\ line - 5.38 \times run + 0.07 \times conflict + 3.21 \times yellow\ light\ timing\ 2.8\ s - 0.18 \times yellow\ light\ timing\ 3.5\ s - 1.58 \times age$$

where:

gap to stop line [ft; negative value = location before stop line]
run = 0 if stopping for the light; 1 if running
conflict = 0 if the intersection has no conflict, 1 if the intersection has conflict
yellow light timing 2.8 s, yellow light timing 3.5 s =
(1,0) for 2.8 s, (0,1) for 3.5 s, (0,0) for 4.2 s;
age = 0 for younger, 1 for older;

6. How did longitudinal acceleration and jerk vary as the driver approached each intersection and was it indicative of any crash related behavior?

Condition – Approaching a…	Action
green light with no conflict	stable jerk data
green light with conflict	changes in jerk but not as salient as acceleration
run yellow light with no conflict	changes in jerk but not as salient as acceleration
run yellow light with conflict	changes in jerk but not as salient as acceleration
stop for yellow light	changes in jerk but not as salient as acceleration

Conclusion: Acceleration is a better indicator of crash related behavior than jerk. However, there are reservations about this conclusion because the brake signal was based on pedal displacement, not pedal application velocity (as is the case for real hydraulic braking systems)

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INTRODUCTION

In the United States, approximately 30,000 people die in motor vehicle crashes each year and more than another 2 million are injured (U.S. Department of Transportation, 2013). Crashes at intersections comprise about 40% of all crashes in the U.S. (U.S. Department of Transportation, 2013).

The literature on motor vehicle crashes is vast and reviewing it is beyond the scope of this project. This particular NSF-funded report deals with an unresolved question – How effective are augmented-reality warning systems in warning drivers about impending intersection crashes? To implement such a system, the entire windshield would become a head-up display (HUD), with the warning presented on or in the windshield. An important part of answering this question is understanding and modeling how people drive when approaching intersections, the context for the warning (e.g., Green, Demeniuk, and Jih, 2008; Green, Schweitzer, Alter, and Demeniuk, 2008; Hafner, Cunningham, Caminiti, and Del Vecchio, 2013; Hoehener, Green, and Del Vecchio, 2015; Colombo and Del Vecchio, 2015). In doing such, exploring new methods and models, especially models related to the crash-warning systems is encouraged in light of NSF's mission to promote the progress of science.

The first step in conducting this research project was to create and evaluate a test scenario for exploring augmented reality warnings, the focus of this report (year 1). Subsequent reports examine the proposed system independently (Lin, Kang, and Green, 2016) and in comparison with a baseline and another warning system (Liu, Kang, Green, and Lin, 2016).

Given the larger goals of this project and the need to support modeling to be done by MIT, a collaborator in this project, baseline data was collected in a driving simulator for urban signalized intersections for which crashes could occur. Four basic questions were addressed:

1. How often did crashes occur for each scenario of interest?

2. How did drivers respond to traffic signals?

3. How did the probability each subject stopped for an intersection vary as a function of speed and/or gap to stop line, yellow-light timing, throttle and brake pedal positions, and subject age/gender, when the light just changed to yellow?

4. What was the speed vs. distance profile for approaching each intersection? (Note: Going through and departing are of secondary interest as they are post-decision. However, they are included in the appendix.)

5. How does speed approaching an intersection vary as a function of gap to stop line, yellow-light timing, other traffic maneuver, and subject age/gender?

6. How did longitudinal acceleration and jerk vary as the driver approached each intersection and was it indicative of any crash related behavior?

The first question relates to what needs to be done to set up an appropriate experiment, to have enough crash-provocative events. The second question concerns modeling the driving context before a crash occurs. The situation of particular interest is when there is indecision due to a yellow traffic light, the driver decides to drive through, but is then confronted with vehicles that are a threat. It is in these complex situations that warning may be most useful. The third question is concerned with predicting the initial conditions of the event. Finally, as the consequence of responding to a crash warning, this study literally explores what should be an informative derivative measure of deceleration, namely the derivative of acceleration or jerk. With those questions in mind, the literature was examined.

What equations predict the number of crashes at signalized intersections?

As context, a number of authors have developed equations to predict the number of crashes that occur at signalized intersections (Abdel-Aty and Keller, 2005; Abdel-Aty, Kellyer, and Brady, 2005; Wang, Abdel-Aty, and Brady, 2006; Mitra and Washington, 2007; Huang, Chin, and Haque, 2008; Lord and Mannering, 2010). Depending on the study, the number of key predictors usually include the number of vehicles per hour (or average daily traffic, ADT) on the major and minor road, the number of through lanes on each road, the number of left and right turn lanes, the posted speeds, the fraction of vehicles that are trucks, and the intersection angle. Which factors are significant vary somewhat, in part because the study context varies – land use (e.g., rural vs. urban), the traffic level, geography, and other factors. Thus, driving simulator experiments to simulate driving at intersections should include these factors, though including all of them in a single experiment is not feasible. Some example studies follow.

Oh, Lyon, Washington, Persaud, and Bared (2003) examined models used by the Federal Highway Administration (FHWA) for rural intersections, specifically for the Interactive Highway Safety Design Model (IHSDM). Table 1 shows the parameter estimates for the 5th (and final) model examined. In this case, the important predictors are the traffic on both roads and if there is a protected left turn.

Table 1. Parameters Used to Estimate Number of Crashes

Variable	Value
constant	-6.08
log of average daily traffic of major road	0.60
log of average daily traffic of minor road	0.29
major road median width (feet)	0.00
number of residential and commercial driveways on the major road within 250 feet of the intersection center	0.00
percentage of all incoming major road traffic during peak hours that turns left	0.00
1 if protected left turn lane on major road, 0 otherwise	-0.47
percentage of all incoming minor road traffic during peak hours that turns left	-0.02
Mean curvature rate along the major & minor road within 800 feet of the intersection center	0.11
% of trucks passing through the intersection	0.03

Source: Oh, Lyon, Washington, Persaud, and Bared, 2003, p. 45

Abdel-Aty, Keller, and Brady (2005) in contrast to previous research, used hierarchical tree-based regression to develop predictions of crash frequency. Their data set was intersections in mid-Florida. For those unfamiliar with this method, a tree diagram that serves as the basis of this approach (for angle crashes only) is in Figure 1.

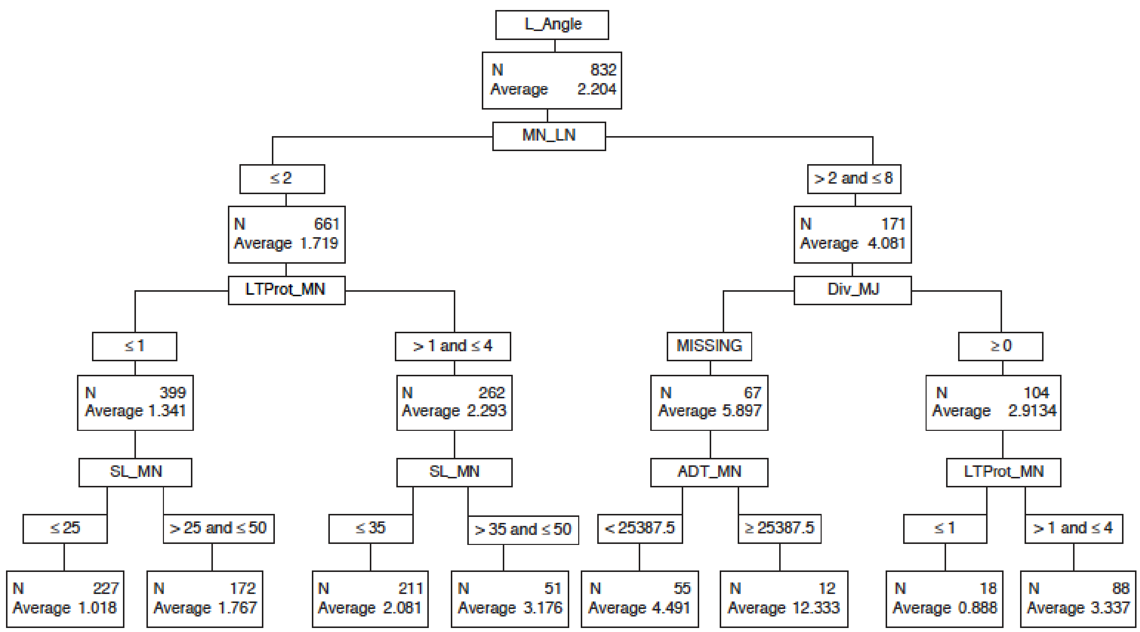


Figure 1. Hierarchical Tree-based Regression for Crash Frequency Prediction
Source; Abdel-Aty, Keller, and Brady, 2005, p. 40.

They examined 2 data sets (complete and restricted), with the restricted data set having less detail. The data set included 33,592 crashes from 832 intersections for 2000 and 2001. They found that the factors that were most important were consistent for rear-end, right-turn, and sideswipe crashes when minor crashes were considered. However, the model terms that were most important were different for angle and head-on crashes. For the experiment to be conducted, the focus is on all crash types. As shown in Table 2, the most important factors were the number of lanes on the minor road, the presence of left turn lanes on the main road, a right turn lane on the minor road, and the traffic volume on both roads in that order.

Table 2. Importance Weights for 2 Data Sets

Variable	Restricted Data Set	Complete Data Set
number of lanes on minor road	1.00	1.00
exclusive left turn lanes on main road	0.85	0.89
right turns channelized on major road	0.76	0.75
speed limit on major road	0.54	0.25
number of lanes on major road	0.53	0.47
daily traffic volume on major road	0.43	0.69
daily traffic volume on minor road	0.33	0.41
speed limit on minor road	0.16	0.00
median present on major road	0.00	0.11
median present on minor road	0.00	0.27
exclusive left turn lanes on major road	0.00	0.00
right turn lanes channelized on main road	0.00	0.00
total left turn lanes on major road	0.00	0.00
total left turn lanes on minor road	0.00	0.00

Source; Abdel-Aty, Keller, and Brady, 2005, p. 42.

Kim, Washington, and Oh (2006) developed several models data from 837 crashes on rural intersections in the state of Georgia. They nicely summarize prior research which along with their research appears in Table 3. Notice that traffic volume (here the log of average annual daily traffic) predominates and in their research the primary factors were traffic volume, the presence of a right turn lane, and if the major road was lit.

Table 3. Crash Type Models for 4-legged intersection
from Previous Research and Kim, Washington, and Oh

Variables	**Vogt & Bared (1998)**	**Lyon et al. (2003)**	**Their Findings**
constant	-10.43	-9.25	-4.45
log of average daily traffic for major road	0.60	0.71	0.44
log of average daily traffic for major road	0.61	0.52	0.32
major road median width in ft			-0.07
major road should width in ft			
sum of curvature in degrees/100 ft of major road within 250 of intersection divided by # of curves	0.04		
sum of absolute change of grade in %/100 ft for each crest with 250 ft of intersection	0.29	0.08	
mean posted speed of main road			
average roadside hazard on major road within 250 ft of intersection			
1 = right turn lane on major road, 0 otherwise			0.75
1 = right turn lane on minor road, 0 otherwise			
intersection angle in degrees	-0.01		
number of driveways with 250 ft of intersection	0.12	0.14	0.12
lighting indicator (1 if light on major road, 0 otherwise)			-0.48

Modified from: Kim, Washington, and Oh, 2006, p. 284

Aguero-Valverde and Jovanis (2008) examined crash data for 2-lane rural roads in Pennsylvania using a variety of analysis method. The examined a number of calculation methods to predict crash frequency. Table 4 lists the terms in the final model and their weights. Notice that by far the most prominent factor is traffic volume.

Table 4. Aguero-Valverde and Jovanis Model Terms

Variable	Mean
intercept	-6.152
volume (average annual daily traffic)	0.676
functional class - expressway and arterial	0.187
speed limit > 35 mi/hr	-0.296
lane width < 10 ft	-0.374
lane width > 10 ft and <12 ft	0.101
lane width > 12 ft and <14 ft	-0.055
lane width >= 14 ft	0.613
shoulder width < 4 ft	0.504
shoulder width > 4 ft and < 6 ft	0.302
shoulder width > 6 ft and < 10 ft	0.394
shoulder width >= 10 ft	0.248

Source: Aguero-Valverde and Joavanis, 2008, p. 60.

There are many other studies that provide similar data (e.g., Wang, Abdel-Aty, and Brady, 2006; Kim, Lee, Washington, and Choi, 2007; Ye, Pendyala, Washington, Konduri, and Oh, 2009; Pei, Wong, and Sze, 2011). The basic conclusions are that traffic matters most, follow by the presence of turn lanes (depending on the study), follow by geometric factors such as curvature, lane and shoulder width, and finally the number of driveways nearby the intersection. The size of the coefficients for terms varies substantially between studies, possibly because of the site and the modeling method used to develop the equation. In terms of this particular experiment, the intersection was expected to be quite simple, without turn lanes, and the approach was expected to be straight and flat, all factors that would reduce the expected number of crashes. As this was an initial effort, it was not feasible to include those complexities in the experiment given the resources available.

How can the probability a driver stops at an intersection (in the dilemma zone) be predicted?

One of the more important aspects of driving though an intersection is the probability that a driver stops, a topic that has been studied for some time. This issue originally arose in the context of the dilemma zone and establishing the desired duration for the yellow phase of a traffic light (Gazis, Herman, and Maradudin, 1960; Liu, Herman and Gazis, 1996; Liu, Chang, Tao, Hicks, and Tabacek, 2007; Urbanik and Koonce, 2007; Gates, Noyce, Laracuente, and Nordheim, 2007; Wei, Li, and Ai, 2009; Tong, Yu, Yong-Hong, and Xiao-Guang, 2009).

The probability that a driver stops (or continues) has been modeled as a log-linear function of the approach speed and distance to the intersection, the time to arrival.

(See for example, Demirarslan, Chan, and Vidulich, 1998; Gates, Noyce, Laracuente, and Nordheim, 2007; Rakha, Amer, and El-Shawarby, 2008; Abdel-Aty, Yan, Radwan, and Wang, 2009; Wei, Li, Yi, and Duemmel, 2011.) The reasoning for a log-linear function is as follows.

If p = probability the driver proceeds, then

odds = probability drivers proceed divided by the probability they stop, that is,

odds = $\frac{p}{1-p}$.

In these types of models, what of interest is not the odds, but the log of the odds, which make sense, in part, because the odds are range limited, they cannot be less than zero.

Thus, what matters is the relationship between the log odds and the factors that matter, the distance or time to the intersection and the approach speed.

Accordingly,

$$\log\left(\frac{p}{1-p}\right) = a + b \times distance + c \times speed$$

Raising both sides to the e power

$$\frac{p}{1-p} = e^{a+b \times distance+c \times speed}$$

where:

distance = distance from stop bar when light changes to yellow
speed = speed when light changes to yellow

to make the next steps easier to follow, let $x = e^{a+b \times distance+c \times speed}$, so

$$\frac{p}{1-p} = x$$

then multiplying both sides by (1-p),

$$p = x - xp$$

adding xp to both sides

$$p + xp = x$$

pulling out p on the left side

$$p(1 + x) = x$$

dividing by (1 + x)

$$p = \frac{x}{1 + x}$$

substituting $e^{(a+b \times distance+c \times speed)}$ for x

$$p = \frac{e^{a+b \times distance+c \times speed}}{1 + e^{a+b \times distance+c \times speed}}$$

Figure 2 shows an example of that function from Sheffi and Mahmassani (1981). Notice that increasing speed shifts the function to the right and decreases its slope. Increasing distance has a similar effect.

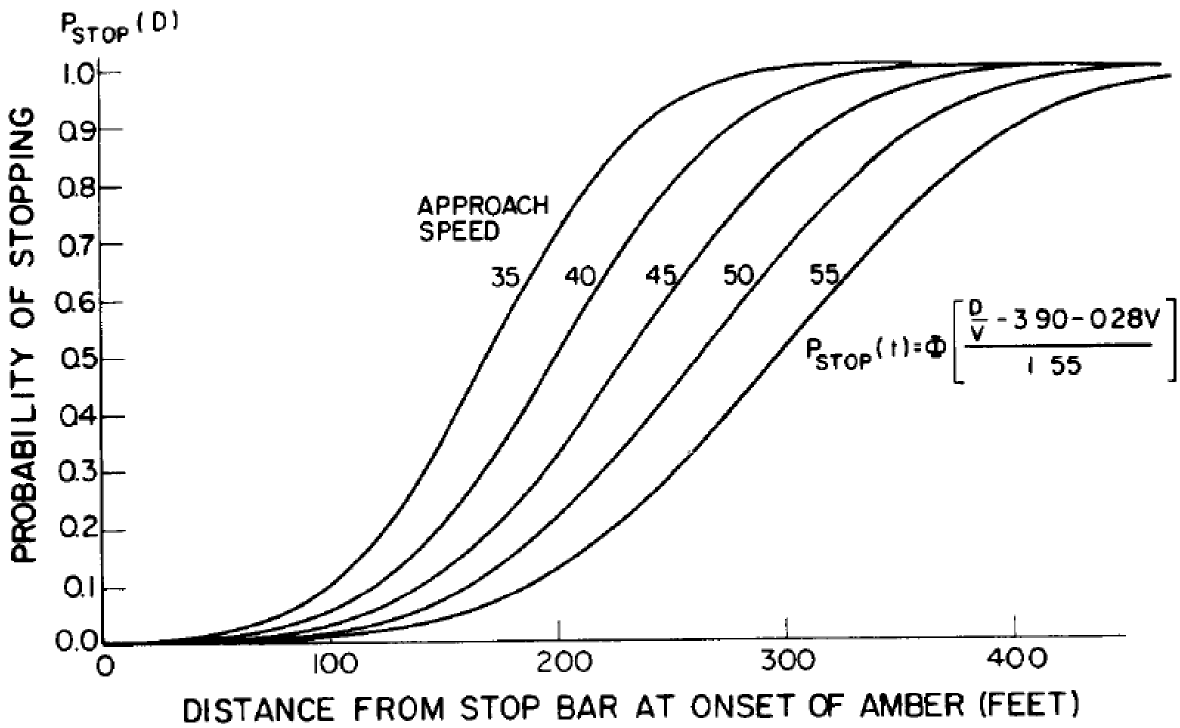


Fig. 3. Dilemma-zone curves for speed dependent critical time model.

Figure 2. Dilemma zone curves
Source: Sheffi and Mahmassani (1981), page 58

Another study that provides a parameterized dilemma zone equation is Papaioannou (2007), who examined drivers in Greece in the middle of a platoon approaching an intersection. That author expressed the probability of stopping (1-p) as

$$1 - p = \frac{1}{1 + e^{-z}}$$

where z = -1.811 + 2.637*Sex + 0.142*V_distance - 0.088*V_speed
or z = -1.594 + 2.766*Sex + 0.147*V_distance - 0.102*V_speed - 0.684*Age
or z = 0.769 + 2.706*Sex + 0.143*V_distance - 0.126*V_speed

V_distance = distance from intersection when signal turns yellow, probably in meters
V_speed = speed from intersection when signal turns yellow, probably in km/hr
Sex = 1 for female, 0 for male
Age is middle aged and young plus old, but the coding values are not given.

Other studies offer other expressions for the equation in the right side of the log odds expression. For example, Gates, Noyce, Laracuente, and Nordheim (2007) examined more than 400 vehicles approaching 4 high-speed and 2 low-speed intersections in Madison, Wisconsin after the light changed to yellow. They estimated the log odds ratio to be:

$$3.170 - 2.041 \times travel\ time(s) + 0.44 \times speed(mi/hr) + 0.804 \times yellow\ interval(s) \\ + 0.662 \times adjacent - 1.396 \times vehicle\ type + 1.006 \times waiting\ vehicle$$

where:

adjacent = 1 for presence of adjacent go-through vehicle(s), 0 for all other cases;
vehicle type = 1 for passenger vehicle, 0 for heavy vehicle; and
waiting vehicle = 1 for absence of side-street vehicle, bike, pedestrian, and opposing left-turning vehicles; 0 for presence of side street vehicle, bike, pedestrian, or opposing left-turning vehicles.

Given these results, this study will develop a probability of stopping function as a function (log-linear) of speed and distance to intersection and other characteristics.

How can the approach speed to a signalized intersection be predicted?

Another critical performance when driving through intersections is the approach speed before the intersection an important element of the Design Consistency Model (DCM) of the Interactive Highway Safety Design Model (IHSDM) developed by the Federal Highway Administration. Perco, Marchionna, and Falconetti (2012) examined the approaches to 30 at-grade intersections and 20 roundabouts in northeastern Italy. The speed limit (not posted) was 90 km/hr. They report the 85th percentile speed for approaching the intersection could be estimated as follows:

$$v_{85}(km/hr) = 0.41 \times L_{int}(m) + 31.15$$

where:

L_{int} = intersection length (in meters).

Liu (2007) observed 1538 vehicles as they approached 2 intersections in Taipei City and Taipei County, both 2-way arterials with 3 lanes in each direction, with speed limits of 40 km/hr and 50 km/hr respectively. Data was collected in rush and non-rush hour periods on weekdays. Liu reports the mean approach speed (km/hr) 10 m before the intersection can be estimated as follows:

$$\begin{aligned}Approach\ speed \\ &= 9.821 + 4.847 \times site + 2.892 \times rush\ hour\ status + 23.702 \times green\ light \\ &+ 10.323 \times amber\ light + 5.25 \times Sedan + 3.148 \times gender + 3.384 \times van \\ &+ 1.662 \times age + 1.02 \times weather - 0.784 \times passenger\end{aligned}$$

where:

site	1 = suburban area, 0 = urban area;
rush hour status	1 = non-rush hour (11am-3pm), 0 = rush hour (8-10am, 3-5pm);
(green light, amber light)	(1,0) = green, (0,1) for amber, (0,0) = red;
(sedan, van)	(1,0) = sedans, (0,1) = vans, (0,0) = trucks;
gender	1 = male, 0 = female;
age	1 = drivers ,< 55 yr old, 0 for drivers > 55 yr old;
weather	1 = sunny day, 0 = cloudy day;
passenger	1 = passenger, 0 = no passenger.

The model shows that traffic light condition contributes more than other variables to the approach speed, whose effects are +24 km/hr for green light and +10 km/hr for amber light comparing to the red light condition. Also, younger (<55 yr) and male drivers had slightly faster approach speeds.

In a National Cooperative Highway Research Project (NCHRP) report, McGee, Moriarty, Eccles, Liu, Gates, and Retting (2012) performed a comprehensive review of guidelines and research for timing yellow and red lights at signalized intersections. Their review emphasized guidelines from the Manual of Uniform Traffic Control Devices and the Institute of Transportation Engineers. In addition, they also report experimental work they conducted from 83 sites distributed across 5 states. They reported that the mean and 85th percentile approach speeds could be predicted as follows:

$$Mean\ approach\ speed\ (mi/hr) = 0.8262 \times speed\ limit\ (mi/hr) + 7.745$$
$$85th\ precentile\ approach\ speed\ (mi/hr) = 0.8846 \times speed\ limit\ (mi/hr) + 11.369$$

They also provided distributions of deceleration rates of first-to-stop vehicles, with the mean value being approximately 10 ft/s^2 (0.31 g).

In this study, the predictions will be not only for the vehicle speed at 10 m before the intersection, but for the speed profile from the traffic light change until approaching the stop line, as the function of distance to the stop line under different traffic light states, yellow light timing, and subject age and gender.

Indecision, Erratic Driving Performance (Use Jerk As an Indicator)

Erratic driving has long been recognized as a potential cause of crashes and thereby an indicator of crash risk. For example, the most recent FARS Analytical Manual (U.S. Department of Transportation, 2014) has attribute codes concerning driver behavior related to erratic driving. They include D24 (related factors – driver level), code 27 - Improper or Erratic Lane Changing and code 36 - Operating the Vehicle in an Erratic, Reckless, Careless or Negligent Manner or Operating at Erratic or Suddenly Changing Speeds, among others. For something to be erratic, it must be unexpected and unstable. Notice that for the codes cited, reference is to both lateral and longitudinal control.

Erratic performance relates to both driver inputs to the vehicle and how the vehicle behaves in response, and may take the form of rapid lane changes, unstable car following, and short following gaps. Unstable signals, by definition, are changing, and that change could be reflected in the first derivative or the second derivative of the signal. For the longitudinal movement of a vehicle, this would imply looking at the derivative of speed, namely acceleration, or the change in (derivative of) acceleration, namely jerk.

In addition, one of the driver's objectives is to make the ride in the vehicle comfortable – to make it smooth -- and for both the driver's and passenger's sake. Quantitatively, this leads the driver to minimize longitudinal jerk (and lateral jerk as well).

For these reasons, and because it has been investigated less often than other measures and could potentially provide new information, this project examined longitudinal jerk in detail.

As jerk is the derivative of acceleration, considering the literature on vehicle acceleration is a reasonable starting point. As an example, af Wåhlberg (2000) examined the statistical relationship between the frequency with which drivers had high acceleration levels and their crash rates, not the details of a particular incident. af Wåhlberg collected longitudinal and lateral g-force data (to the nearest 0.01 g) from 47 local bus drivers in Sweden. He found weak correlations between the lateral g-values and the frequency of crashes, but not longitudinal values. It is unclear if the longitudinal g-force is the mean, maximum, minimum, or standard deviation. af Wåhlberg also notes there were issues related to outliers that may have affected the outcome of the analysis.

In a subsequent study, af Wåhlberg (2004) mentions traffic as factor to be considered as the number of acceleration/deceleration episodes increases as traffic volume increases. In the second study, there were 125 drives from the same bus company, of which various subsamples were used for analysis. The highest correlations found were between longitudinal acceleration and frequency of responsible accidents (and also lateral acceleration and crash frequency), which were on the order of $r=0.31$, quite low.

In a third experiment concerning bus drivers, af Wåhlberg (2006), the correlations between "celeration" (the sum of all lateral and longitudinal speed changes) and crashes appears even less, with the correlations with speed also being less than those for celeration. Thus, as a whole, these studies show that various acceleration is weak but significant predictors of crash frequency.

As an example of more recent research, Wu and Jovanis (2013) examined of relevance are the maximum lateral acceleration difference > 0.4 g and the instantaneous maximum lateral acceleration for a 3 s time window, as well as the longitudinal accelerations to predict crash frequency. Interestingly, they used ROC curves to examine how various thresholds affected the tradeoff between hits, false alarms, and misses. Of these measures, the maximum lateral acceleration difference appears to be the most useful predictor of crashes.

Thus, as greater frequencies of high accelerations are associated with greater crash frequencies, one would suspect the changes needed to achieve them are also linked with crashes. Bagdadi and Várhelyi (2011), in citing Nygård (1999) notes that average braking leads to decelerations of -3.1 m/s^2 (-0.32 g) and average jerks are -3.6 m/s^3, though jerks could be as low as -8.0 m/s^3. For conflict situations brake jerk ranged from -9.9 m/s^3 to -12.6 m/s^3, a noticeably different value.

Bagdadi and Várhelyi (2011) collected speed data at 5 Hz (rather low for this purpose) from 166 drives. After removing spikes and missing data, and using a weighted exponential smoothing function, they examined all the jerk data that were less than 9.9 m/s^3. Their analysis found that for each addition critical jerk increased the expected number of self-reported crashes by 1.13 over a 3-year period, and this seems to be true to a greater degree for women than men.

Following up on that work, Simons-Morton, Zhang, Jackson, and Albert (2012) based on naturalistic driving data from 42 teenage drivers found that the frequency of rapid starts (g>0.35), hard stops (g<=0.45), and hard turns (g>=0.05) were correlated with crashes and near crashes (correlations of 0.28 to 0.76).

To determine which measure of jerk was most indicative of safety-critical events, Bagdadi and Várhelyi (2013) had 2 subjects drive through a series of intersections, either being asked to pull over and stop as quickly as possible or stop immediately as if another vehicle appeared in front of the vehicle without prior notice, a safety-critical event (22 events). They found that peak-to-peak jerk was a better measure for detecting critical events, which in term was better than negative acceleration. Based on the method developed, 35 traffic conflicts with severity measures in the SemiFOT field test data (10 cars, 4 heavy vehicles) were examined. An analysis showed the peak-to-peak jerk data were better able to distinguish between crash events with TTC above and below 1.5 s than negative deceleration. They suggest values of 1.0 g/s (9.8 m/s^3) for the detection of serious conflicts and 1.5 g/s (14.7 m/s^3) for critical values.

Bagdadi (2013) analyzed 637 near-crash events from the 100-car study (109 drivers) in which either the driver or other vehicles maneuvered. About 40 s before the event and 25 s afterwards, sampled at 10 Hz, was analyzed. A second order Savitzky-Golay filter was used to improve the signal to noise ratio. They found that a longitudinal acceleration threshold of 0.6 had a success rate of 54% for identifying crashes, but the success rate was 86% for a jerk threshold of 1.0 g/s (9.8 m/s^3), much better. The success rate varied with the crash scenario, but overall, the success rate for jerk was 1.6 times that for acceleration. Others thresholds could increase the success rate (e.g., 0.8 g/s), with a consequent increase in false alarms.

Zaki, Sayed, and Shaaban (2014) examined video data for vehicle positions for 2 intersections, 1 in North America and 1 in the Middle East that was filtered using a Savitzky-Golay filter and then differentiated to give acceleration values and differentiated again to provide jerk values. The examined 150 manually identified rear-end conflicts for which TTC was calculable. They found that a jerk threshold (8 m/s^3) was much more likely to identify a traffic conflict than a maximum deceleration value, and that in general, the correlation between maximum deceleration and minimum jerk was low (r=0.1).

Thus, collectively, their data suggest that if a single measure is to be used, jerk is likely to indicate a crash event, and the value at or slightly below 1 g/s is an important threshold.

METHODS

Driving simulator

A fixed-base medium-fidelity driving simulator running MiniSim v2.0 software was used for this experiment (http://www.nads-sc.uiowa.edu/minisim/). The MiniSim software suite included the tools to create the virtual environment (Tile Mosaic Tool, TMT), create scenarios (Interactive Scenario Authoring Tool, ISAT), simulate the scenarios (core software), and reduce the data (nDAQTools) for Matlab output.

This driving simulator road scene was presented on 3 24-inch LED monitors (ViewSonic, VG2439m-LED) project to cover a 130-degree forward field (Figure 3) though the actual viewing angle was about 90 degrees. A modified Logitech G27 RT racing wheel set served to collected driver input. The Logitech steering wheel was replaced with a larger steering wheel (12-inch diameter) to make the simulation less game-like. In addition, the foot pedals were modified to remove the clutch pedal (which was not used) and to make the accelerator and brake pedals non-coplanar as is common in passenger cars (Figure 4). See Green, Jeong, and Kang (2014). The instrument cluster was shown on a 16-inch LCD monitor (HANNS-G HL161) in front of the 3 scene monitors (Figure 5). For the experimenter, a 24-inch monitor was set up at a workstation to the side of the simulator to control and supervise the software simulation and calibrate the output of the steering wheel and pedals. The experiment was controlled by a custom-built Intel i7 Sandy Bridge 3.20GHz computer with a GeForce GTX 680 graphics card.

Figure 3. Driving Simulator Set-up

Figure 4. New Foot Pedals

Figure 5. Speedometer/Tachometer Cluster

To simulate engine and ambient sounds, a set of Bose Companion 2 Series II multimedia speakers straddled the monitors on the table in front of the subject supporting the forward scene monitors. To simulate engine and road vibration, 2 AuraSound AST-2B-4 bass shakers were installed underneath the steering wheel support and under driver’s seat (from an unknown Hyundai car). Finally, there was also a tabletop radio tuned to an FM easy listening station that was played during the experiment at low volume. This made the simulation more like on-road driving and made the experiment not as boring.

The simulated urban driving environment consisted of repeated tiles of intersections with traffic lights 200 m (660 ft) apart. The same 2 tiles were used for all intersections, but they were rotated (the entrance path changed) and the street names changed so that subjects would not notice the repetition. There was 1 travel lane in each direction (Figure 6).

Figure 6. Typical Road Scene

Experiment design

The time allocation for this 2 plus-hour experiment is shown in Table 5. In brief, after subjects completed the experiment paperwork, they were introduced to the simulator. This involved having subjects drive through several intersections and stop at several others, with the experimenter at their side providing feedback. Most important was to teach subjects how to accelerate (gently) and brake because the vestibular motion cues were missing. (The simulator was fixed-based.) However, scene vection and the pitching of the scene (in particular, the hood of the car) provided some visual motion cues. Specifically, subjects were asked not to screech the tires, evidence they were driving too aggressively. Braking and accelerating abruptly also made motion discomfort more likely.

Table 5. Time Allocation

#	Task	Time (min)
1	Introduction to experiment (check driver's license, describe experiment to subject, complete consent form (Appendix B), and complete biographical form (Appendix C)	10
2	Check vision (far, near, color)	5-10
3	Introduction to simulator	5
4	Practice driving	5-15
	Collect data for test block 1	25
	Take a break and save data, load in next test block	2
	Collect data for test block 2	25
	Take a break and save data, load in next test block	2
	Collect data for test block 3	35
5	Collect post test (Appendix D) and pay subject (data saved after subject leaves)	10
	Total	**129-139**

Getting subjects to brake smoothly required practice. Subjects were told to apply the brakes gradually, and then just before the vehicle came to a stop, to slowly release the brake and then re-apply it. Braking in real vehicles occurs in this manner. The source of the problem was that real brakes involve pressing against a hydraulic cylinder, so braking force in proportional to the velocity of pedal movement. The simulator brakes have a spring resisting movement, so braking for is proportional to position.

If necessary, subjects were also guided about how to stop at a desired location, either behind the lead vehicle or near a stop line. Because the simulator was a fixed base device, subjects tended to stop unrealistically far away (sometimes multiple vehicle lengths) from a lead vehicle or stop bar, not a few feet. This was easily overcome with practice.

Afterwards, and if the subject did not experience motion discomfort (1 subject was replaced), the subject completed the first test block. There were 3 test blocks. The second test block was essentially the first block in reverse order (except for the first 5 intersections, whose purpose was to get subjects up to speed and accustomed to the scenario and the last 3, whose purpose was to get subject to drive through the last few intersections, which would have no occurred if the simulated world ended at the last intersection). The third block concerned driving a highway with curves that was for another project. Details concerning that block and the findings from it will be described elsewhere.

In the first 2 test blocks, subjects were asked to drive at approximately 35 mi/hr and follow a lead vehicle approximately 200 ft ahead. They were to comply with traffic signals, and most importantly, not collide with other vehicles. The lead vehicle was driving between 0-40 mi/hr, attempting to maintain a gap of 200 feet, accelerating and deceleration up to ±4 m/s^2 (0.4 g) to maintain it. The lead vehicle was provided to make the simulation more like the real world and to make it less likely subjects would drive well above the posted speed limit. Being asked to follow the vehicle also meant they were less likely to inadvertently turn and drive out of the simulated world.

As was noted elsewhere, intersections were every 200 m (660 ft), and all were signalized. The signal was green 36% of the time, red 11% of the time, and yellow 53% of the time. Red signals were timed so the lead vehicle would stop, and the subject would therefore as well. When a yellow signal appeared, sometimes other traffic was presented at each intersection – to the left, right, or from the opposing direction. Only 1 vehicle would appear from each direction. These vehicles would go straight, turn left/right with/without turning signals on, or approach the intersection and stop. There were also a few cases where crossing vehicles violated traffic rules by running red lights and crossed or turned into the subject's path. What happened at each intersection is described in detail in the next section. The goal was to make the decision both complex and real – the decision to run a yellow light depended not only on the traffic light state, but what other vehicles did or could do.

Further, there was a vehicle driving approximately 150 ft behind subject's vehicle, which could be seen in the (virtual) rear mirror and obeyed traffic signals. If subjects ran yellow light, the vehicle behind would stop before the intersection and the distance to subject's vehicle increased. In that case, the vehicle behind would slowly stop to leave the path and a new following vehicle would appear from the closest intersection behind, into the path the subject just passed so there was always a following vehicle close by. Having a vehicle behind made the driving scenario more realistic, and for some subjects, the distance to the vehicle behind could influence their braking behavior to avoid a rear-end collision.

The experiment ended with subjects completing a post-test form that asked about how often they drove through signalized intersections and questions related to driving on highways. Subjects were paid US $50 for approximately 2 plus hours of their time.

The complete instructions are in Appendix A.

The challenge in designing this experiment was making the scenarios appear realistic and reasonable, including all of the variables of interest, and collecting all of the data in a single session. That time constraint meant that collecting all combinations of the factors of interest was not feasible, and considerable thought was required to develop an appropriate experimental design.

Three scenario-related factors were varied in this experiment: 3 traffic light states (green, yellow, red), 3 time-to-intersection durations at which the traffic signal changed to (2.8 s, 3.5 s, 4.2 s), and 11 combinations of other vehicle maneuvers (no conflict, plus 10 different conflict types). The time-to-intersection durations were selected based on published data for fixed signal timing as well as experience with this and other simulators where subjects (1) were unlikely to stop (2.8 s), (2) may or may not stop (3.5 s), and (3) likely to stop (4.2 s). Thus, subjects could not anticipate if or when the traffic signal would change and what surrounding traffic would do, as in real driving. Table 6 shows all of the scenarios explored sorted by what others vehicles were supposed to do. The subject always drove straight to simplify planning of the experiment.

This experiment was not a full-factorial design because (1) there were far too many scenarios to examine, (2) some scenarios were very rare in the real world (e.g. red light for vehicles from the left and right, but they both ran the light; 2 other vehicles crash into each other which the subject is to avoid), or (3) some scenarios did not make sense (e.g. all vehicles stopped).

The combinations of the conditions are shown in Table 7, which has 61 trials to be tested, plus 4 green-light and 1 red-light conditions in the beginning (for practice), and 3 green-light (so that the subject does not stop at the last intersection of interest) and a stop sign at the end of the world. Ten of the 61 trials had potential conflicts between the subject's vehicle and 1 other vehicle, from left, right, or opposing direction. Figures 7 and 8 show some examples. One could suggest that there should have been more intersections with conflicts so more data could be collected. However, if there are too many potential conflicts, then subjects do not treat the experiment as being realistic and do not drive in a normal manner, probably driving very slowly. The frequency of occurrence of various crossing path crash types in those 10 trials was distributed to reflect NHTSA data (Najm, Koopmann, and Smith, 2001) on crashes of those types – 4 for LTAP/OD, 2 for SCP and RTIP, and 1 for LTIP and LTAP/LD (Table 8). Some cases for yellow-light state only had the middle level (3.5 s for combinations 28, 33, 50, 55 in Table 3) because they were relatively rare and only 1 trial was needed.

Appendix E contains the complete sequence of trials. Each subject responded to 2 blocks of trials, with the order of the second block being the reverse of the first except for a few start up and added end trials that were not included in the analysis. The start up trials served to get the subject up to speed. The added end trials assure subjects drove through the final test intersections of interest. Had the simulated world ended at those intersections, they would have not driven through them.

Table 6. Maneuver Combinations Explored

Variable		Condition (*C* = Conflict; *V* = Violation)	Description
Vehicle maneuver	Left	go straight	green light for left vehicle and it went straight
		stop	red light for the left vehicle and it stopped
		signal left	red light for the left vehicle and it stopped with left turning signal on, waiting until the traffic changed to green
		turn right	red light for the left vehicle and it turned right
		turn left *(C, V)*	red light for the left vehicle, but it turned left into subject's driving path when the subject is just entering the intersection
		go *(C, V)*	red light for the left vehicle, but it ran the red light and went straight
	Right	go straight	green light for right vehicle and it went straight
		stop	red light for the right vehicle and it stopped
		signal left	red light for the right vehicle and it stopped with left turning signal on, waiting until the traffic changed to green
		signal right	red light for the right vehicle and it stopped with right turning signal on, waiting until subject's vehicle passed
		turn left *(C, V)*	red light for the right vehicle, but it turned left into opposing vehicle's driving path, crossing subject's driving path
		turn right *(C)*	red light for the right vehicle, but it turned right into subject's driving path
		go *(C, V)*	red light for the right vehicle, but it ran the red light and went straight
	Opposing	go straight	green or yellow light for the opposing vehicle and it went straight
		slow to avoid crash	green or yellow light for the opposing vehicle, but it slowed down if the left/right vehicle turned into its driving path or ran the red light
		signal left	green light for the opposing vehicle and it stopped with left turning signal on, waiting until subject's vehicle passed
		turn right	green or yellow light for the opposing vehicle and it turned right
		turn left *(C, V)*	green light for the opposing vehicle and it stopped with left turning signal on, but turned left in between lead and subject's vehicle

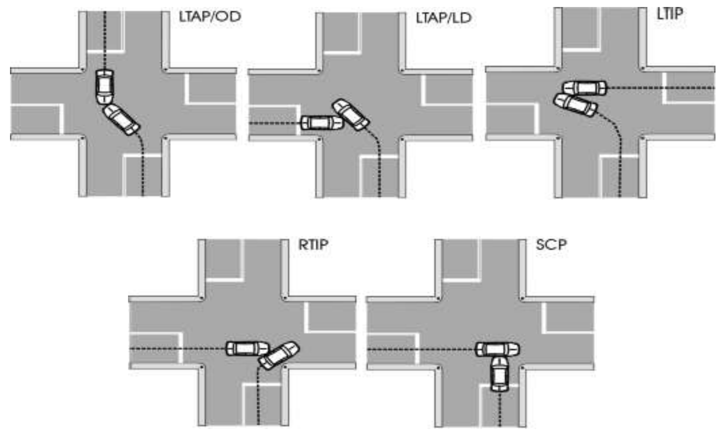
Table 7. Event Numbers Used to Code Data

Vehicle maneuver			Traffic light state					Conflict type
Left vehicle	Opposing vehicle	Right vehicle	Green	Red	Yellow			
					4.2 s	3.5 s	2.8 s	
go straight	slow down	go straight	-	1-7	-	-	-	
stop	go straight (run yellow light if there is)	stop	8-21	-	22-23	24-25	26-27	
Maneuver by vehicle from left								
go straight (run red light)	go straight (run yellow light)	stop	-	-	-	28	-	SCP
stop, left-turn signal on	go straight (run yellow light if there is)	stop	29	-	30	31	32	
turn left (run red light)	go straight (run yellow light)	stop	-	-	-	33	-	LTIP
turn right	go straight	stop	34	-	35	36	37	
Maneuver by vehicle from opposing direction								
stop	stop, left-turn signal on	stop	38	-	39	40	41	
stop	turn left (run yellow light if there is)	stop	42	-	43	44	45	LTAP/OD
stop	turn right	stop	46	-	47	48	49	
Maneuver by vehicle from right								
stop	go straight (run yellow light)	go straight (run red light)	-	-	-	50	-	SCP
stop	go straight (run yellow light if there is)	stop, left-turn signal on	51	-	52	53	54	
stop	go straight (run yellow light)	turn left (run red light)	-	-	-	55	-	LTAP/LD
stop	go straight	stop, right-turn signal on	56	-	57	58	59	
stop	go straight (run yellow light if there is)	turn right	60	-	-	61	-	RTIP

Figure 7. Vehicle from Right Turns (LTAP/LD) in Front of Subject at Yellow Light

Figure 8. Vehicle from Left Turns (LTIP) in Front of Subject at Green Light

Table 8. Crossing Path Crash Scenarios

Code	Scenario	Illustration
LTAP/OD	Left Turn Across Path – Opposite Direction	
LTAP/LD	Left Turn Across Path – Lateral Direction	
LTIP	Left Turn Into Path	
RTIP	Right Turn Into Path	
SCP	Straight Crossing Path	

Modified from: Najm, Koopmann, and Smith (2001)

Dependent variables and data collection periods

Dependent measures were collected at 60 Hz, as shown in Table 9. They were used to verify that vehicles maneuvered as intended and answer the research questions posed. The number of data points collected at any given time depended upon the number of other vehicles nearby. Time-to-collision (TTC) was computed using the raw data as the simulator calculation of TTC was sometimes incorrect. As shown in the table that follows, many variables (shown in bold) were also sometimes incorrect. Table 10 shows which measures were collected for each vehicle.

Table 9. List of Dependent Variables

Category		Variable	Unit	Definition	SAE J2944*
Collected by simulator	longitudinal	longitudinal position	ft	objects' y coordination in the simulated world	-
		speed	mi/hr	objects' speed	-
	lateral	lateral lane position	ft	distance from the midpoint of the driven lane to the center of the vehicle	10.1.1 Option A
	control	steering wheel angle	0-180 degree	steering wheel angle	-
		brake force	0-100 %	force applied by the driver's foot to the brake pedal	-
		throttle position	0-100 %	Normalized value 100 indicating when driver fully stepping on the accelerator pedal,	

				whereas 0 indicating when taking the foot off the pedal	
	orientation	vehicle heading	degree	the angle between vehicle's heading direction and the lane markings	-
Calculated from data collected	longitudinal	**distance to intersection center***	ft	distance between vehicle's front bumper to the center of the closet intersection to the front	-
		distance to stop line	ft	distance between vehicle's front bumper to the front edge of the closet stop line in the front	-
		gap	ft	distance (0-200 ft) between subject's vehicle's front bumper to lead vehicle's rear bumper	8.1.1
		time-to-collision (TTC)	s	time required for subject's vehicle to strike the lead vehicle	8.2.1 Option B
		longitudinal speed	mi/hr	vehicle speed on the longitudinal axis	-
		longitudinal acceleration	ft/s^2	vehicle acceleration along the longitudinal axis	-
		jerk	ft/s^2 per 1/60 s	vehicle jerk along the longitudinal axis	
	lateral	**lateral speed**	mph	vehicle speed along the lateral axis	-
		lateral acceleration	ft/s^2	vehicle acceleration along the lateral axis	-
	control	**turn signal on/off**	boolean	state of the vehicle's turn signal	-
	decision	**pass or not**	boolean	state of vehicle's	-

*SAE J2944 = were in that recommended practice where the variable is defined.
***Bold**: Variables that are incorrectly calculated by the simulator and were recalculated using the x, y values.

Table 10. Measures Collected for Each Vehicle

Category	Measure	Vehicle				
		Subject	Lead	Left	Right	Opposing
longitudinal	longitudinal position	x	x	x	x	x
	longitudinal speed	x	x	x	x	x
	longitudinal acceleration	x	x	x	x	x
	distance to center	x	x			
	distance to stop line	x	x			
	gap	x				
	time-to-collision	x				
lateral	lateral position	x	x	x	x	x
	lateral speed	x	x	x	x	x
	lateral acceleration	x	x	x	x	x
	distance to center			x	x	
	distance to stop line			x	x	
control	steering wheel angle	x				
	brake force	x				
	acceleration position	x				
	turn signal on/off	x	x	x	x	x
orientation	vehicle heading	x	x	x	x	x

Participants

Twenty-four licensed drivers, divided into 4 groups equal in age (18-30 yr, over 65 yr) and gender participated in this experiment. Subjects were recruited for this experiment using a Craigslist advertisement (Appendix F) and by following up with subjects from prior non-simulator UMTRI Driver Interface Group studies with subjects who had expressed interest in participating in future studies (Appendix G). The mean ages for young and older subjects were 22 and 72, driving 14,000 miles annually. They reported they passed through 11 intersections with traffic signals and 10 intersections with stop or yield signs on an average day.

RESULTS

In the design of this experiment, there were 2,928 intersection encounters (trials = 61 intersections x 24 subjects x 2 blocks). However, data for 4 trials was lost because of a program flaw or because subjects drove in an unusual manner not captured by the software. The 4 lost trials were all when a traffic light was changing to yellow, 2 for the 2.8 s timing (1 older male and 1 older female), 1 for 3.5 s (1 older male), and 1 for 4.2 s (1 young male).

Q1. How often did crashes occur and for which scenarios?

The goal of this experiment was to lay the groundwork for follow-on studies concerning crash-warning systems. Thus, it was important that there be crashes or at least crash provocative situations. In this experiment, there were 4 crashes among the 2,924 trials encountered by all subjects (61 intersections x 24 subjects x 2 blocks), which was very rare (Table 11). Interestingly, 3 of the 4 crashes involved the following vehicle colliding with the subject vehicle when the subject braked aggressively in response to a traffic light that changed from green to yellow then to red. This experiment was conducted before the car-following algorithm for the vehicle behind was completed and if these crashes would have occurred for real vehicles is unknown. The algorithm needs further development.

Table 11. Descriptions of the 4 Crashes

Subject	Intersection	Traffic light	Conflict	Crash with
Young male	39	yellow	n/a	vehicle behind
Young male	62	green	LTAP/OD	vehicle opposing
Old female	24	yellow	n/a	vehicle behind
Old female	39	yellow	n/a	vehicle behind

The only trial in which a collision otherwise occurred was a young male subject at an intersection with green light and a LTAP/OD conflict. The data showed that the subject pushed the brake at 167 ms before the collision, and failed to avoid it. Subject’s vehicle hit on the right side of the opposing vehicle at 46 mi/hr.

Thus, there were very few crashes, which suggest making some changes to increase the number of crashes and allow the functionality of a crash warning system to be explored.

Q2. How Did Drivers Respond to Traffic Signals in This Experiment?

To understand when and why crashes occur or do not occur, a more detailed examination of the data is needed. Table 12 shows the number of encounters by traffic light state, pass or not, and the intersection with/without conflict. The goal was to have durations that led to drivers (1) not stopping very often, (2) about half of the time, and (3) most of the time. That was generally achieved, but the probability of stopping was slightly greater overall than desired. As shown in Table 13, 3 subjects selected to stop before every intersection (OM1, OM3, and OF2), all older ones (and highlighted in bold in the table). Ignoring these 3 subjects, the probabilities to stop at the yellow-light times of 2.8 s, 3.5 s, and 4.2 s become 0.31, 0.70, and 0.88, which are still high. For yellow-light timing of 3.5 s, 19 subjects stopped with the probabilities more than 0.5. However, keep in mind that as conflicts occurred most often during yellow light encounters, having subject continue to encounter threat was desired from the experiment design perspective. Further, given the apparent age differences, 1 option in future studies would be to have different yellow light timing for younger and older subjects so that all older subjects experience yellow light conflicts. However, that approach significantly complicates the analysis and would age comparisons very difficult because the test conditions would not be the same.

Table 12. Number of Encounters of This Experiment

Light State	**With conflict**	**Without conflict**	**Total**	**Probability of stopping**
Green	96	960	1056	-
Yellow 2.8 s - run	25	235	260	0.40
Yellow 2.8 s - stop	22	148	170	
Yellow 3.5 s - run	68	108	176	0.74
Yellow 3.5 s - stop	186	309	495	
Yellow 4.2 s - run	2	42	44	0.90
Yellow 4.2 s - stop	46	341	387	
Total	445	2143	2588	-
Red			336	
TOTAL			2924	

Table 13. Probability of Stopping by Individual

Age	ID	2.8 s			3.5 s			4.2 s		
		Run	**Stop**	**P(stop)**	**Run**	**Stop**	**P(stop)**	**Run**	**Stop**	**P(stop)**
Young (M= male F= female)	YM1	15	3	0.17	4	24	0.86	0	18	1.00
	YM2	8	10	0.56	2	26	0.93	1	17	0.94
	YM3	5	13	0.72	1	27	0.96	0	18	1.00
	YM4	18	0	0.00	27	1	0.04	4	14	0.78
	YM5	18	0	0.00	18	10	0.36	2	15	0.88
	YM6	17	1	0.06	11	17	0.61	0	18	1.00
	YF1	18	0	0.00	19	9	0.32	9	9	0.50
	YF2	18	0	0.00	3	25	0.89	0	18	1.00
	YF3	17	1	0.06	13	15	0.54	3	15	0.83
	YF4	7	11	0.61	1	27	0.96	0	18	1.00
	YF5	9	9	0.50	3	25	0.89	1	17	0.94
	YF6	13	5	0.28	0	28	1.00	0	18	1.00
Older	**OM1**	**0**	**18**	**1.00**	**0**	**28**	**1.00**	**0**	**18**	**1.00**
	OM2	14	3	0.17	9	18	0.67	1	17	0.94
	OM3	**0**	**18**	**1.00**	**0**	**28**	**1.00**	**0**	**18**	**1.00**
	OM4	18	0	0.00	20	8	0.29	14	4	0.22
	OM5	3	15	0.83	0	28	1.00	0	18	1.00
	OM6	14	4	0.22	9	19	0.68	1	17	0.94
	OF1	9	9	0.50	6	22	0.79	0	18	1.00
	OF2	**0**	**18**	**1.00**	**0**	**28**	**1.00**	**0**	**18**	**1.00**
	OF3	5	12	0.71	5	23	0.82	1	17	0.94
	OF4	15	3	0.17	15	13	0.46	5	13	0.72
	OF5	16	2	0.11	6	22	0.79	1	17	0.94
	OF6	3	15	0.83	4	24	0.86	1	17	0.94

Of particular interest was how subjects responded to yellow lights (Figure 9). For these 1,532 encounters (430 + 671 + 431), subjects could (1) run a red light (approaching and passing the stop line when the traffic light was red), (2) run a yellow light (approaching and passing the stop line when the traffic light was yellow), (3) stop beyond the stop line, and (4) stop before the stop line. As was noted previously, the probability of stopping for the traffic light was 0.40, 0.74, and 0.90, for the yellow light timing of 2.8, 3.5, and, 4.2 s respectively. If subjects decided to pass the intersection when the traffic light state changed to yellow at 3.5 s and 4.2 s before the stop line, they would run the red light, which was a violation (175/176=99% for 3.5 s; 44/44=100% for 4.2 s). They could have passed through the intersection with a yellow light if they had accelerated sharply. However, doing so would increase the probability of a crash with another vehicle if that vehicle drove in an unexpected manner.

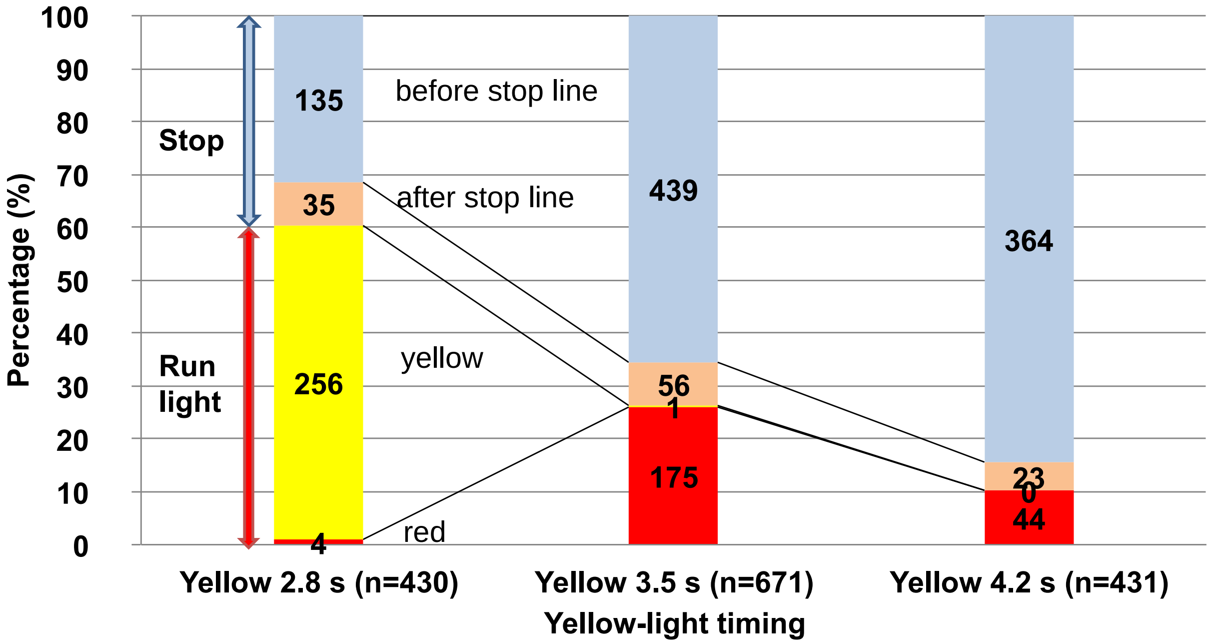


Figure 9. Did Subjects Stop or Run a Yellow Light (for 3 Yellow Light Durations)

Light timing had a significant effect on the probability a subject stopped ($\mathbf{X}^2$=270.37, p<0.001) as did subject age ($\mathbf{X}^2$=12.12, p<0.001), but not subject gender ($\mathbf{X}^2$=0.97, p<=0.32). As shown in Figure 10, age differences were most pronounced for the 2.8 s timing. When the traffic light changed to yellow at 2.8 s before the stop line, young subjects were half as likely (53/216 = 0.25) to stop for the light, than older subjects (117/216 = 0.54). No difference was found for timing of 4.2 and 3.5 s.

In terms of the interactions between factors, the age x yellow-light timing was significant ($\mathbf{X}^2$=18.31, p<0.001). When the yellow light timing was 2.8 s, young subjects had smaller probability than older ones of stopping (0.25 vs. 0.55), larger than the differences at 3.5 s (0.70 vs. 0.78) and 4.2 s (0.91 vs. 0.89).

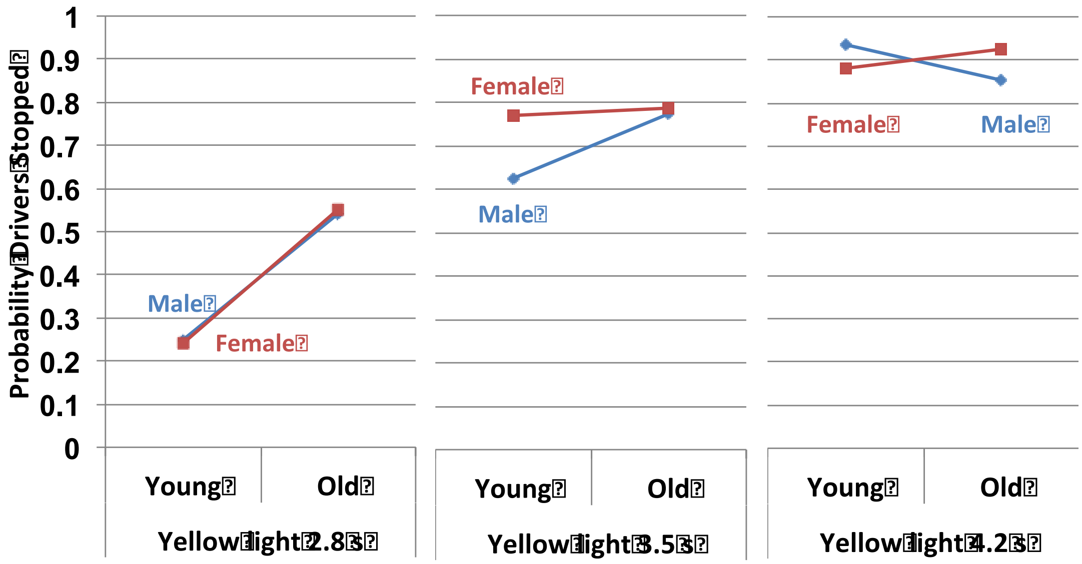


Figure 10. The Probability Drivers Stopped for the Yellow Light

Q3. How did the probability each subject stopped an intersection vary as a function of speed and/or gap to stop line, yellow-light timing, throttle and brake pedal positions, and subject age/gender, when the light just changed to yellow?

Stepwise logistic regression was used to predict the probability of stopping using speed, pedal position, and distance to stop line when the traffic light just changed to yellow. Interestingly, speed was not a significant factor ($\mathbf{X}^2$=0.03, p=0.87), probably because the range of speeds was small.

The logistic regression shown below accounted for 19% of the variance of the dependent measure, which is quite low.

$$P(stop) = \frac{e^x}{1 + e^x}$$

where:

$$x = -5.84 - 0.01 \times gap\ to\ stop\ line + 1.49 \times yellow\ light\ timing - 2.93 \times pedal\ position + 0.29 \times age + 0.15 \times gender$$

and:

gap to stop line [ft; negative value = location before stop line];
yellow light timing = 2.8, 3.5, or 4.2 [s].
pedal position is between ±1;
age = 0 for younger, 1 for older
gender = 0 for male; 1 for female;

To understand the role of individual differences, logistic regression models were computed for each subject using the factors of distance to stop line, yellow light timing, and, pedal position, for which the R^2 values are shown in Table 14. Note that even when partitioned in this manner, the R^2 were not extremely high, but they were larger than the subject means. Furthermore, the only consistently significant factor was distance to stop line. In summary, the probability of stopping in this experiment could not be accurately predicted using the measures available. The distance to stop line was typically the best predictor, but only for some subjects.

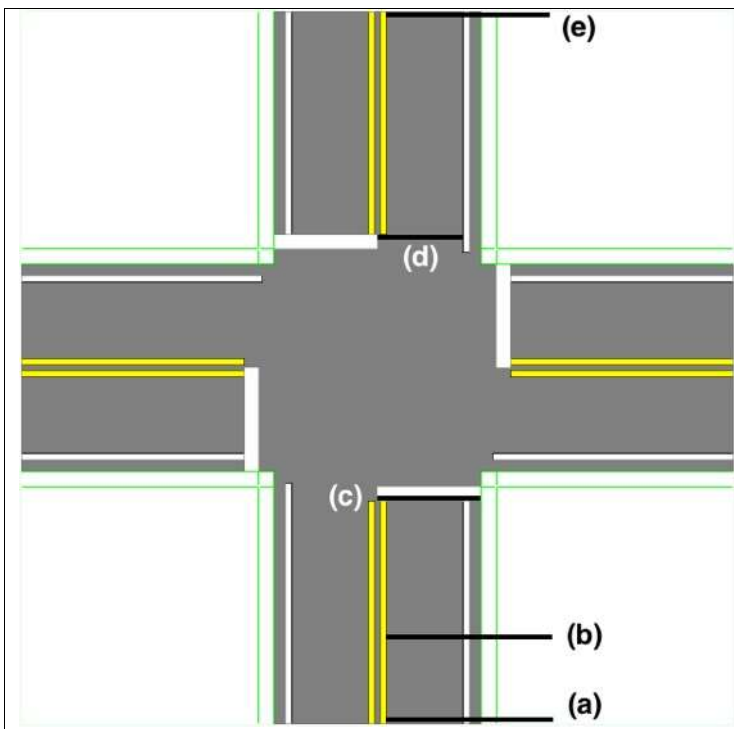
Table 14. R^2 for Logistic Regression Models by Subject

Subject #	Young male	Young female	Older male	Older female
1	0.58	0.18	***X**	0.32
2	0.39	0.77	0.31	**X**
3	0.47	0.29	**X**	0.14
4	0.69	0.39	0.11	0.31
5	0.48	0.38	0.58	0.41
6	0.49	0.67	0.37	0.07

*X=subject stopped for every intersection, no prediction can be made

Q4. What was the speed vs. distance profile for approaching each intersection?

The intersections with red-light conditions were excluded because subjects were forced to slow down by the lead vehicle and their behavior was less interesting for the issues being examined. Therefore, the remaining scenarios were divided into 3 groups, (1) green light, (2) yellow light and subjects passed, and (3) yellow light and subjects did not pass. Three time periods were examined for each intersection encounter (1) approaching, (2) going through, (3) and departing. Figure 11 shows the intersection landmarks used to determine those time periods, as defined in Table 15. The approaching scenarios are included in the results section of this report. The going through and departing analyses are in Appendix H.



(a) beginning of the tile (100 m from the center of the intersection)
(b) when the traffic light changed to yellow
(c) when subject's vehicle's front bumper approached the edge of the stop line (enter the intersection) – 57 ft from the center of the intersection, 45 ft from the edge of the intersecting street
(d) when subject's vehicle's rear bumper approached the rear edge of the stop line at the opposing direction (depart the intersection)
(e) end of the tile

Figure 11. Intersection Data Collection Cut-Point

Table 15. Timing Periods

Data Collection Period	Approaching	Going Through	Departing
Green	(a) – (c)	(c) – (d)	(d) – (e)
Yellow – no pass	(b) – stop*	(c) – (d)	(d) – (e)
Yellow – pass	(b) – (c)	(c) – (d)	(d) – (e)
Red	N/A		

*stop - when the speed of subject's vehicle just decreased to 0.

When approaching intersections, distances were calculated from subject vehicle's front bumper to the front edge of the stop line. When departing intersections (covered in the appendix), distances were calculated from rear edge of the stop line to the rear bumper. This was done so gaps could be determined. Going through intersections is a more complex case because subjects approached the center of the intersection and then departed. For ease of calculation, the distance was calculated from subject vehicle's front bumper to the center of intersection when approaching the center, and from the center of intersection to the rear bumper when departing the center. During the time subject vehicle physically overlapped the center of intersection, the distance was counted as 0. Therefore, sometimes the vehicle speed changed while the distance to the intersection center remained 0.

Approaching Green light

How subjects approached each intersection should not only be affected by what happened during that approach but also their experience in their approach to other intersections in similar circumstances. Table 16 identifies those circumstances. There were 22 intersections (scenarios) for each of the 2 blocks with a green traffic light (44 total). To save the space and avoid the confusion, intersections are identified using a code as noted below the table.

Table 16. Vehicle Maneuvers for the Green Light Intersections

Conflict	# of Intersections	Intersection #	From Direction of Other Vehicles		
			Left	Opposing	Right
no	14	Int-8 to 21	stop	go straight	stop
	1	Int-29	turn signal on	go straight	stop
	1	Int-34	turn right on red	go straight	stop
	1	Int-38	stop	turn signal on	stop
	1	Int-46	stop	turn right	stop
	2	Int-51 & 56	stop	go straight	turn signal on
	20	SUBTOTAL			
yes	1	Int-42	stop	turn left	stop

	1	Int-60	stop	go straight	turn right
	2	SUBTOTAL			

Note: Intersection coding: B1-Int-20 is the 20th intersection of block 1

Figure 12 shows speed of the subject vehicle as a function of the distance of the front bumper to the stop line when approaching intersections with green lights without a conflict. In theory, the speed should not change very much (usually between 30-40 mi/hr) because the traffic was stable and the traffic light remained green. However, drivers slowed down when approaching some intersections, in particular B1-Int-8, B1-Int-11, B1-Int-15, B2-Int-9, and B2-Int-10. When traffic was not stable, the situation was quite different. Appendix H1 shows that almost all subjects braked at the intersections B1-Int-15 and B2-Int-9 where the lead vehicle was replaced by the vehicles turning into subjects' path (RTIP and LTIP) and the gap was reduced. Otherwise, no braking occurred except for 2 subjects (1 young and 1 old female) who braked under non-risky circumstances at B1-Int-8 and B2-Int-10.

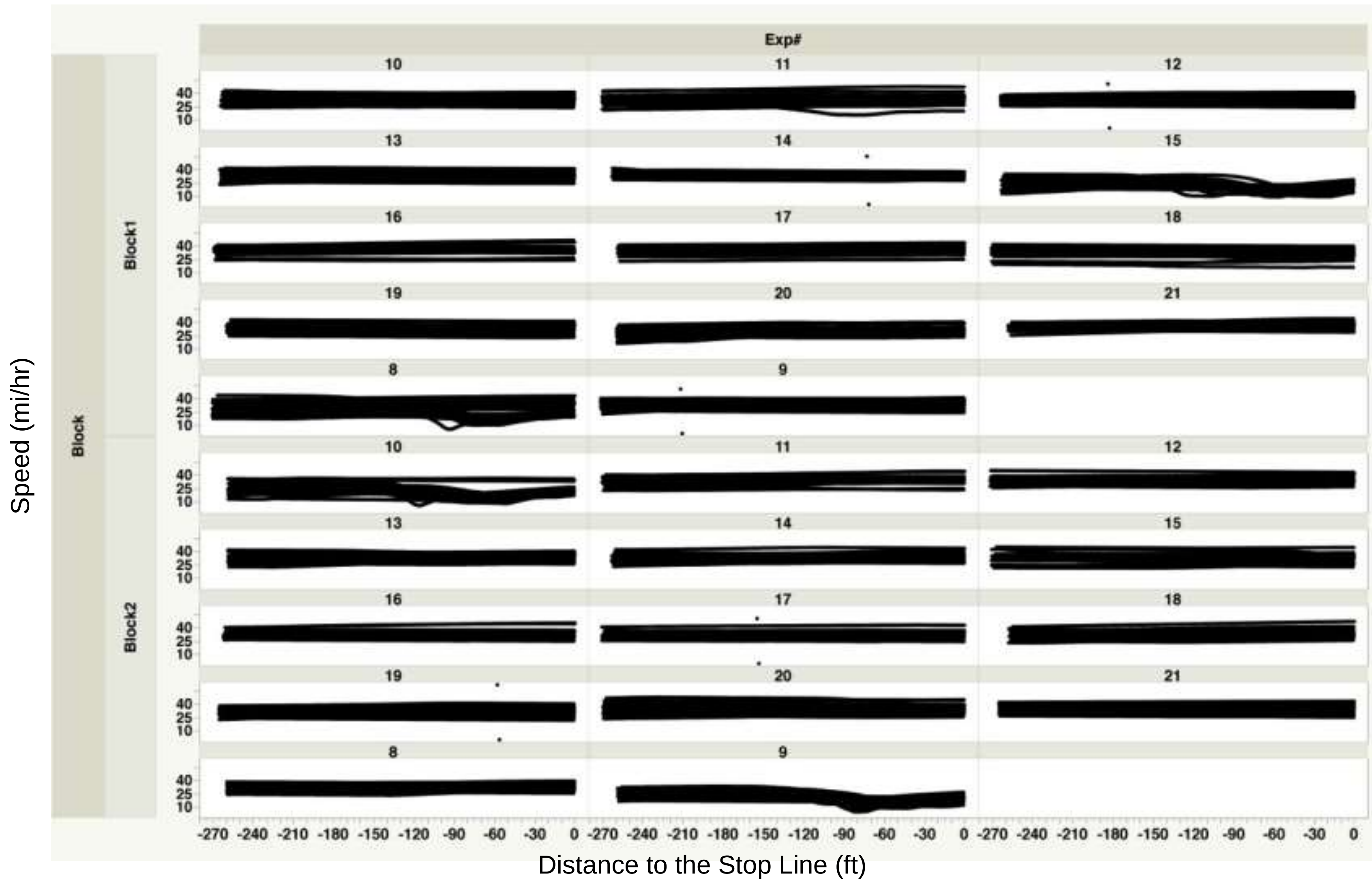


Figure 12. Vehicle Speed as a Function of Distance to the Stop Line for Each of the 24 Subjects by 2 Blocks (Green Light, No Conflict, When Approaching Intersections)

Note: The distance was negative when subjects were approaching the stop line.

For 6 other intersections (Int-29, 34, 38, and 46, 51, and 56) where there was neither unimpeded flow nor conflicts. However, at several of those intersections, there were potential precursors to crashes, namely other vehicles stopped at the intersection with their turn signals on their expected path. If they violated the traffic signal, it would put them in conflict with the subject. Noting that potential, some subjects slowed down, such as at B1-Int-34 and B2-Int-46 (Figure 13). Only 2 subjects (1 old male, 1 old female) slowed down substantially.

In fact, there were 2 scenarios subject vehicles violated or at least stretched the rules of safe driving and turned in front of subjects (LTAP/OD (Int-42) and RTIP (Int-60)). This reflects real world behavior where other drivers do not always drive safely. Figure 12 shows subjects' control of speed when approaching these 2 intersections. At Int-42, subjects slightly slowed down at 10 times out of the 48 opportunities (24 subjects x 2 blocks). In addition, there was 1 instance of more forceful braking (by an older female). For this intersection scenario, the opposing vehicle finished the left turn before subject vehicle approached the stop line, so it was not so close (Appendix H2a) and subjects did not need to slow down to avoid the incident.

For Int-60 of RTIP, at 13 of the 48 intersections subjects slowed down and braking was more forceful than for LTAP/OD (Figure 14). As shown in Appendix H2b, however, even though subjects saw the merging of the vehicle from the right before approaching the stop line, only some slowed down. Subject responses were not consistent.

The analyses for when going through and departing from intersections with green light are shown in Appendices H3 - H7.

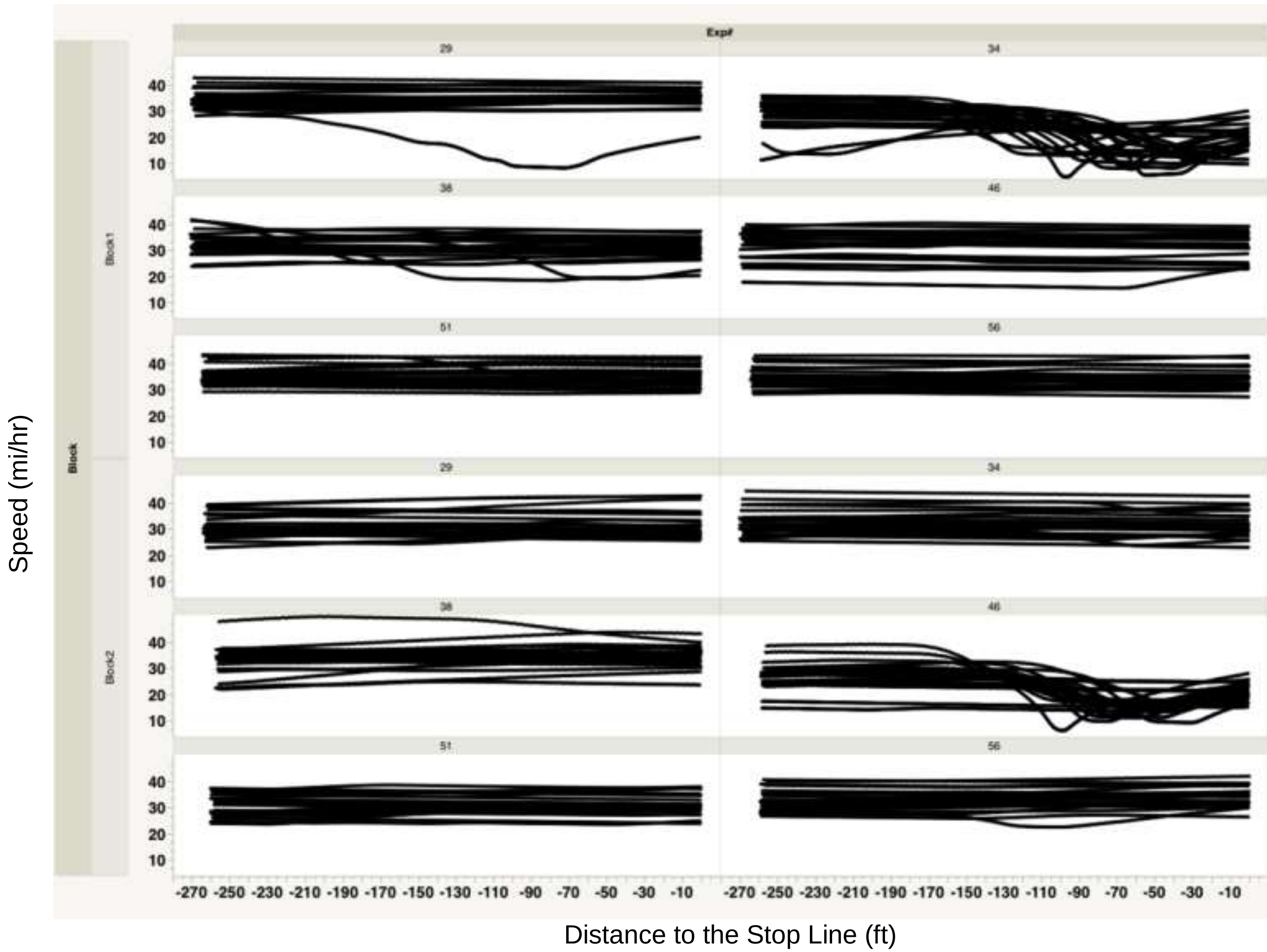


Figure 13. Vehicle Speed as a Function of Distance to the Stop Line for Each of the 24 Subjects by 2 Blocks (Green Light, No Conflict, Other Traffic Had Maneuvers, When Approaching Intersections)

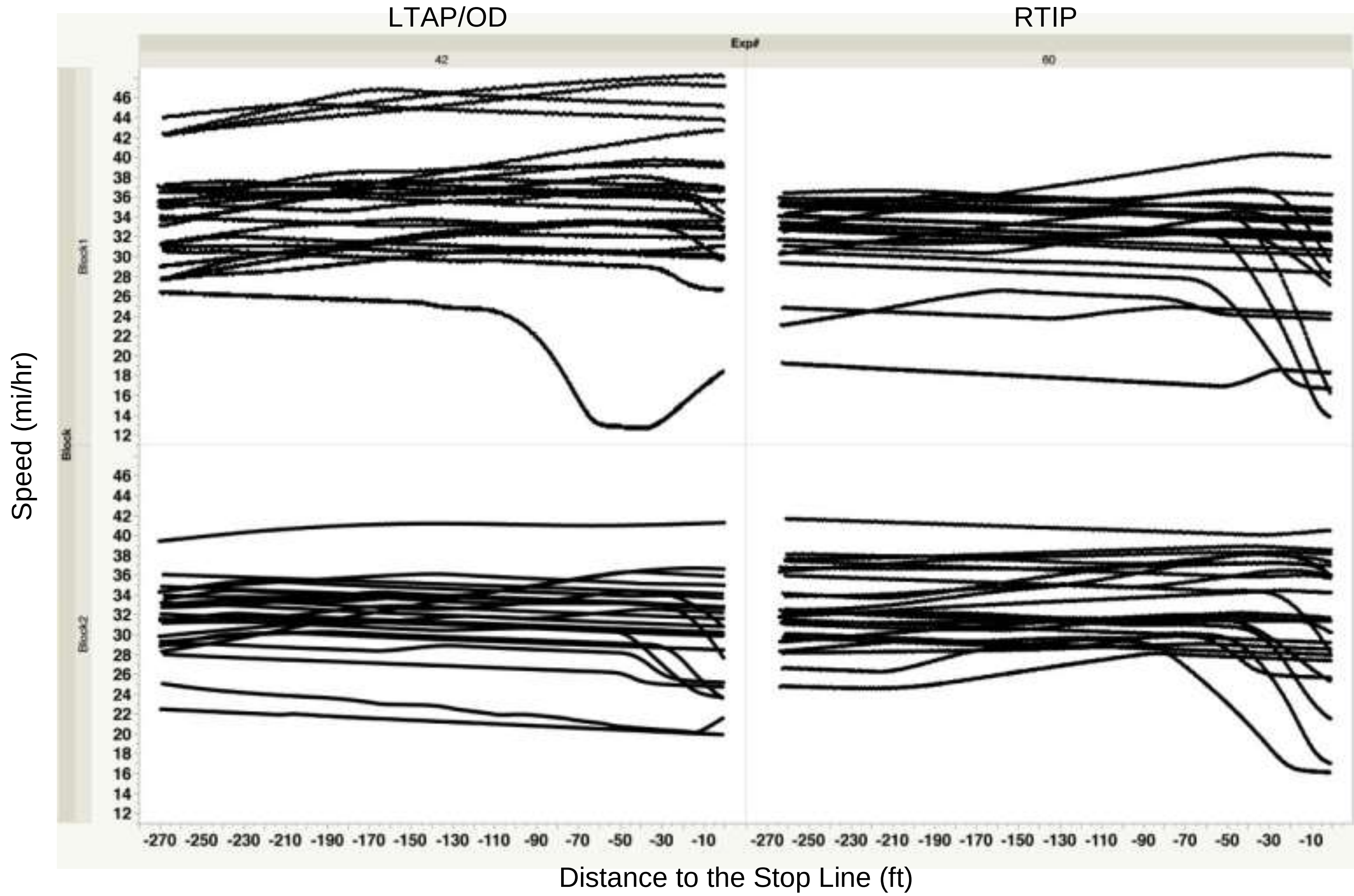


Figure 14. Vehicle Speed at Different Distances to the Stop Line, When Approaching the Intersection with a Green Light (Scenarios with Conflicts)

Approaching Yellow Light - Running Light

As a reminder, there were 64 intersections (32 intersections/block x 2 blocks) where each subject experienced a traffic light changed to yellow upon approach, occurring when the front bumper of subject vehicle was 2.8 s, 3.5 s, or 4.2 s from the front edge of the stop line. Thus, the faster the subject drove, the farther before the stop line the light would change. In total, subjects drove through 480 of the 1,532 intersections when traffic light changed to yellow.

Appendix H8 shows how the speed changed when subjects decided to run the yellow light from different distances to the stop line. Once the decision was made, vehicle speed either remained constant or increased prior to passing through the intersection. Appendix H9 shows the intersections at which other vehicles maneuvered. These maneuvers affected subject behavior for 3 encounters, 2 by an older male (opposing vehicle with left-turn signal on) and 1 by an older female (left vehicle with left-turn signal on). Subjects decelerated for these maneuvers.

The analysis for the intersections with conflicts that subjects ran yellow light is shown in Figure 15. No subject slowed down for the intersection with LTAP/OD for any of the 3 yellow-timing conditions. Otherwise, subjects would begin decelerating (3 intersections of SCP, 3 for LTIP, 2 for LTAP/LD, and 2 for RTIP), but there were few cases of such.

The analyses for when going through and departing from intersections with yellow light are shown in Appendices H10, H11 and H13.

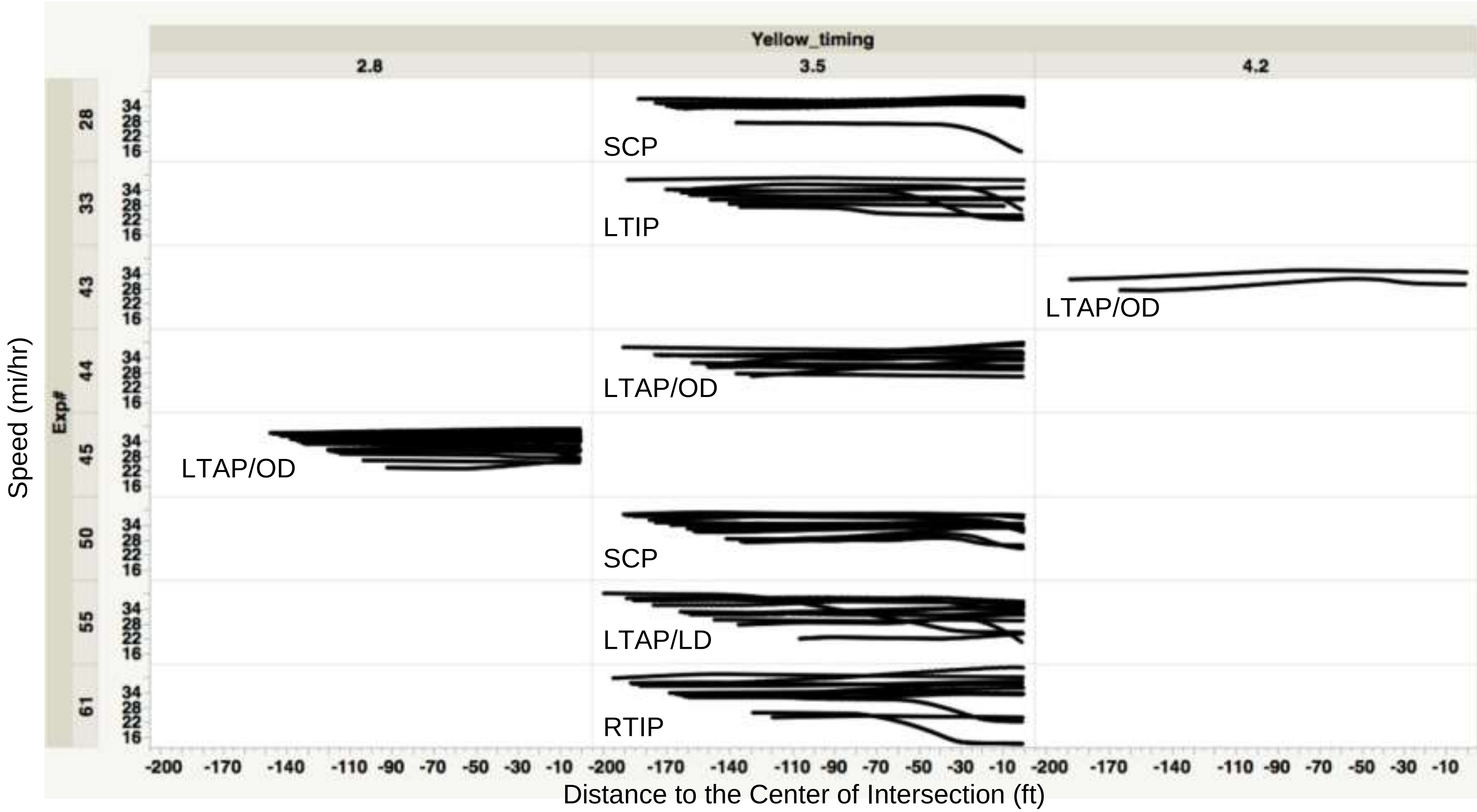


Figure 15. Vehicle Speed as a Function of Distance to the Stop Line for Each of the 24 Subjects (Yellow Light, Scenarios with Conflicts, When Approaching Intersections, Subjects Ran Lights)

Approaching Yellow Light - Stopping for the Traffic Light

Figure 16 shows the speed profiles when the traffic light changed to yellow and subjects decided to stop for the 3 yellow light time settings. Braking was more aggressive when traffic light changed later as one would expect.

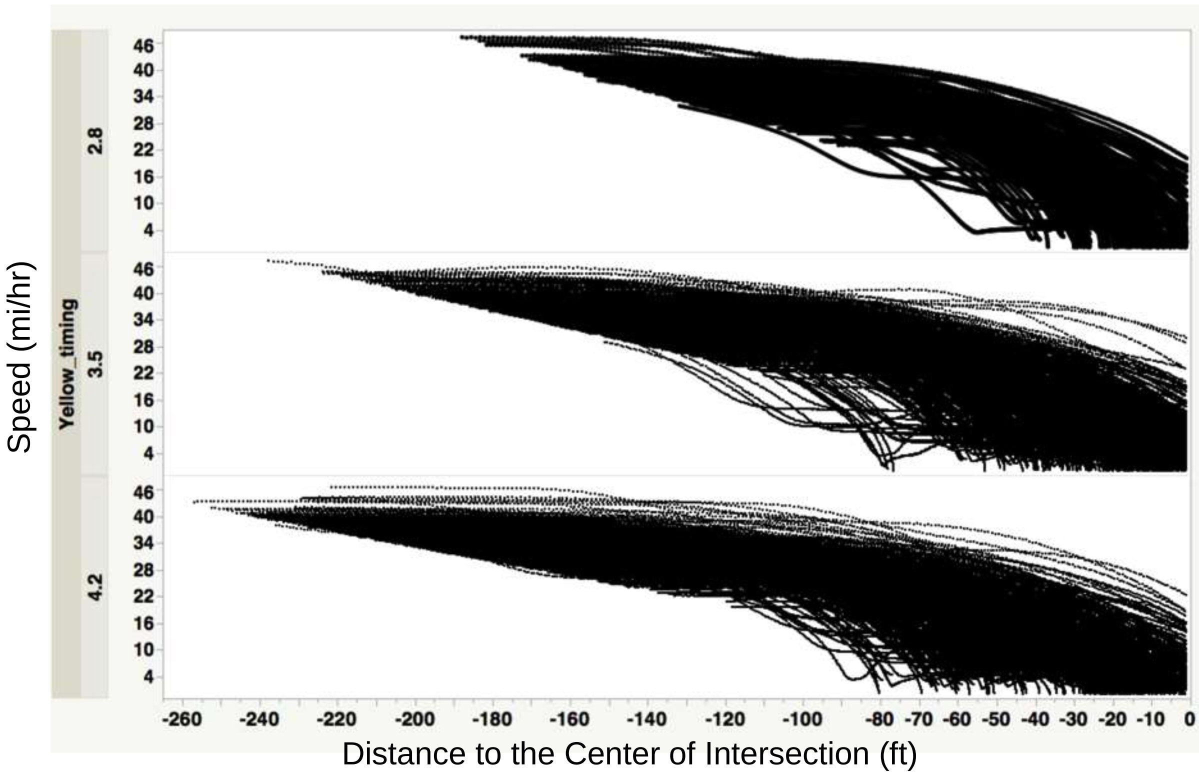


Figure 16. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects
(Yellow Light, When Approaching Intersections, Subjects Stopped for Light)

Q5. How does speed approaching an intersection vary as a function of the gap to the stop line, yellow light timing, other traffic, and subject age and gender?

There were 817,197 data points from 2,588 encounters with green and yellow lights (24 subjects x 54 intersections x 2 blocks - 4 missing encounters). For simplicity, the full regression model was used, which fit the data quite well (R^2=0.74).

$$Speed = 13.70 - 0.17 \times gap\ to\ stop\ line - 5.38 \times run + 0.07 \times conflict + 3.21 \times yellow\ light\ timing\ 2.8\ s - 0.18 \times yellow\ light\ timing\ 3.5\ s - 1.58 \times age - 0.10 \times gender$$

where

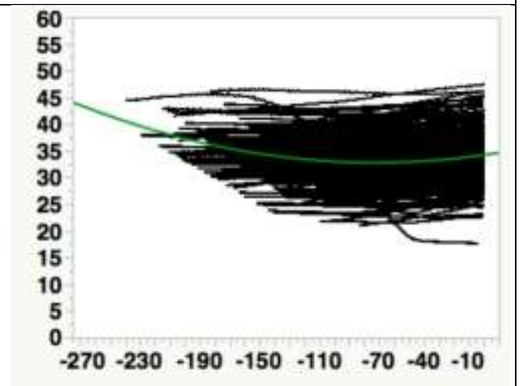
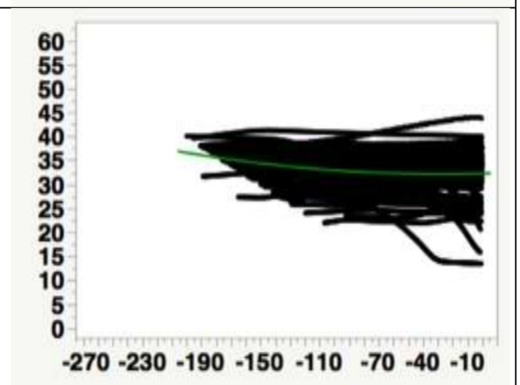
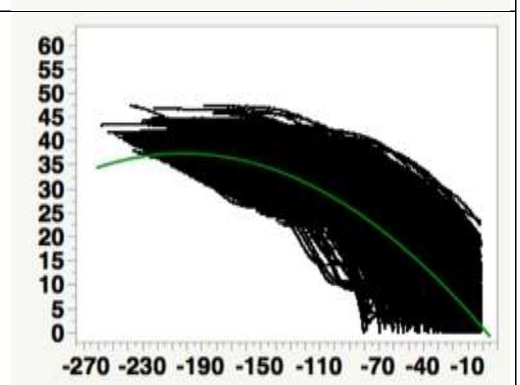
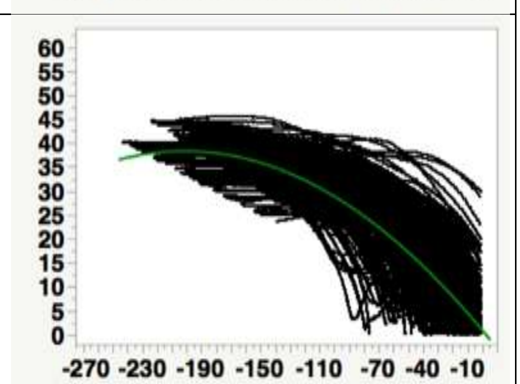
gap to stop line [ft; negative value = location before stop line]
run = 0 if stopping for the light; 1 if running
conflict = 0 if the intersection has no conflict, 1 if the intersection has conflict
yellow light timing 2.8 s, yellow light timing 3.5 s =
(1,0) for 2.8 s, (0,1) for 3.5 s, (0,0) for 4.2 s;
age = 0 for younger, 1 for older;
gender = 0 for male, 1 for female.

Note that the effect of subject gender was not significant (p=0.81) and the contribution (0.1 × 1 = 0.1) was small, so the gender effect can be removed from the equation with only minor consequences. The prediction was modified as below (R^2=0.74). The equation is the same as above, except the effect from subject gender.

$$Speed = 13.70 - 0.17 \times gap\ to\ stop\ line - 5.38 \times run + 0.07 \times conflict + 3.21 \times yellow\ light\ timing\ 2.8\ s - 0.18 \times yellow\ light\ timing\ 3.5\ s - 1.58 \times age$$

Table 17 shows that the predicted speed as a function of distance to the stop line for all combinations of 4 conditions (run/not run yellow and conflict/no conflict. The variance of speed that could be accounted for was greater when subjects chose to stop for the yellow light, mostly because there was very little speed change when they did not stop. In both cases, the presence of a conflict had a minimal effect on the prediction.

Table 17. Speed at Each Gap to the Stop Line by Traffic Light State

Traffic light state	Prediction Y = Speed (mi/hr) X = Gap to stop line (ft)	Plot
Yellow light Pass No conflict	$Y = 34.1973 + 0.0396X + 0.00003X^2$ R^2=0.03 Min Y when X = -72.02	
Yellow light Pass With conflict	$Y = 32.2400 + 0.0081X + 0.0001X^2$ R^2=0.04 Min Y when X = -27.08	
Yellow light No pass No conflict	$Y = 1.0189 - 0.3584X - 0.0009X^2$ R^2=0.76 Max Y when X = -202.42	
Yellow light No pass With conflict	$Y = 0.9591 - 0.3711X - 0.0009X^2$ R^2=0.77 Max Y when X = -201.36	

Q6. How did longitudinal acceleration and jerk vary as the driver approached each intersection and was it indicative of any crash related behavior?

As noted in the introduction, longitudinal acceleration, especially when large and possibly jerk, can be indicative of situations where crashes are more likely, and accordingly, were examined in this study. Jerk was calculated as the difference between 2 successive samples of acceleration (ft/s^2) 1/60 s apart.

Green light – no conflict (338,852 data points, 960 encounters)

There were 338,852 data points from 960 encounters with green lights and without conflict (24 subjects x 20 intersections x 2 blocks).

As shown in Figure 17, there are clear differences in the levels of acceleration between runs, some being quite stable, and others changing dramatically (because lead vehicle changed and gap was shortened). In contrast, the jerk data were quite stable. Of course, as not much of interest was happening during the green approaches, the lack of a change in jerk is consistent with expectations.

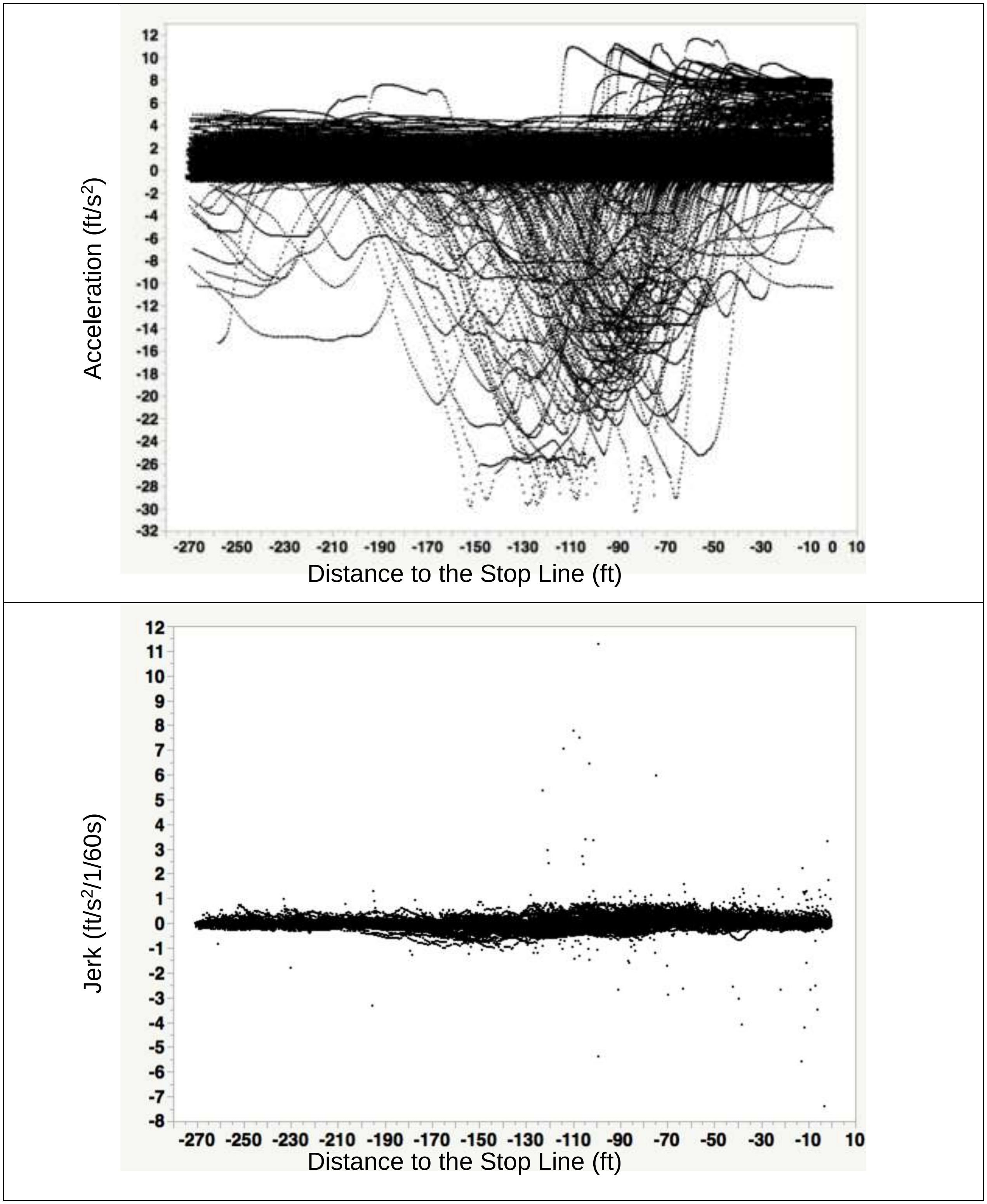


Figure 17. Acceleration and Jerk When Approaching an Intersection
(Green Light, No Conflict)

Green light – with conflict

There were 32,650 data points from 96 encounters with green lights and with conflict (24 subjects x 2 intersections x 2 blocks).

However, for the intersections with a conflict (LTAP/OD and RTIP), subjects slowed down the vehicle to avoid the incident (Figure 18). Changes in acceleration are very apparent. Figure 19, showing jerk for LTAP/OD only, shows that the deceleration started at about 60 ft before the stop line and the jerk became more apparent at that time, but overall the change in the jerk signal is not as salient as the original acceleration data in Figure 17. About 67% of encounters (32/48 for each block) just had minor change of acceleration (within ±0.2 ft/s^2 per 1/60 s) before the stop line. (See Appendix H14.) Given the instability in the jerk signal, means and standard deviations were computed, averaging over every 10 ft (Figure 20). In this instance, the mean jerk was approximately 0 until the distance to the stop line decreased to 50 ft. The jerk decreased to -0.05 ft/s^2 per 1/60 s (-0.1 g per second) and its standard deviation increased to 0.25 ft/s^2 per 1/60 s (0.5 g per second).

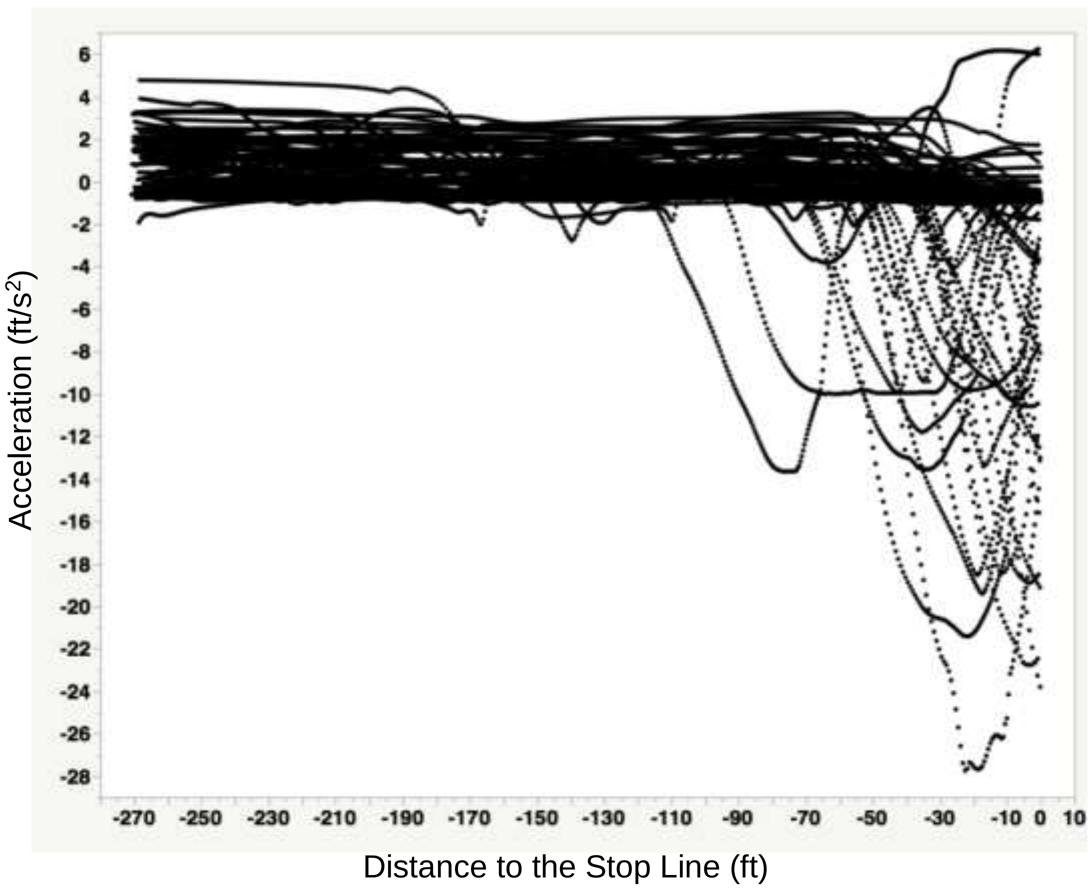


Figure 18. Acceleration When Approaching an Intersection
(Green Light, LTAP/OD and RTIP)

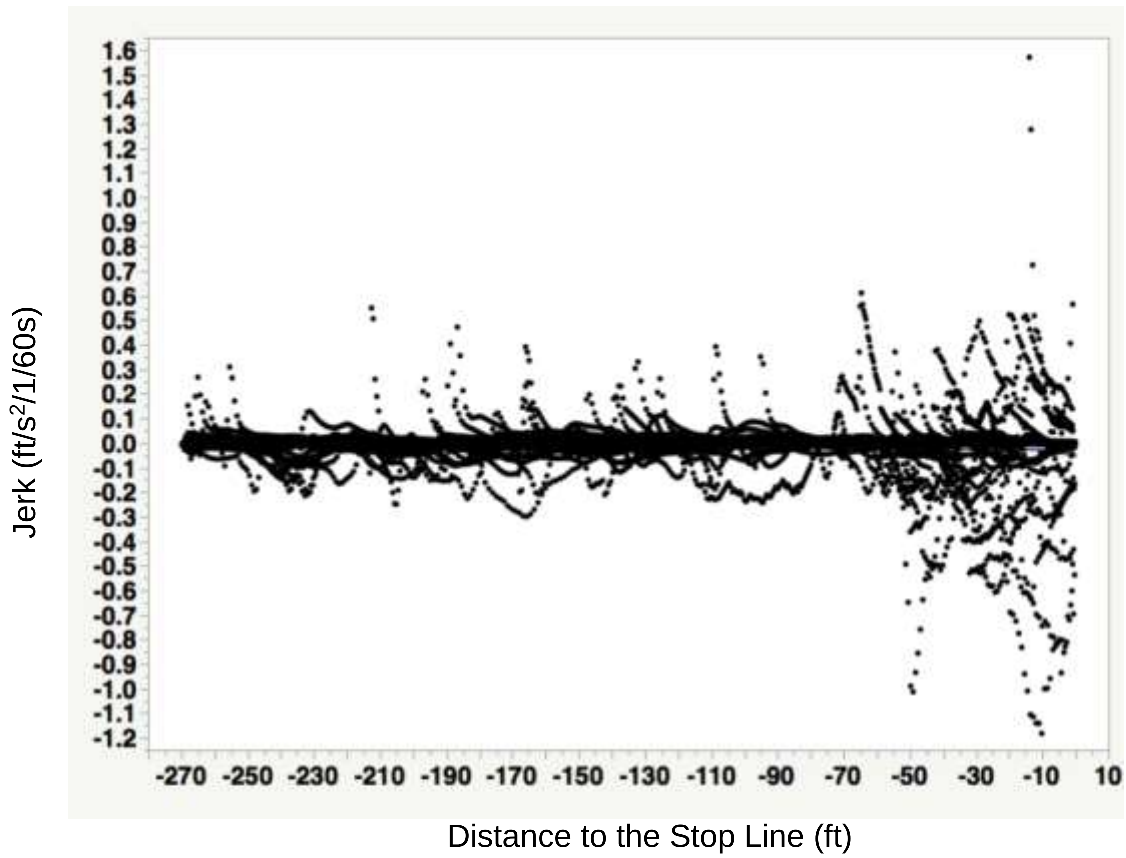


Figure 19. Jerk When Approaching the Intersection (Green Light, LTAP/OD)

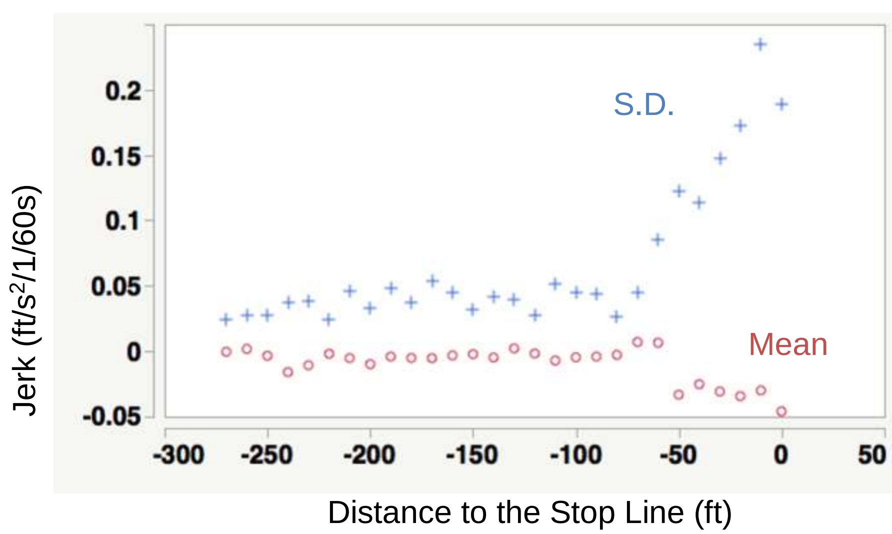


Figure 20. Mean and Standard Deviation for Jerk from Figure 19 (LTAP/OD)

Note that averaging the jerk signal over other time windows was not explored due to resource constraints. However, obtaining a jerk signal and using it to make crash avoidance decisions is of little practical value if that information is available once every 10 feet (about ½ car length).

For the RTIP scenario with conflicts, subjects maneuvered in a similar manner to the LTAP/OD maneuver just discussed, but the deceleration started at 100 ft before the stop line (Figure 21), which was earlier than LTAP/OD. Figure 22 shows that the mean of jerk remained very close to 0 until the distance to the stop line decreased to 90 ft. The jerk decreased to -0.08 ft/s^2 per 1/60 s (-0.15 g per second) and its standard deviation increased to 0.2 ft/s^2 per 1/60 s (0.4 g per second). However, starting at 30 ft to the stop line, the deceleration became moderated and subjects accelerated afterwards. Compared to LTAP/OD, subjects had braked more forcefully, but nonetheless for 51% (24/47) of the encounters the jerk was within ±0.2 ft/s^2 per 1/60 s before the stop line (Appendix H15).

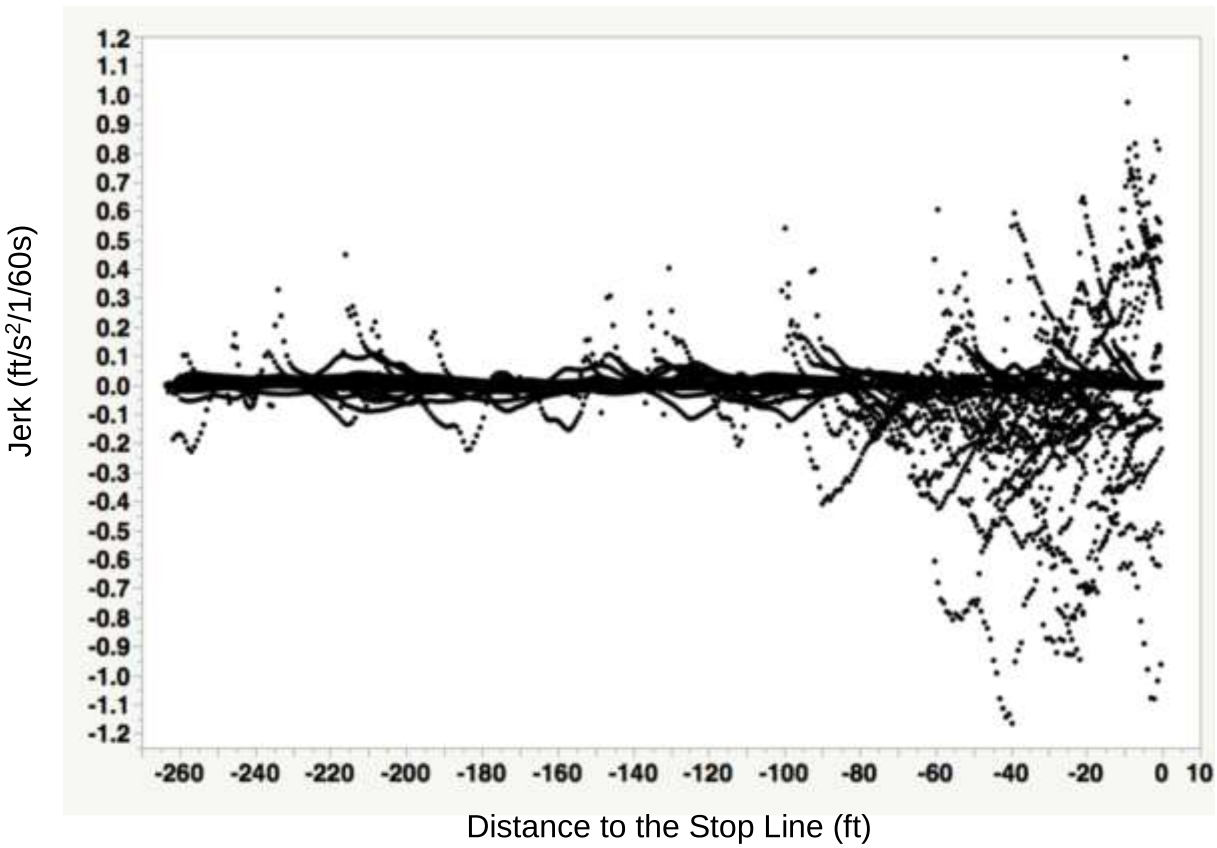


Figure 21. Jerk When Approaching the Intersection (Green Light, RTIP)

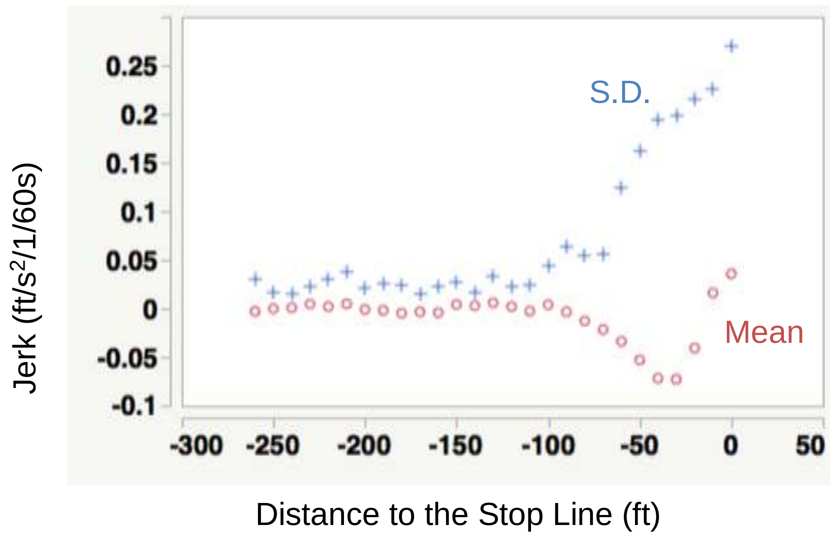


Figure 22. Mean and Standard Deviation for Jerk from Figure 21 (RTIP)

Yellow light – Running yellow lights, no conflict

There were 68,986 data points from 385 encounters that subjects ran yellow lights at the intersections without conflict.

Before running yellow lights at intersections without conflicts, most subjects remained constant speed to pass the intersection and there were only 18 of 385 encounters (5%) that subjects braked within the dilemma zone (top of Figure 23). Most of the acceleration and deceleration sequences were stable (over 97% of jerk was between ± 0.2 ft/s^2 per 1/60 s; 67,241/68,986). Figure 24 shows that the mean jerk was close to 0, and standard deviation increased because of individual differences. However, there was no salient point at which jerk changed, whereas changes were more apparent in the acceleration signal.

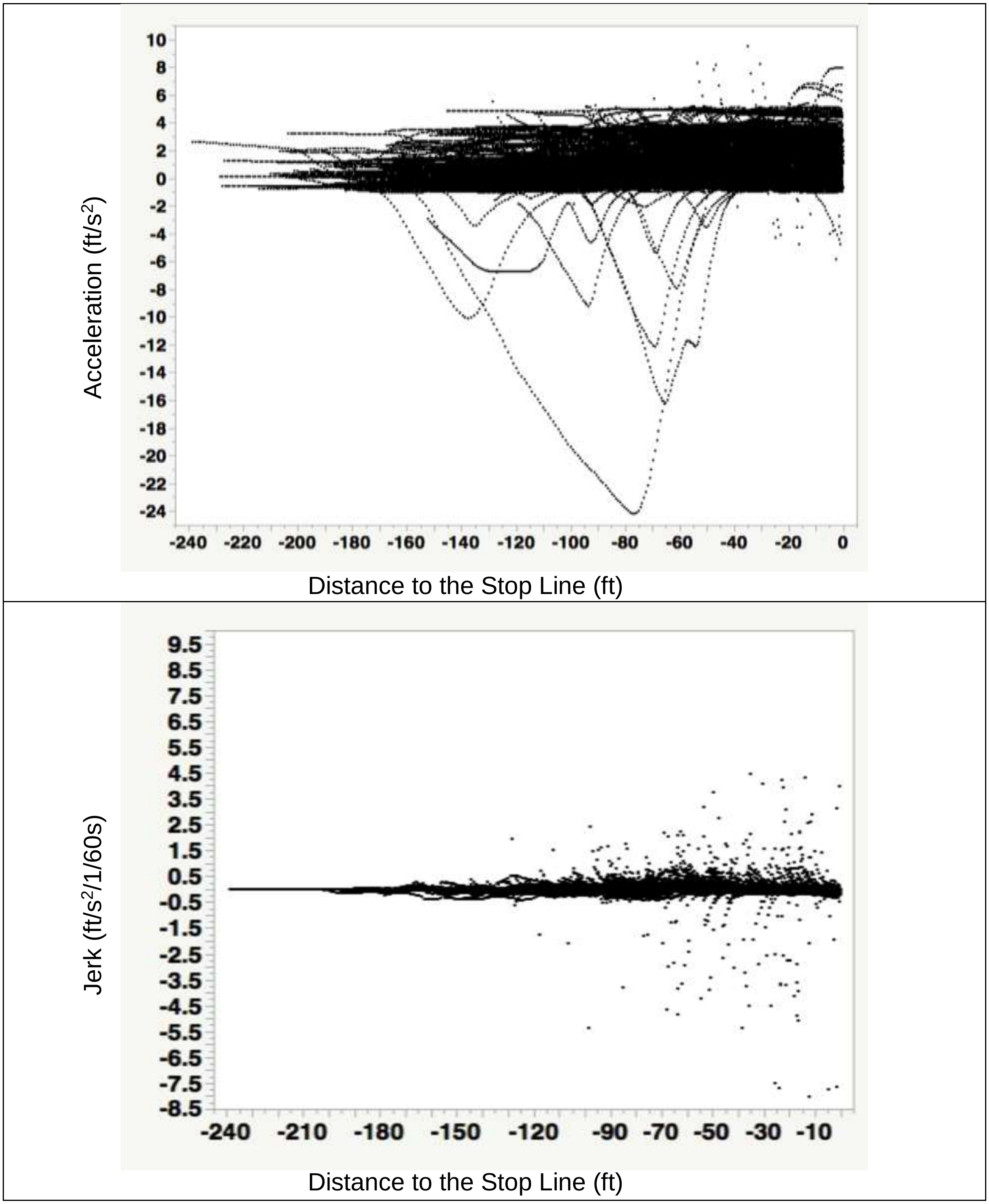


Figure 23. Acceleration and Jerk When Approaching the Intersection
(Yellow Light, No Conflict, Subjects Passed)

Figure 24. Mean and Standard Deviation for Jerk from Figure 23

Yellow light – Running yellow lights, with conflict

There were 18,233 data points from 95 encounters that subjects ran yellow lights at the intersections with conflict.

Figure 25 shows the acceleration and jerk when subjects ran yellow lights at intersections with conflicts. Subjects decelerated to avoid conflicts, and the jerk was greater for than intersections without conflicts. About 8% (1,441/18,233) of jerk measures were over ±0.2 ft/s^2 per 1/60 s for when the traffic light changed to yellow, and subjects had obvious braking (-0.2 ft/s^2 per 1/60 s for 1 s or more), the case for 31 of the 95 encounters (33%). The other 2/3 of subjects maintained a constant speed or coasted through the intersection.

The mean of jerk decreased to -0.1 ft/s^2 per 1/60 s and its standard deviation increased to 0.25 ft/s^2 per 1/60 s (Figure 26) at 60 ft to the stop line, which had similar results to the encounter of green light with RTIP (Figure 22). Also, subjects reaccelerated after the conflict had passed.

Again, the signal changes of interest were more apparent in the acceleration signal than the jerk signal.

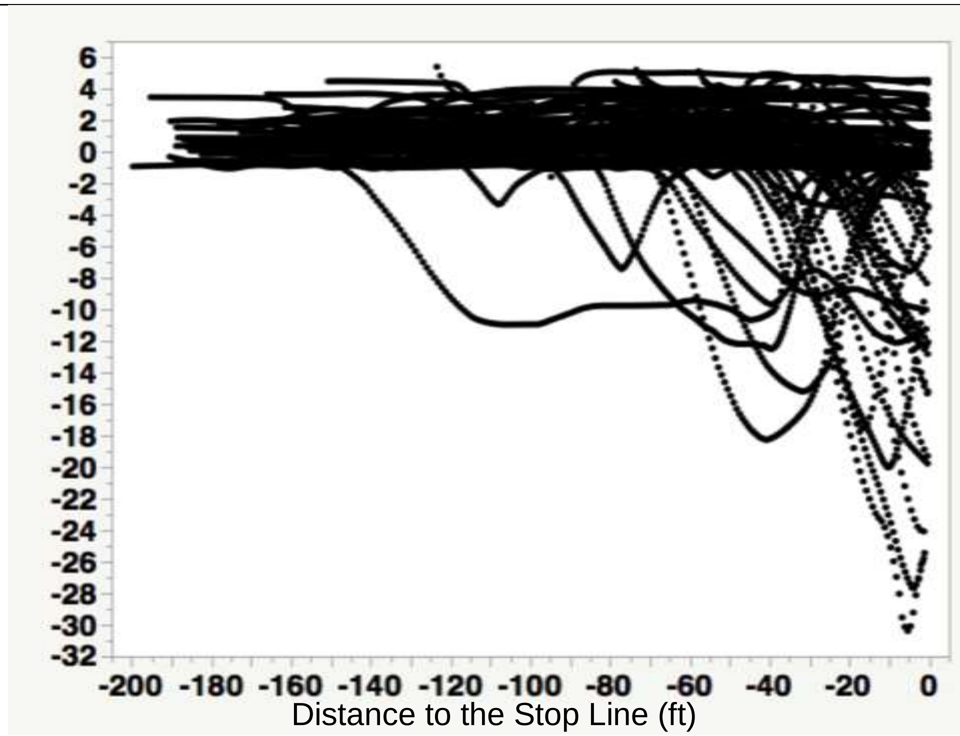
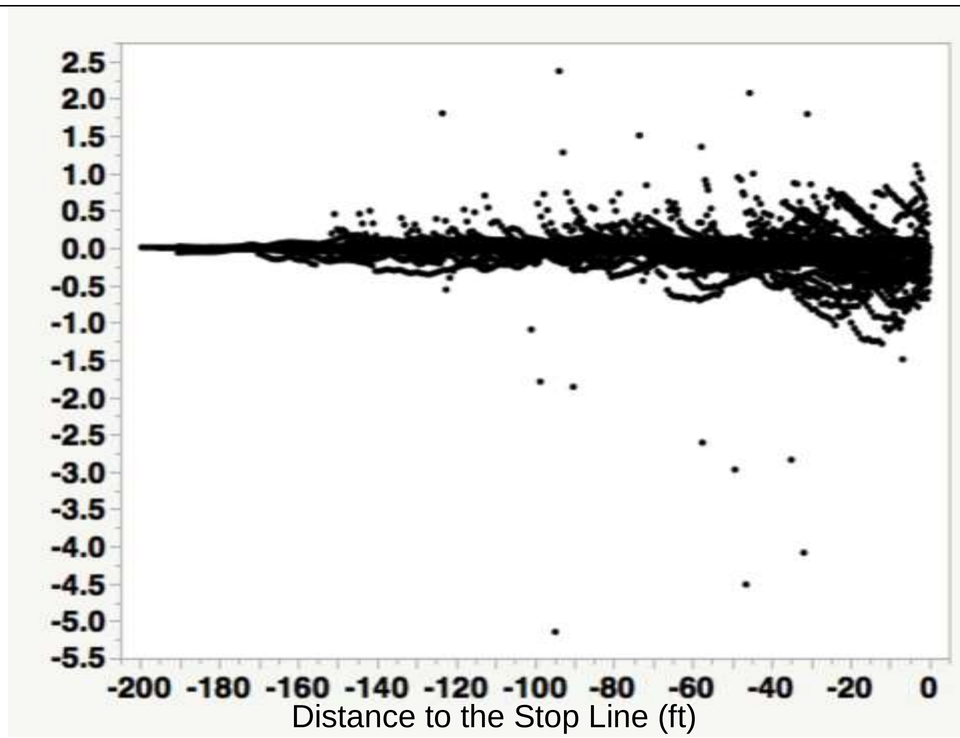
Acceleration (ft/s^2)	
Jerk (ft/s^2/1/60s)	

Figure 25. Acceleration and Jerk When Approaching the Intersection (Yellow Light, with Conflict, Subjects Passed)

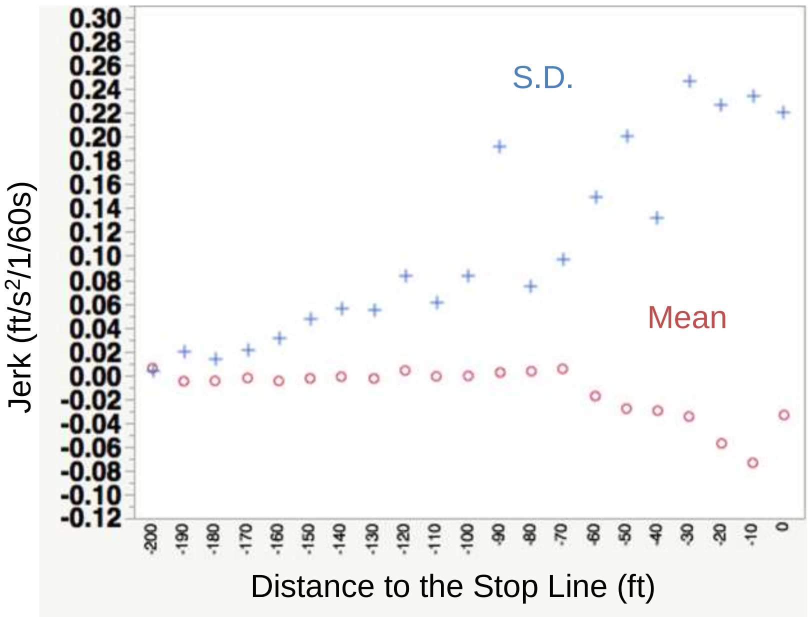


Figure 26. Mean and Standard Deviation for Jerk from Figure 25

Yellow light – Stopping before the stop line

There were 358,476 data points from 1,052 encounters that subjects stopped for the yellow light. For intersections with conflicts, it could not be determined if subjects stopped because of the traffic light state (yellow) or due to conflicts, so the conflict factor was not considered in this analysis.

Subjects decelerated more when they stopped for the traffic light than when they ran the light as expected. Figure 27 shows that decelerations as large as -30 ft/s^2 (-9.1 m/s^2 ~ –1g) occurred and the mean of jerk decreased to -0.15 ft/s^2 per 1/60 s (Figure 28). Again, the raw acceleration signal was more indicative of the changes of interest than the jerk signal.

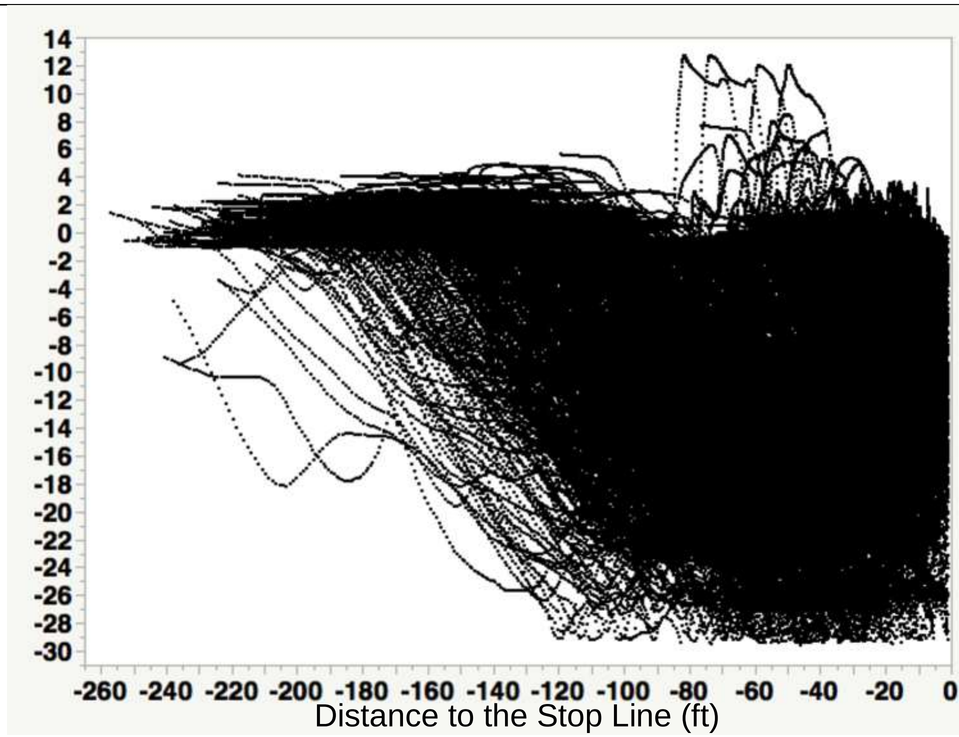
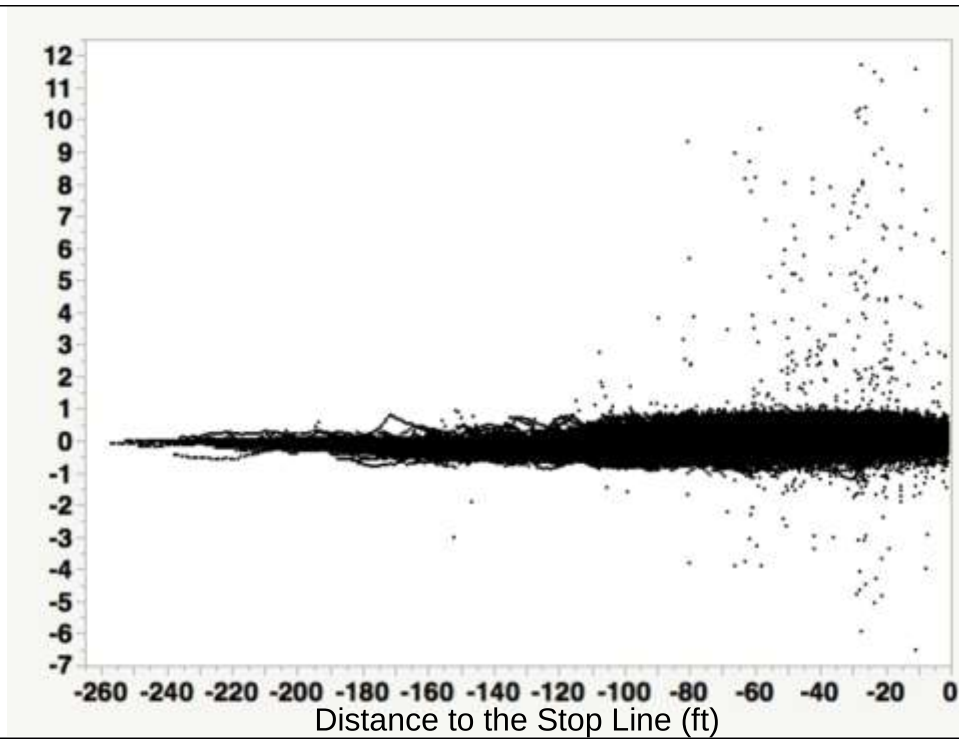
Acceleration (ft/s^2)	
Jerk ($ft/s^2/1/60s$)	

Figure 27. Acceleration and Jerk When Approaching the Intersection
(Yellow Light, Subjects Stopped)

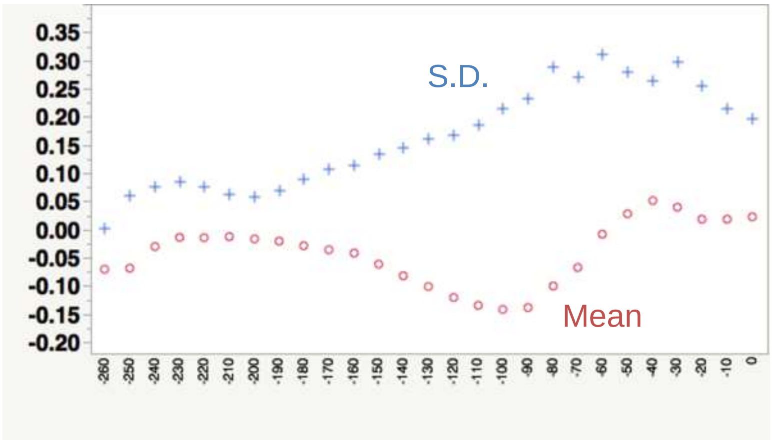


Figure 28. Mean and Standard Deviation for Jerk from Figure 27

CONCLUSIONS

1. How often did crashes occur and for which scenarios?

Only 4 crashes occurred over the 2,924 intersection encounters and 3 of them were that the subject was rear-ended by a following vehicle. There were too few crashes to for a detailed further analysis, though the 1 non-rear-end that did occur was LTAP/OD, the most common intersection crash scenario. In some sense, having few crashes is a desired outcome as crashes can end a subject's participation in the experiment.

2. How Did Drivers Respond to Traffic Signals in This Experiment?

The probabilities that subject ran yellow light were 0.4, 0.74, and 0.9 for the yellow-light timings of 2.8, 3.5, and 4.2 s, which were higher than previous expected. A desired outcome would be probabilities of 0.0 for 2.8 s, 0.5 for 3.5 s, and 1.0 for 4.2 s. One explanation for greater than expected stopping probabilities was that after subjects experienced the intersections with conflicts, they would be more careful for all intersections, even for those without conflicts. For example, 3 older male subjects stopped for all the 64 yellow light encounters and the other 4 older subjects stopped for more than half of the encounters with 2.8 s yellow-light timing.

Also, the number of conflicts for each timing condition was different (1 conflict out of 9 for 2.8 and 4.2 s; 6 conflicts out of 14 for 3.5 s). This experiment did not control the confounding by intersection conflict to the relation between yellow-light timing and subject response, so subject response could be affected. Of course, when a traffic signal changed to yellow, the subject did not know the duration, mitigating the confounding effect.

3. How did the probability each subject stopped an intersection vary as a function of speed and/or gap to stop line, yellow-light timing, throttle and brake pedal positions, and subject age/gender, when the light just changed to yellow?

The probability that subjects stopped in response to a yellow traffic light is as shown below. Due to large individual differences, this equation only accounted for 19% of the variance, not very good. Looking at the data by subject led to greater R^2 values as one would expect.

$$P(stop) = \frac{e^x}{1 + e^x}$$

where:

$$x = -5.84 - 0.01 \times gap\ to\ stop\ line + 1.49 \times yellow\ light\ timing - 2.93 \times pedal\ position + 0.29 \times age + 0.15 \times gender$$

and:

gap to stop line [ft; negative value = location before stop line];
yellow light timing = 2.8, 3.5, or 4.2 [s].
pedal position is between ±1;
age = 0 for younger, 1 for older

gender = 0 for male, 1 for female;

One possible explanation for the low variance accounted for may be due to some inconsistencies in the brake function action and the fact that the brake was force/travel based, not velocity based as in a real vehicle. Learning the mapping of the brake should have been overcome by practice, but nonetheless, a modified brake would remove any uncertainties.

4. What was the speed vs. distance profile for approaching each intersection?

Green light

The subject's speed remained constant except when a vehicle from the left (LTIP) or right (RTIP) replaced the lead vehicle at a previous intersection. For the intersections with conflicts, subjects slowed down the vehicle in 10 (LTAP/OD) and 13 (RTIP) of 96 encounters (about 25% of the total). For LTAP/OD encounters, drivers either decelerated from 40 mi/hr or accelerated from 20 mi/hr to avoid collision. Of these encounters, RTIP presented the least risk because the other vehicle turning ahead of it, not crossing the subject's path..

Yellow light (run lights)

Subjects decided if they would run a yellow light well before the intersection. When there was no conflict, the approach speed was stable although subjects often accelerated slightly upon entering the intersection. When there was a conflict, their response depended upon the specific encounter as follows:

SCP - more slow-downs for the vehicle from left (4 encounters) than from right (1 encounter)
LTAP/OD - constant speed
LTIP - hard brake (only 2 encounters)
LTAP/LD - hard brake (only 1 encounter)
RTIP - brake after the center of the intersection (only 2 encounters)

Yellow light (stop)

As expected, as the time before intersection that the yellow light changed decreased, the deceleration to stop increased (shorter distance to reduce speed from 35 to 0 mi/hr). Once the subject began to apply the brake, the braking became more and more aggressive with time (slope increases in Figure 16), especially obvious for the 2.8 s yellow-light timing. There was no proprioceptive feedback by the simulator cab, so subjects did not know how aggressively they braked and that could lead to more aggressive braking as indicated by screeching tires, sometimes during normal braking. This occurrence is very rare for real vehicles. Again, as a reminder, the brakes in the simulator used springs to provide force feedback, not a hydraulic mechanism, so braking force was proportional to pedal position, not application velocity.

5. How can the speed approaching an intersection vary as a function of gap to the stop line, yellow light timing, other traffic, and subject age/gender?

The prediction can be shown as below (R^2=0.74).

$$Speed = 13.70 - 0.17 \times gap\ to\ stop\ line - 5.38 \times run + 0.07 \times conflict + 3.21 \times yellow\ light\ timing\ 2.8\ s - 0.18 \times yellow\ light\ timing\ 3.5\ s - 1.58 \times age$$

where:

gap to stop line is [ft]
run = 0 if stopping for the light, 1 if running;
conflict = 0 if the intersection has no conflict, 1 if the intersection has conflict;
yellow light timing 2.8 s, yellow light timing 3.5 s =
(1,0) for 2.8 s, (0,1) for 3.5 s, (0,0) for 4.2 s;
age = 0 for younger, 1 for older;

Subject age, yellow-light timing of 2.8 s, and whether the subject stopped for the traffic light were 3 predictors that contributed more than others. People drove faster when the traffic light changed to yellow at 2.8 s ahead of the stop line, and slower when they stopped for the yellow light and if they were female. This prediction was more accurate than predicting the probability of stopping for the yellow light because this prediction was a continuous process, rather than a binary outcome. Therefore, the approach speed to an intersection can be predicted using driver performance and demographic data.

6. How did longitudinal acceleration and jerk vary as the driver approached each intersection?

When passing through the intersection when the light was green and there was no conflict, there was some deceleration and the amount of jerk was negligible. If there was a conflict, subjects decelerated at about 50 ft before the stop line for LTAP/OD and 100 ft for RTIP. When subjects braked for LTAP/OD, the mean jerk decreased to -0.05 ft/s^2 per 1/60 s and its standard deviation increased as approaching the intersection. This level jerk did not lead to motion sickness.

For RTIP, the mean jerk decreased to -0.08 ft/s^2 per 1/60 s at after 100 ft to the stop line, and increased to 0.05 ft/s^2 per 1/60 s at 30 ft. About half of the subjects did not brake for the conflict.

When subjects ran the yellow light, the conflict influenced subject behavior. For the intersection without conflict, their change of speed was stable that more than 97% of jerk values being between ±0.2 ft/s^2 per 1/60 s. Subjects braked for 5% of intersections. If there was a conflict, jerk was more variable and subjects braked for 33% of intersections. The mean jerk decreased to -0.1 ft/s^2 per 1/60 s when braking, which was similar to what occurred when responding to a green light with an RTIP conflict.

Compared to the scenario of running yellow light, stopping for the traffic light led to a stable decrease in jerk (about -0.01 ft/s^2 per 1/60 s every 10 ft closer to the stop line).

In this experiment, examination of the jerk data did not provide any insights beyond those gleaned from reviewing the acceleration data. Thus, the jerk data do not merit special consideration in future studies.

Again, in this driving simulator, only visual cues and auditory cues (tire screeching) were available to judge braking aggressiveness. The physical discomfort of aggressive braking (other than secondary cues connected with motion discomfort) did not occur. Had a motion-based simulator providing proprioceptive cues to subjects been used, the jerk levels experienced could have been different.

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APPENDIX A. INSTRUCTIONS FOR EXPERIMENTERS

Instructions to Subjects - NSF Intersection Experiment 1
Paul Green, June 6, 2013 revision
Guofa Li, Heejin Jeong, July 10, revision
Paul Green July 15,16 revision

1. Before the subject arrives

Check
__ you have a key for the lab or the door is unlocked
__ the *** is on (start up list for the Minisim)
__ the two video recording systems are on. (one is for subject behavior from back of subject, other is for backup recording simulation (screen only))

__ title card used at start of video (with a subject number) is in the lab
__ consent form in the folder
__ biographical form in the folder
__ post test form in the folder.
__ pencils or pens for subject and experimenter
__ blank paper for notes
__ experimenter and subject clipboards
__ payment form
__ have money for subject
__ first aid kit
__ sickness bag
__ events checklist
__ procedure list
__ cup of water for subject
(if they are thirsty or their mouths are dry from talking)
__ name tag for experimenter

Fill in as much information in the biographical form for the subject before they arrive.

2. Greet the subject and take them to the lab

- Meet the subject in the lobby
- Introduce yourself and verify the subject:
  "Hello, my name is - Say your name, You must be - Say subject name"
  "Can I check your ID?"
- Ask if the subject wants to go to the restroom or get a drink

Let's go into lab on the basement and get started. Ask them if they want to use the stairs or elevator. Go to the lab. Flip the sign on the door (experiment in progress)

3. Introduce the intersection project to the subject

"As a reminder, my name is **. Please sit here."
Sit next to the subject to aid conversation.

"To avoid any interruptions, I am going to turn my phone off. Could you check yours is off as well."

"Today, we are going to examine how people normally drive through intersections to provide data that will be used to design crash warning systems. (Show the procedure list to subject) First, you will fill some forms, and then have your vision checked. Then you will drive the simulator for about 5 minutes or maybe longer to become familiar with it. Next, you will drive though a long series of intersections. It will probably take about 25 minutes for each series of them, and there are 3 series. The entire experiment could take about 2 hours to complete, but many finish in less than 2 hours. You will be paid $50 for your efforts. You can stop at any time."

"The first thing to do is to sign this consent form. Please read it carefully. Particularly, note that we will be videotaping what you do and maybe showing some of what you say and do to others. (If there is a web camera for MIT, point it out.) If you have any questions, please ask them at any time." (Have them sign the form. Then, you sign the form as a witness.)

For students, if they cannot estimate mileage, ask them to estimate the number of trips and mileage/trip in the spring summer, and then do the same for the fall and winter when school is in session.

"Next, for reporting purposes, we need some information about you."

Give them the biographical form and a pen. When they return it, check all the bold bordered boxes are filled in.

4. Check their vision

Prior to the vision check, wipe the button with tissue.

- "We need to check your vision. Put your glasses on or contacts in if you have not already done so. Please place your forehead against the button. For the entire test, keep looking straight ahead. "
-

  For each number or letter they get right, circle the number. For each number they get wrong, slash the number or letter. End the test when the subject gets two consecutively incorrect.

  "Thank you very much." or "That's all I need, thank you."

- Test visual acuity (FAR #2) (no black eye piece, knob set to 2)

  “Can you see in the first diamond that one of the circles is complete but the other three are incomplete? For each diamond, tell me its number and the location of the complete circle - Top, Bottom, Left, or Right. If you are not sure, please guess”

  Adjust the knob from 2 and back to make it appear something has changed.
  Insert the black eye piece.

- Test near vision (80 cm) (FAR #2) with Lenses (black eye piece, knob set to 2)

  To avoid them remembering the sequence they just saw, rotate the knob to another number and rotate back to 2 so they think the sequence was changed.

  “Can you see in the first diamond that one of the circles is complete but the other three are incomplete? For each diamond, tell me its number and the location of the complete circle - Top, Bottom, Left, or Right. If you are not sure, please just guess”

  Remove the black eye piece.

- Color-abnormality (FAR #6) (no black eye piece, knob set to 6)

- "In each circle, there is a number. Starting with Circle A, could you tell me the color pattern digit (number) if there is one?" (Circle F does not really have a number).

  Note: Do not call it color abnormality, but a color vision check.

  Turn off the device.

  Flip the sign on the door (experiment in progress)

5. Give subject practice driving the simulator and check for motion discomfort. Help them get a sense of stopping location.

“Have them sit in the driving simulator and adjust the seat. “Please sit in the driver’s seat and adjust the seat so you are comfortable.” If applicable, say “The controls are on the left side of the seat move it forward and backward, and adjust the seat back angle.”

When you introduce this experiment to the subject, keep your eyes in the same or lower height with the subject.

Give the subject a brief introduction to the MiniSim.

“This is a desktop driving simulator. The 3 screens in front of you show you the road scene including traffic lights and all other vehicles. This small screen is the dashboard with a speedometer. The red buttons on the left side of the steering wheel are all for a left turn signal, and the buttons on the right are for a right turn signal. (Maybe cover the turn signal later.)

There are 3 foot pedals. The right one is the acceleration pedal, and the middle one is the brake pedal. We do not use the left one.

The gear position (P, R, N, and D from left to right) is shown in the dashboard. The paddle on the left scrolls though the gears from left to right, and the right paddle shifter scrolls from right to left. To change gears, press the brake pedal and pull on a pedal shifter.”

“It is easier to see the simulation with some of the room lights off. Would you mind if I do that now?” Turn lights off.

In this next segment, we need to make sure there will be not motion discomfort issues with the simulator. To do that, you will drive a short distance in an urban section that resembles the experiment, except that traffic is well behaved. Your goal is to drive straight through this world, not turning at any intersections and obeying the traffic signals. The speed limit is 35 mi/hr. Please keep a safe following distance with the lead vehicle. When you are ready to begin, put the car in D and begin to drive. If you feel any motion discomfort, close your eyes and gently bring the car to a stop.

If they stop far from the intersection... If you look, you can see you are quite far from the intersection. Please move forward a few to where you would normally stop.

If they brake aggressively… When you were stopping, did you notice how the front of the car dipped down? Because the simulator does not move like a real car, sometimes people brake harder than normally. To bring the simulator to a stop, you just need to brake gently. Also, in a real car, in the instant just before you stop, most people release the brake just a bit so the stop is smooth. At the next intersection, try that.

Or… I assume you heard the tires screech when you just braked. Try to brake sooner and less aggressively.

If they continue to have problems coach them as they approach the intersection…ok, now just brake gently…ok, just before you stop, back off the brake pedal so the nose of the car does not go down.

If they burn rubber when accelerating…”When you begin to press on the accelerator, be a bit less forceful so you do not burn rubber.

Repeat the practice drive if needed.

6. Begin the test session

Start the video recording. "Ok, the camera is now recording what we do." Check the sound levels by speaking and check the levels are adequate.   The title card should be in place.

"As a reminder, in this experiment, you will drive through about 60 intersections, following a lead car. The speed limit is 35 mi/hr. Your goal is to drive safely, being sure not to run any red lights or crash into other vehicles. In this simulated world, there will be lots of drivers doing stupid things. Don't hit them. You can do whatever you think you should do to avoid a crash. Even if you crash, please ignore it and just keep going."

"Do you have any questions? Ok, then put the car into D and start driving.

If they drive the first few green lights too fast or too slow, encourage them to adjust their speed as needed.

When they have reached the end of the world (where there are some drums on the road)… "Ok, bring the car gently to a stop, and put it in park. This is the end of the first series of intersections. Give me a minute to save the data and then we can restart." Save the data and load in the next series.

"Ok, I am ready for the next 25-minute sequence." When you are ready, shift the car into D and begin.

Repeat for a 3rd block as appropriate.

Next, we are going to do something a bit different. In this segment, you will drive on urban roads first and then on an expressway. You just need to drive as you usually do without violating any traffic rules and try to finish this block as soon as possible.

When they have reached the end of the world (where there are some drums on the road)… "Ok, bring the car gently to a stop, and put it in park. This is the end of the last driving segment. Give me a minute to save the data and then there are some final post-test questions." Save the data and get the questions ready.

Turn lights on. Turn off the recording equipment and have it save the data.

7. Post-test questions

"You have been very helpful, but we have a few additional questions for you on this form. The survey takes about 5 to 10 minutes to complete.   This survey includes some questions on your how many intersections will you drive through every day, your driving habits, and other questions. If you have any questions about this survey, ask them."

Give them a pad and the survey on a clipboard.

“Thank you. Please give me a minute to check there is nothing missing.” You have said a great deal, but just in case we missed something, is there anything to add?”

“I wanted to thank you for participating. Here is $50 for your time. Please sign the form that you were paid.”

“Ok, I will walk you out.”

Flip the sign on the door.

8. End the session

Go back to the lab. Save the video recording. If there are no other subjects, shut off the simulator and the AV equipment. Throw away the cup of water for the subject. As a final check, when you leave the room, turn off the lights and see if anything is glowing. If something is on, turn it off.

APPENDIX B. CONSENT FORM

INDUSTRIAL AND OPERATIONS ENGINEERING UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING	Participant # __________

Consent Form: Driving Through Intersections

Investigator: Paul Green (763 3795, pagreen@umich.edu) Center for Ergonomics

This experiment is the first of several driving simulator experiments to develop warning systems to prevent intersection crashes. In this experiment, only baseline (no warning system) driving will be considered.

This experiment will consist of several 25-minute drives in which you drive through a sequence of over 60 intersections following a lead vehicle and obeying the traffic signals. At each intersection there may be other vehicles turning that you will avoid. In addition, at the end, there will a drive to examine how you follow other vehicles and change lanes as well as a short questionnaire about the experiment. During the experiment, we will record your speed, lane position, and so forth, as well as "videotape" your driving and you, and what you say.

The experiment consists of one 2-1/2 hour session, for which you will be paid $50. Parking at IOE is free, but we will need to give you a parking pass when you arrive. After you sign this consent form, we will obtain some biographical data (your age, driving experience, etc.) and driving data (e.g., miles drive/year), and check your vision, followed by a brief drive in the driving simulator to verify there are no problems with motion discomfort. Because there is minimal turning in this experiment and the simulator uses small screens, motion discomfort is much less likely than for other simulators and experiments. However, should it occur, we will stop the experiment. Should there be a problem, you can elect to stop at any time, and we will pay you in full even if you do not complete the experiment. There are no other risks associated with this experiment.

What you say and do (but not your name) will appear in a publicly available report whose results will make future vehicles safer. Your data, but no uniquely identifying personal information such as your name, will be shared with colleagues at MIT who are working on this project. (They can also watch a live feed from a web camera.) Records will otherwise be kept confidential to the extent provided by federal, state, and local law, though various officials can inspect them, and disposed of after 10 years.

Should you have any questions about the study, please contact Paul Green at the phone and email address above.

If you have questions about your rights as a research participant, or wish to obtain information, ask questions or discuss any concerns about this study with someone other than the researcher(s), please contact the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board, 540 E Liberty St., Suite 202, Ann Arbor, MI 48104-2210, (734) 936-0933 [or toll free, (866) 936-0933], irbhsbs@umich.edu.

> **As was stated when you were scheduled for this experiment, all participants must be "videotaped." I therefore agree to be viewed and recorded, and realize my face may appear. I understand that segments from my sessions may be used in presentations by the authors, by the sponsor, and by the media (e.g., on TV) to help explain this research. My full name will not be disclosed.**

I have read and understand the information presented above, and all of my questions have been answered. My participation is voluntary. I agree to participate.

____________________ Print your name	____________________ Date
____________________ Sign your name	____________________ Witness (experimenter)

Note: Keep one copy for the records and give the other to the participant.

APPENDIX C. BIOGRAPHICAL FORM

Intersection Experiment – Biographical Form

Date: ____ Participant # ____

Personal Information			
* Name		Gender	Male Female
* Phone			
* Email			
* May we contact you for future studies?			no yes
* Born (month / day / yr)			___ / ___ / ___
* Occupation (if retired, main occupation before retirement)			
* Education (circle highest completed)			High-School Some-College College-Degree Graduate-School
* Major (Ex: Cognitive Psychology, Micro-Biology, Accounting)			
* In how many UMTRI studies have you participated in the past 2 years excluding this one?			

Driving and Technology Use			
* What do you drive most often?	Year __________ Make __________ Model ________		
* How many miles do you drive per year?			
* When did you get your first driver's license? (the year)			
* For an expressway with 3 lanes in each direction, in which lane would you typically drive?	Left	Center	Right
* How many moving violation tickets have you had in the past 12 months?			
* How many police-reported crashes have you had in the past 5 years?			
* Have you been involved in any crashes that occurred at an intersection in the last 10 years?	Yes	No	
* If yes, please describe each crash (month and year approximately, time of day, which intersection, drawing of crash, etc.). Include the location of stop signs, yield signs and traffic lights (if applicable).			

Vision Circle what vision correction you use			
When driving:	no-correction	contacts	glasses: multifocal, bifocal, reading, far-vision
When reading:	no-correction	contacts	glasses: multifocal, bifocal, reading, far-vision

For the experimenter only

Far Acuity		1	2	3	4	5	6	7	8	9	10	11	12	13	14
		T	R	R	L	T	B	L	R	L	B	R	B	T	R
	20/200		100	70	50	40	35	30	25	22	20	18	17	15	13
80 cm Acuity		1	2	3	4	5	6	7	8	9	10	11	12	13	14
		T	R	R	L	T	B	L	R	L	B	R	B	T	R
Color-Abnormality		A	B	C	D	E	F								
		12	5	26	6	16	~								

APPENDIX D. POST TEST QUESTIONNAIRE

Post-Test Questions

Date: ______ **Participant Number:** ______

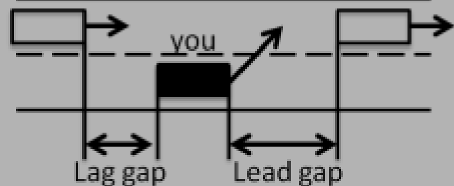
Intersections: On an average day, how many intersections do you drive through	that have a sign where you must stop or yield	
	that have a traffic light	

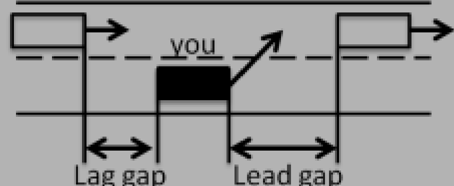
Note: 1 All of the questions that follow concern driving in the day time, in good weather and on a dry, paved road.
2 **Heavy** traffic: traffic is moving below the speed limit and changing lanes is not easy
3 **Moderate** traffic: traffic is near the speed limit, and lane changing occurs
4 **Light** traffic: traffic is moving the above speed limit, and lane changing is easy

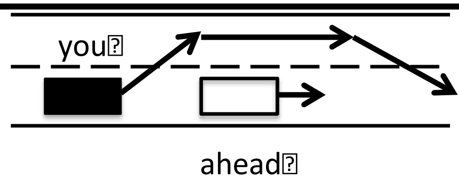
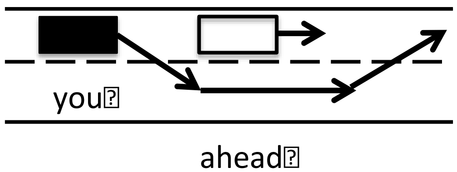
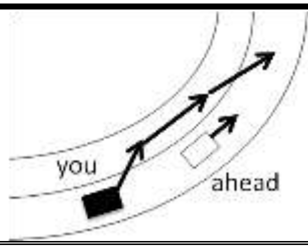
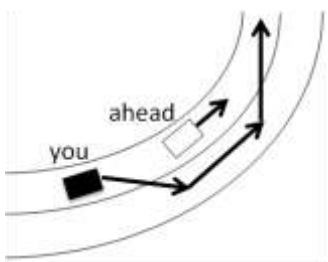
Driving on an urban road (speed limit = 35 mph) 1 lane in each direction	How fast do you normally drive? (mi/hr)	How many car lengths behind?		
		For usual following	How close would be uncomfortable	
heavy traffic				
moderate traffic				
light traffic				

Driving on an urban road (speed limit = 45 mph) 2 lanes in each direction, driving in the right lane	How fast do you normally drive? (mi/hr)	How many car lengths behind?		When changing lanes, what % of the time do you use a turn signal?
		For usual following	How close would be uncomfortable	
heavy traffic				
moderate traffic				
light traffic				

Driving on an expressway (speed limit = 70 mph) 2 lanes in each direction, driving in the right lane	How fast do you normally drive? (mi/hr)	How many car lengths behind?		When changing lanes, what % of the time do you use a turn signal?
		For usual following	How close would be uncomfortable	
heavy traffic				
moderate traffic				
light traffic				

Changing lanes on an urban road (speed limit = 45 mph) 2 lanes in each direction, driving in the right lane 	How many car lengths for the lead gap?		How many car lengths for the lag gap?	
	For usual driving	How close would be uncomfortable	For usual driving	How close would be uncomfortable
heavy traffic				
moderate traffic				
light traffic				

Changing lanes on an expressway (speed limit = 70 mph) 2 lanes in each direction, driving in the right lane 	How many car lengths for the lead gap?		How many car lengths for the lag gap?	
	For usual driving	How close would be uncomfortable	For usual driving	How close would be uncomfortable
heavy traffic				
moderate traffic				
light traffic				

How dangerous is passing on expressways (speed limit = 70 mph)								
2 lanes in each direction		not at all						very
	**heavy** traffic	1	2	3	4	5	6	7
	moderate traffic	1	2	3	4	5	6	7
	light traffic	1	2	3	4	5	6	7
	**heavy** traffic	1	2	3	4	5	6	7
	moderate traffic	1	2	3	4	5	6	7
	light traffic	1	2	3	4	5	6	7
How dangerous is passing on a curve on expressways (speed limit = 70 mph) See example on next page								
2 lanes in each direction		not at all						very
	**heavy** traffic	1	2	3	4	5	6	7
	moderate traffic	1	2	3	4	5	6	7
	light traffic	1	2	3	4	5	6	7
	**heavy** traffic	1	2	3	4	5	6	7
	moderate traffic	1	2	3	4	5	6	7
	light traffic	1	2	3	4	5	6	7

APPENDIX E. FULL INTERSECTION LIST

Block 1

Its#	Road Name	Combo	code	Signal	Conflict
1	Martin Dr			Green	
2	Taylor Dr			Green	
3	Adams Dr			Green	
4	Queen Dr			Red	
5	Holt Dr			Green	
6	Park Dr	30	SLGoSt	yellowE	
7	Cobb Dr	20	StGoSt	Green	
8	Neff Dr	28	*GoSlSt*	yellowM	SCP
9	Fox Dr	57	*StGoSR*	yellowE	
10	Taylor Rd	25	StGoSt	YellowM	
11	Adams Rd	32	SLGoSt	yellowL	
12	Queen Rd	46	StTRSt	Green	
13	Holt Rd	61	*StGoTR*	yellowM	*RTIP*
14	Park Rd	15	StGoSt	Green	
15	Cobb Rd	3	GoStGo	Red	
16	Neff Rd	10	StGoSt	Green	
17	Fox Rd	**31**	**SLGoSt**	**yellowM**	
18	Martin Rd	**4**	**GoStGo**	**Red**	
19	Adams St	**38**	**StSLSt**	**Green**	
20	Queen St	**55**	***StSlTL***	**yellowM**	***LTAP/LD***
21	Holt St	**11**	**StGoSt**	**Green**	
22	Park St	**45**	***StTLSt***	**YellowL**	***LTAP/OD***
23	Cobb St	18	StGoSt	Green	
24	Neff St	40	StSLSt	yellowM	
25	Fox St	47	StTRSt	yellowE	
26	Martin St	54	StGoSL	yellowL	
27	Taylor St	1	GoStGo	Red	
28	Adams St	44	*StTLSt*	yellowM	*LTAP/OD*
29	Queen Ln	39	StSLSt	YellowE	
30	Park Ln	12	StGoSt	Green	
31	Cobb Ln	19	StGoSt	Green	
32	Neff Ln	53	StGoSL	yellowM	
33	Fox Ln	26	StGoSt	YellowL	
34	Martin Ln	60	*StGoTR*	Green	*RTIP*
35	Taylor Ln	34	TRSlSt	Green	
36	Adams Ln	7	GoStGo	Red	
37	Queen St	41	StSLSt	yellowL	

38	Park Ave	14	StGoSt	Green	
39	Cobb Ave	48	StTRSt	yellowM	
40	Neff Ave	21	StGoSt	Green	
41	Fox Ave	56	*StGoSR*	Green	
42	Martin Ave	29	SLGoSt	Green	
43	Taylor Ave	2	GoStGo	Red	
44	Adams Ave	36	TRSlSt	YellowM	
45	Queen Ave	9	StGoSt	Green	
46	Holt Ave	**33**	***TLSlSt***	**YellowM**	**LTIP**
47	Cobb Way	35	TRSlSt	YellowE	
48	Neff Way	16	StGoSt	Green	
49	Fox Way	50	*StSlGo*	YellowM	*SCP*
50	Martin Way	6	GoStGo	Red	
51	Taylor Way	23	StGoSt	YellowE	
52	Adams Way	13	StGoSt	Green	
53	Queen Way	17	StGoSt	Green	
54	Holt Way	51	StGoSL	Green	
55	Park Way	43	*StTLSt*	yellowE	*LTAP/OD*
56	Taylor St	24	StGoSt	YellowM	
57	Adams St	58	StGoSR	yellowM	
58	Queen St	49	StTRSt	yellowL	
59	Holt St	27	StGoSt	YellowL	
60	Adams Rd	5	GoStGo	Red	
61	Park St	22	StGoSt	YellowE	
62	Cobb St	42	*StTLSt*	Green	*LTAP/OD*
63	Neff St	52	StGoSL	YellowE	
64	Fox St	59	StGoSR	yellowM	
65	Martin Rd	8	StGoSt	Green	
66	Taylor Rd	37	TRSlSt	YellowL	
67	Adams Rd			Green	
68	Queen Rd			Green	
69	Holt Rd			Green	
70	Park Rd				

Block 2

Its#	Road Name	Combo	code	Signal	Conflict
1	Martin Dr			Green	
2	Taylor Dr			Green	
3	Adams Dr			Green	
4	Queen Dr			Red	
5	Holt Dr			Green	
6	Taylor Rd	37	TRSlSt	YellowL	
7	Martin Rd	8	StGoSt	Green	
8	Fox St	59	StGoSR	yellowM	
9	Neff St	52	StGoSL	YellowE	
10	Cobb St	42	*StTLSt*	Green	*LTAP/OD*
11	Park St	22	StGoSt	YellowE	
12	Adams Rd	5	GoStGo	Red	
13	Holt St	27	StGoSt	YellowL	
14	Queen St	49	StTRSt	yellowL	
15	Adams St	58	StGoSR	yellowM	
16	Taylor St	24	StGoSt	YellowM	
17	Park Way	43	*StTLSt*	yellowE	*LTAP/OD*
18	Holt Way	51	StGoSL	Green	
19	Queen Way	17	StGoSt	Green	
20	Adams Way	13	StGoSt	Green	
21	Taylor Way	23	StGoSt	YellowE	
22	Martin Way	6	GoStGo	Red	
23	Fox Way	50	*StSlGo*	YellowM	*SCP*
24	Neff Way	16	StGoSt	Green	
25	Cobb Way	35	TRSlSt	YellowE	
26	Holt Ave	**33**	***TLSlSt***	**YellowM**	**LTIP**
27	Queen Ave	9	StGoSt	Green	
28	Adams Ave	36	TRSlSt	YellowM	
29	Taylor Ave	2	GoStGo	Red	
30	Martin Ave	29	SLGoSt	Green	
31	Fox Ave	56	*StGoSR*	Green	
32	Neff Ave	21	StGoSt	Green	
33	Cobb Ave	48	StTRSt	yellowM	
34	Park Ave	14	StGoSt	Green	
35	Queen St	41	StSLSt	yellowL	
36	Adams Ln	7	GoStGo	Red	
37	Taylor Ln	34	TRSlSt	Green	
38	Martin Ln	60	*StGoTR*	Green	*RTIP*

39	Fox Ln	26	StGoSt	YellowL	
40	Neff Ln	53	StGoSL	yellowM	
41	Cobb Ln	19	StGoSt	Green	
42	Park Ln	12	StGoSt	Green	
43	Queen Ln	39	StSLSt	YellowE	
44	Adams St	44	*StTLSt*	yellowM	*LTAP/OD*
45	Taylor St	1	GoStGo	Red	
46	Martin St	54	StGoSL	yellowL	
47	Fox St	47	StTRSt	yellowE	
48	Neff St	40	StSLSt	yellowM	
49	Cobb St	18	StGoSt	Green	
50	Park St	**45**	***StTLSt***	**YellowL**	***LTAP/OD***
51	Holt St	**11**	**StGoSt**	**Green**	
52	Queen St	**55**	***StSlTL***	**yellowM**	***LTAP/LD***
53	Adams St	**38**	**StSLSt**	**Green**	
54	Martin Rd	**4**	**GoStGo**	**Red**	
55	Fox Rd	**31**	**SLGoSt**	**yellowM**	
56	Neff Rd	10	StGoSt	Green	
57	Cobb Rd	3	GoStGo	Red	
58	Park Rd	15	StGoSt	Green	
59	Holt Rd	61	*StGoTR*	yellowM	*RTIP*
60	Queen Rd	46	StTRSt	Green	
61	Adams Rd	32	SLGoSt	yellowL	
62	Taylor Rd	25	StGoSt	YellowM	
63	Fox Dr	57	*StGoSR*	yellowE	
64	Neff Dr	28	*GoSlSt*	yellowM	SCP
65	Cobb Dr	20	StGoSt	Green	
66	Park Dr	30	SLGoSt	yellowE	
67	Adams Rd			Green	
68	Queen Rd			Green	
69	Holt Rd			Green	
70	Park Rd				

APPENDIX F. CRAIGSLIST FLYER

Subjects are needed
Center for Ergonomics experiment
Warning Systems for Driving Intersections

1. Experiment involves driving a simulator with many intersections
2. Subjects will be videotaped and performance recorded
3. Data will be sent to collaborators at MIT (without your name)
4. Outtakes will be used in presentations, and by the media (on TV)

Qualified participants must be:

1. licensed driver
2. in generally good health for driving
3. 18-30, >65 years old
4. native US English speaker
5. no susceptible to motion sickness (the experiment involves a driving simulator)

Pays $50 total = 1 2-1/2 hour session

Contact Guofa or Heejin at 734 763 6081 or email guofali@umich.edu, heejinj @umich.edu

APPENDIX G. PHONE SPIEL

NSF PHONE SPIEL

Hello, this is ***. Who is calling? XXX.

XXX, The University of Michigan is conducting a series of experiments to evaluate driver responses to crash warning systems at intersections.   At this point, we are only are collecting data how people normally drive through intersections, not how they react to warnings.

Here is what we will be doing. At our lab, for which directions will be provided later, you will begin by signing a consent form. Next, we will obtain some biographical data (your age, driving experience, etc.) and driving data (e.g., miles drive/year), and check your vision, followed by a brief drive in the driving simulator to verify there are no problems with motion discomfort. Because there is minimal turning in this experiment and the simulator uses small screens, motion discomfort is much less likely than for other simulators and experiments. However, should it occur, we will stop the experiment. Should there be a problem, you can elect to stop at any time, and we will pay you in full even if you do not complete the experiment. There are no other risks associated with this experiment.

However, just to check…

As a passenger, can you read a book or newspaper in a moving vehicle (for motion discomfort)?

In general, do you get car sick easily?

Have you been in other driving simulator experiments before? If yes, did you have any motion discomfort?

Are you susceptible to other forms of motion discomfort—when flying, on a boat or ship…?

Do you take any medicine that have side effect of dizziness? If yes, then "Thank you for your time, unfortunately, you can not participate in this experiment."

This main portion of the experiment will consist of several 25-minute drives in which you drive through a sequence of over 60 intersections following a lead vehicle and obeying the traffic signals. At each intersection there may be other vehicles turning that you will avoid. In addition, we are also collecting some additional data on how drivers follow lead vehicles for another project. At the end, there will a short questionnaire about the experiment. For this 2-1/2 hour experiment we will pay you $50.

While you are driving, computers will record your driving, and we will collect video recordings of you, your driving and what you say. The video recordings are of great interest to the sponsor, to us, and to the media. In fact, if we cannot release the videos, then you cannot participate. Who knows, you could end up on TV.   Of course, we will not give them your name, phone number, etc.

With the understanding that your actions would be recorded/videotaped and those clips could be released without asking you again, are you interested in participating?

Great, I need to ask you a few questions before I know whether you can be a subject,

1. What's your name? (note male or female)
2. What is your date of birth?
3. Do you wear corrective lenses when driving?

Ok, let's schedule a time for you to come in *<schedule time>.*

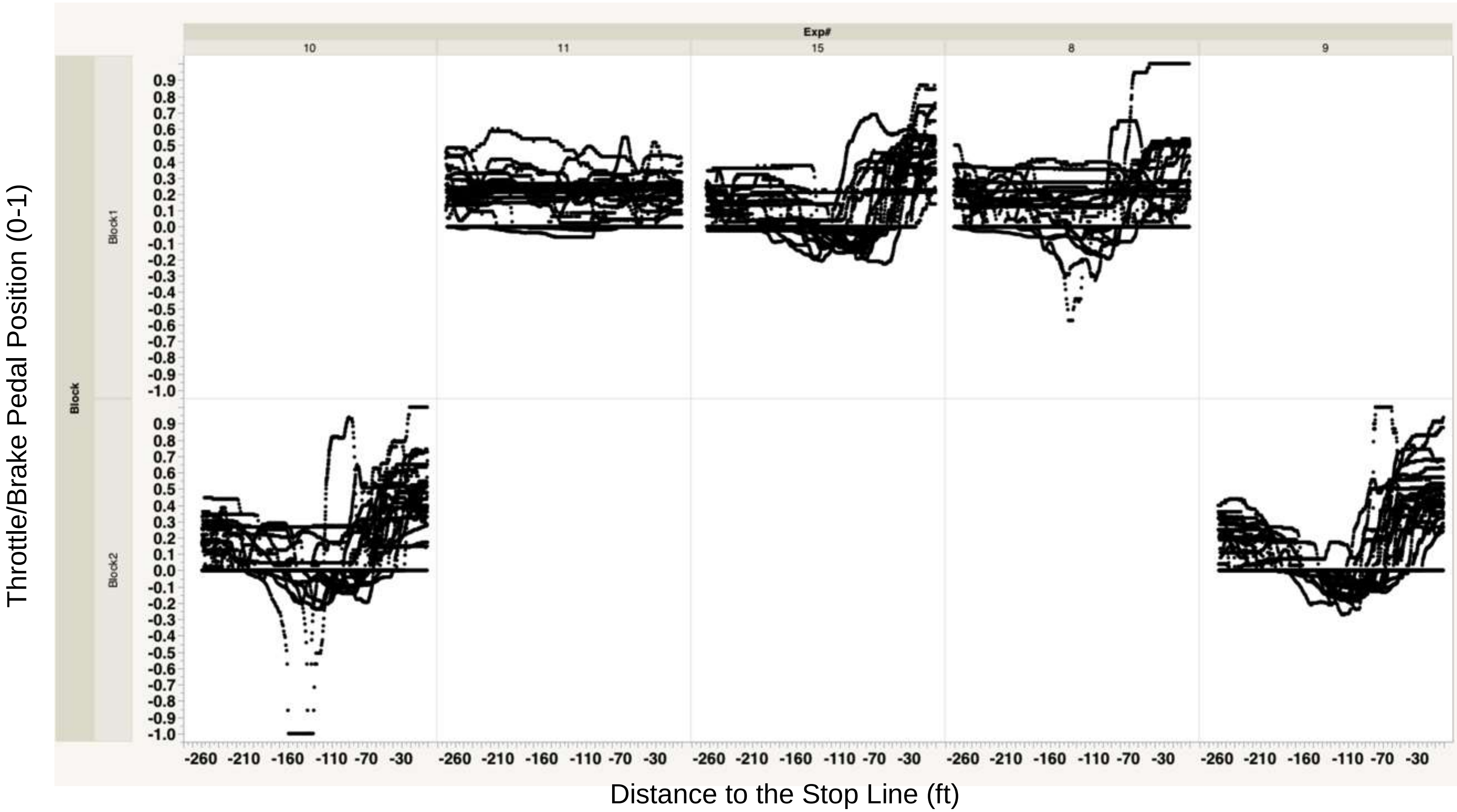
Thanks very much, I've got all of the information I need. When you come in, please bring whatever vision correction you use while driving as will be checking your vision. Go to the Industrial and Operations Engineering Building and I will meet you in the lobby with a parking pass and then take you to the experiment. Do you need directions to the Industrial and Operations Engineering Building?

<If directions are needed to one of the following: give directions at this time, tell them they can visit our website for directions or get their e-mail address and send directions>

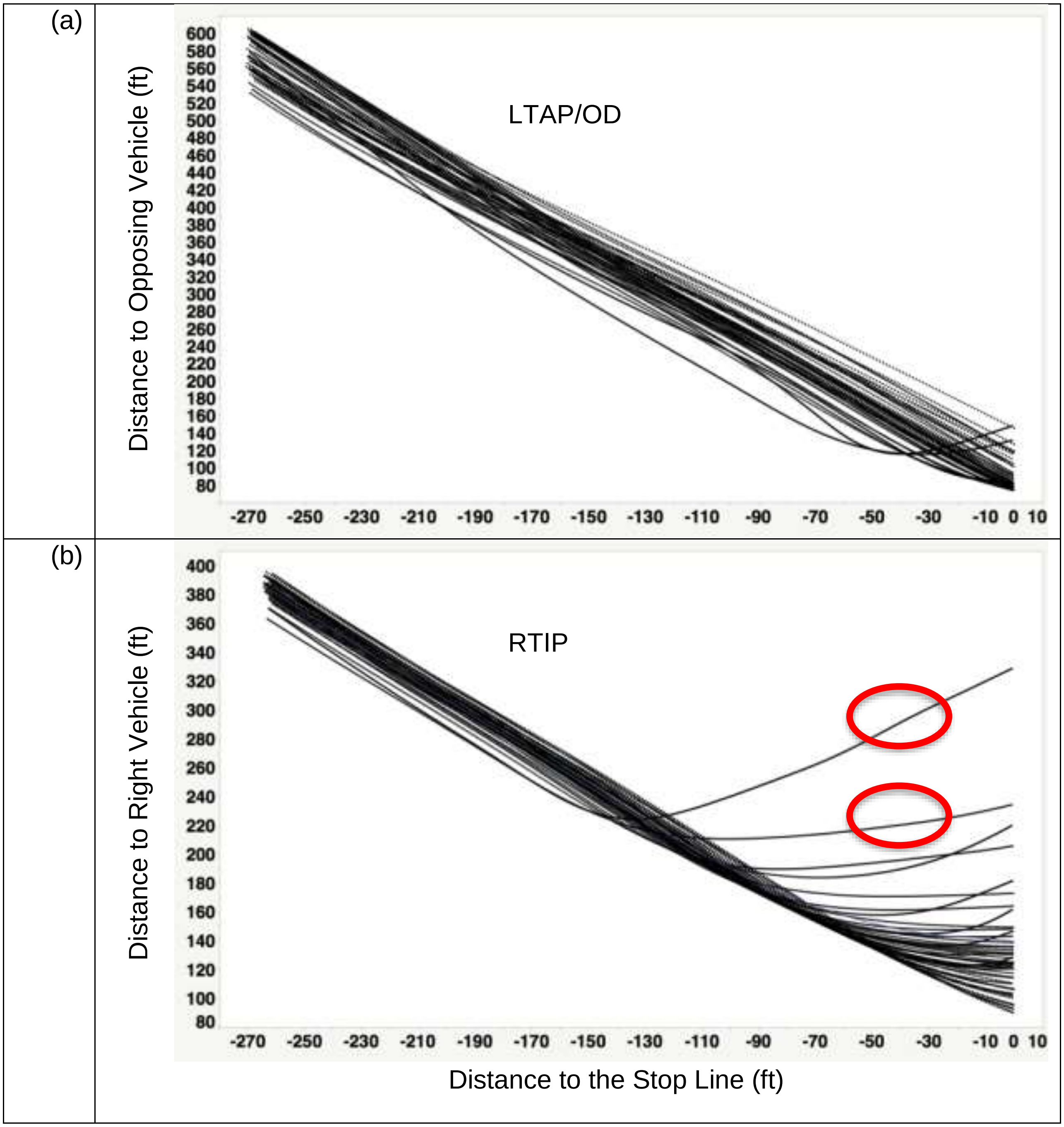
<Tell subject not to wear eye make-up when they come in>

Do you have any other questions? Ok, we'll see you at *<time>* on *<date>*.

APPENDIX H. FIGURES FOR PASSING THROUGH AND EXITING INTERSECTION CASES

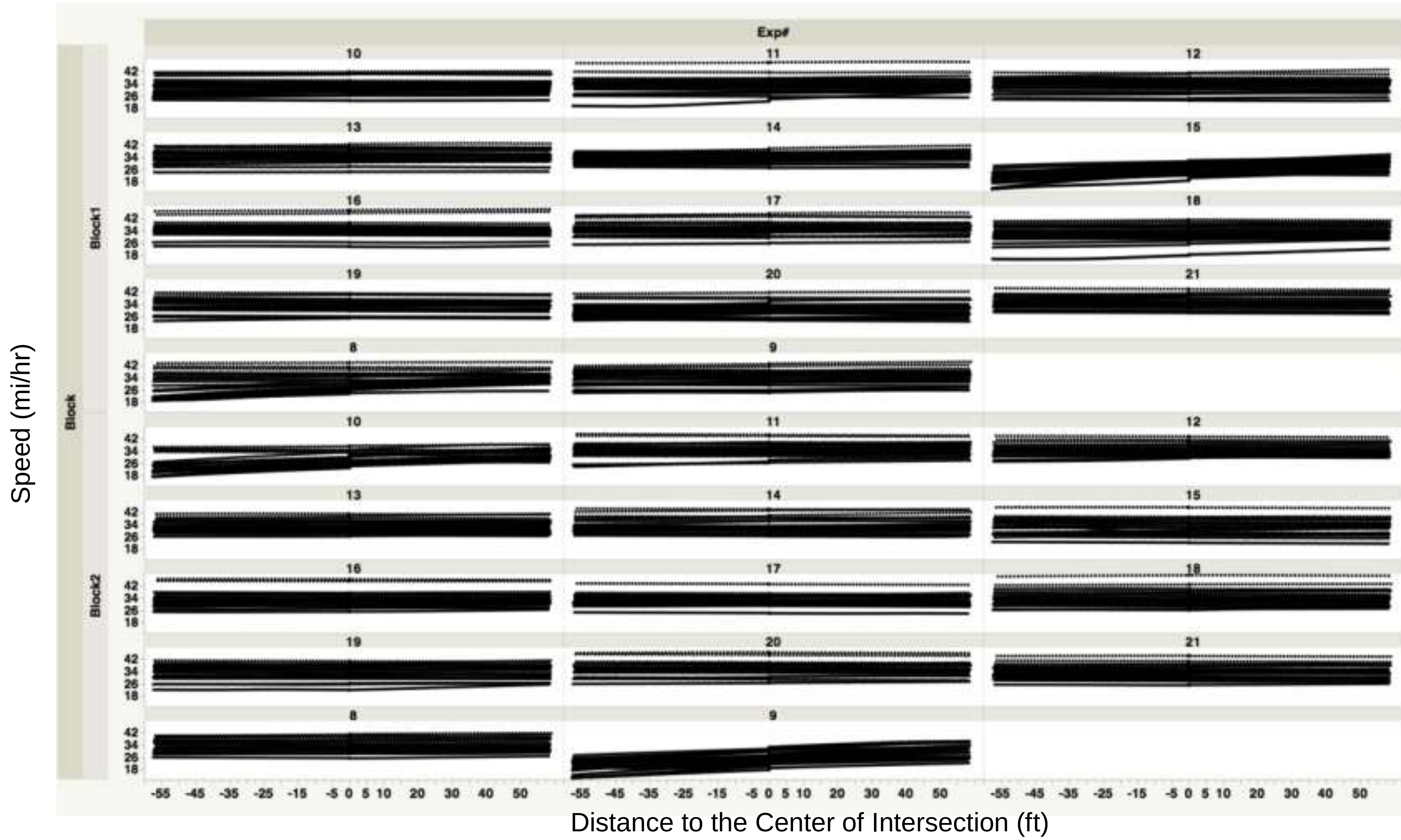


Appendix H1. Accelerator and Brake Pedal Positions for 5 Intersections at Different Distances to the Stop Line for 24 Subjects (Green Light, No Conflict, When Approaching Intersections)



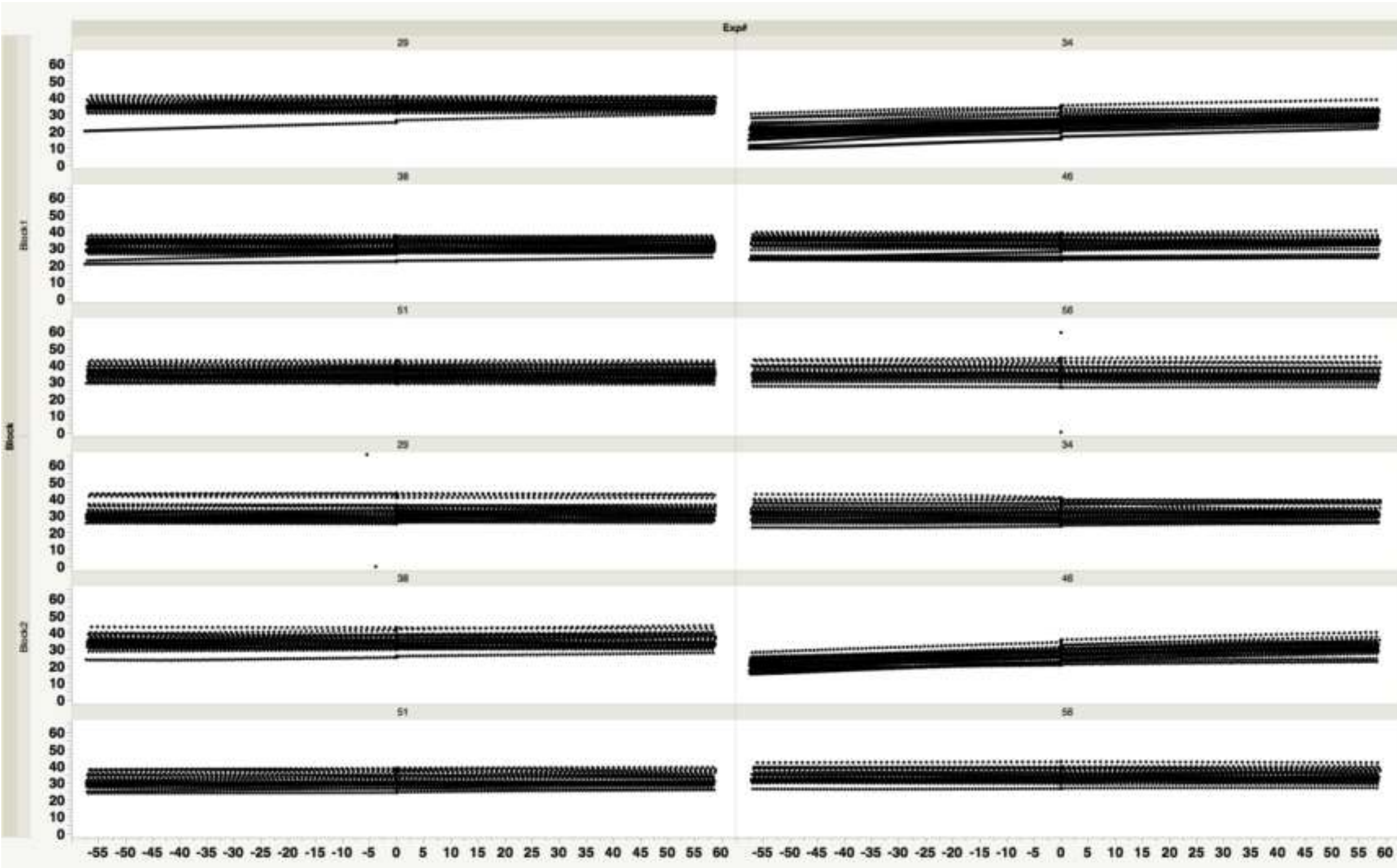
Appendix H2. Distance to (a) Opposing Vehicle of LTAP/OD and (b) Right Vehicle of RTIP at Different Distances to the Stop Line, When Approaching the Intersection with a Green Light (Scenarios with Conflicts)

Note: The red circles in Figure 13b are cases where subjects drove slower (about 20 mi/hr) than the right vehicle, so the distance in between them increased.



Appendix H3. Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects by 2 Blocks (Green Light, No Conflict, When Going through Intersections)

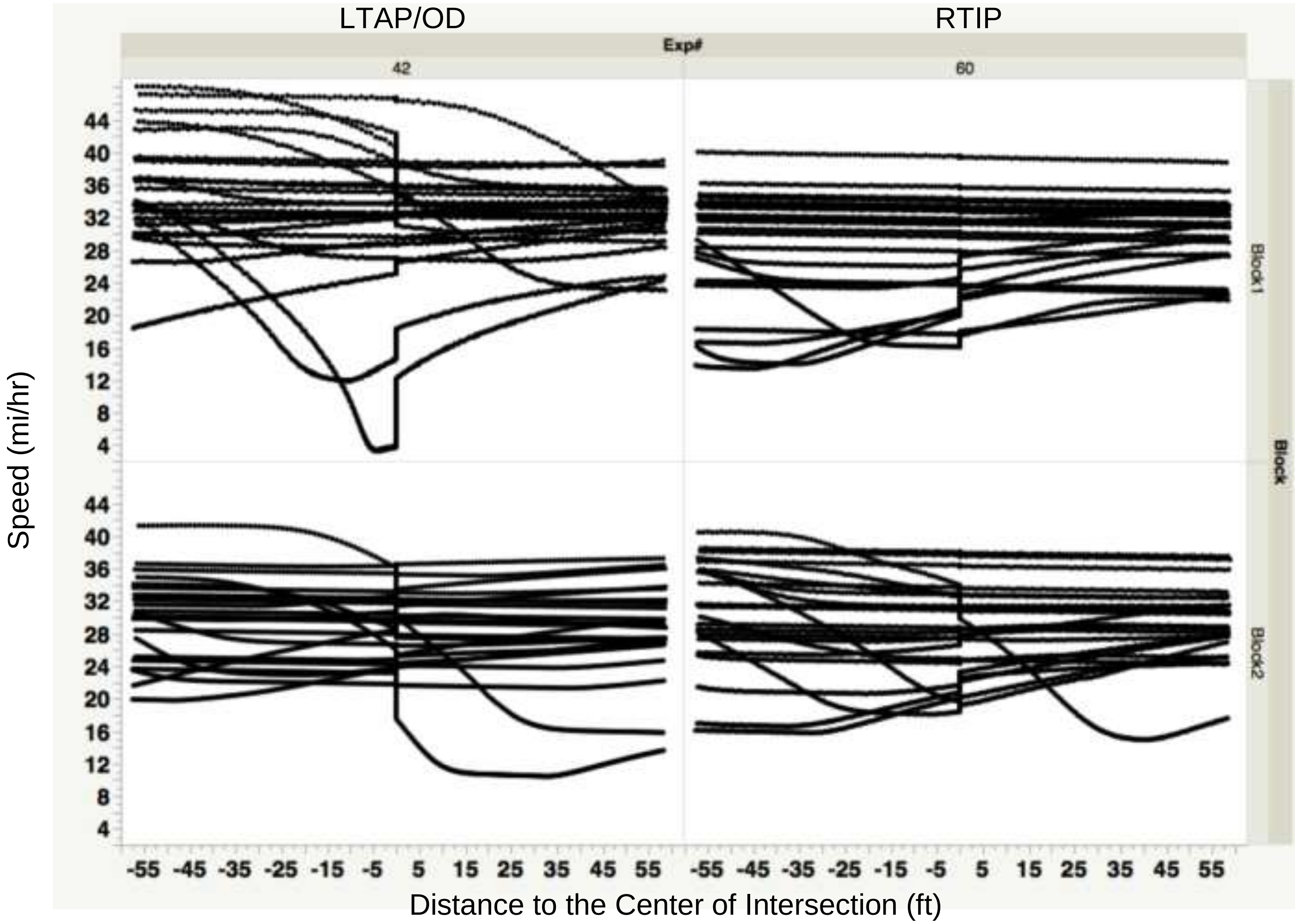
For no conflict scenarios (nor maneuvers by other vehicles), the speed was very stable. For some intersections, the speed increased (e.g. B1-Int-15 and B2-Int-9) because the lead vehicle changed.



Distance to the Center of Intersection (ft)

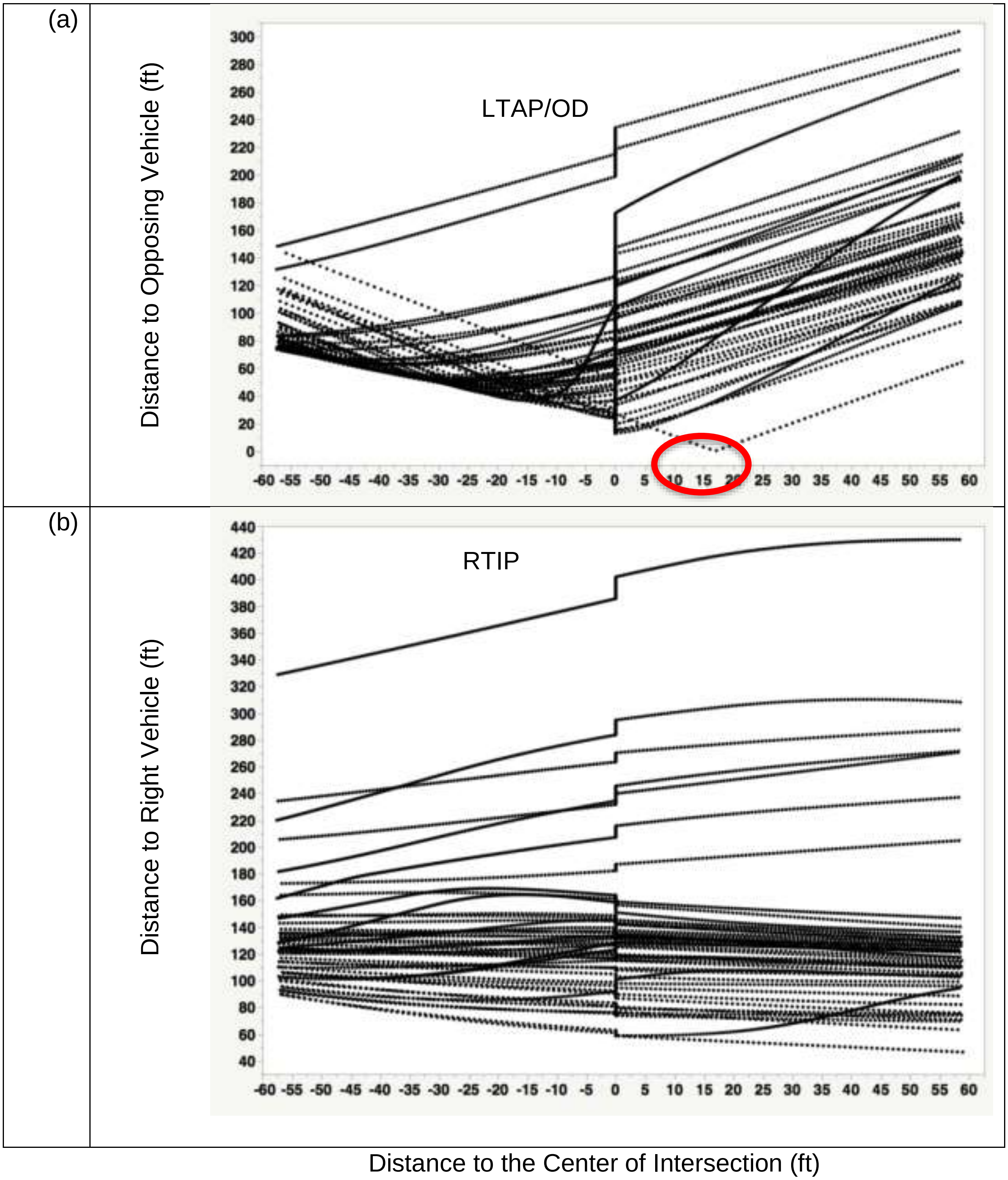
Appendix H4. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects by 2 Blocks (Green Light, No Conflict, Other Traffic Had Maneuvers, When Going through Intersections)

Appendix H4 shows the scenarios for which there was no conflict but other vehicles maneuvered. When subjects were in the intersection, subjects had previously confirmed that no conflict occurred, so they would either maintain their speed or accelerate if they slowed down for potential risks before entering the intersection.



Appendix H5. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects by 2 Blocks
(Green Light, Scenarios with Conflicts, When Going through Intersections)

For the intersections with LTAP/OD and RTIP conflicts, the change of speed was shown as Appendix H5. At 12 of the 48 intersections (25%) of LTAP/OD, subjects chose to slow down to avoid the vehicle from opposing direction. When they drove at 40 mph or faster, they would decelerate. If subjects drove slowly, say 20-25 mph, they would accelerate when passing through the intersection because there was no longer a conflict and the intersection was free of other traffic.

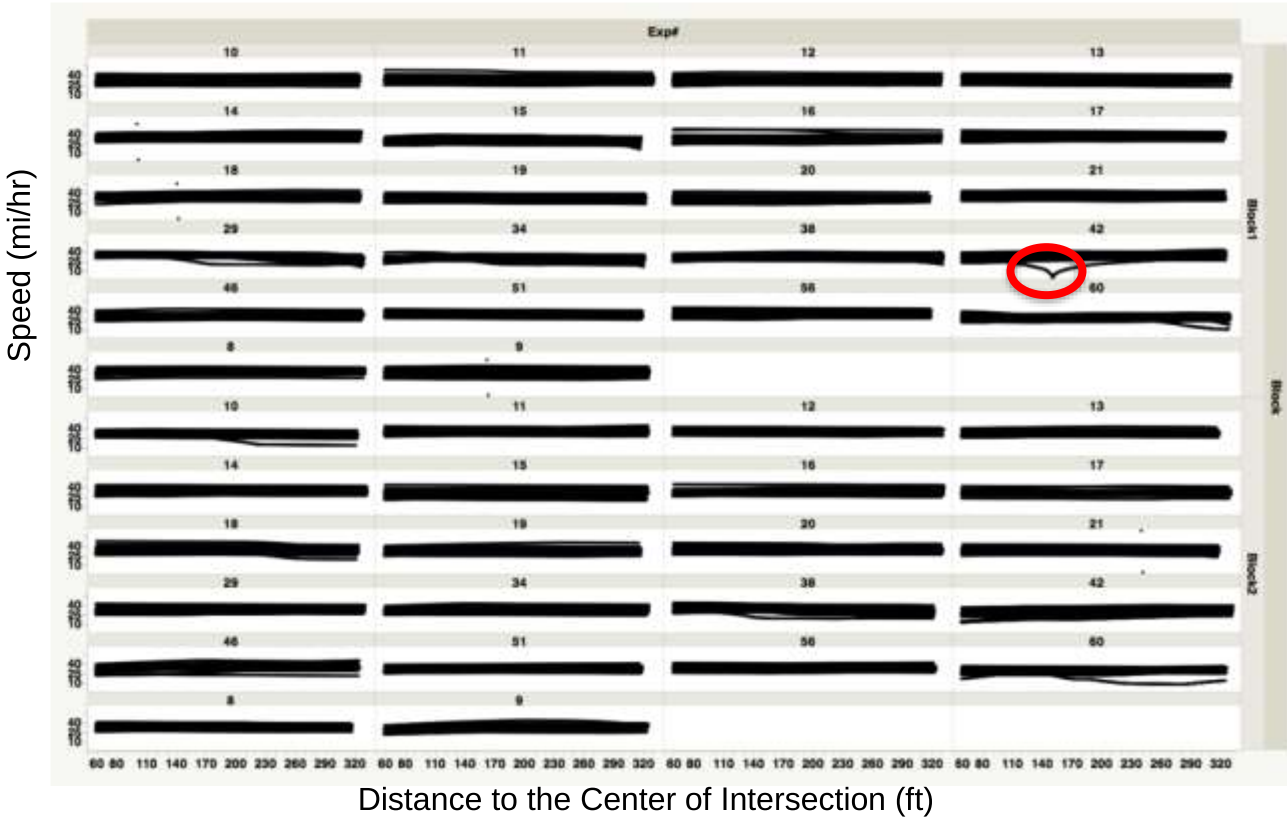


Appendix H6. Distance to (a) Opposing Vehicle of LTAP/OD and (b) Right Vehicle of RTIP at Different Distances to the Stop Line,
(Green Light, Scenarios with Conflicts, When Going through Intersections)

Appendix H6a shows the change of distance to the opposing vehicle.

The RTIP conflict intersections resulted in less aggressive deceleration than LTAP/OD because the vehicle toe the right moved in the same direction as the subjects vehicle. Most subjects who decided to slow down did so before they reached the stop line (Figure 14) not while going through it (Appendix H5). Therefore, the distance to the vehicle to the right did not change substantially overall, but varied by individual (Appendix H6).

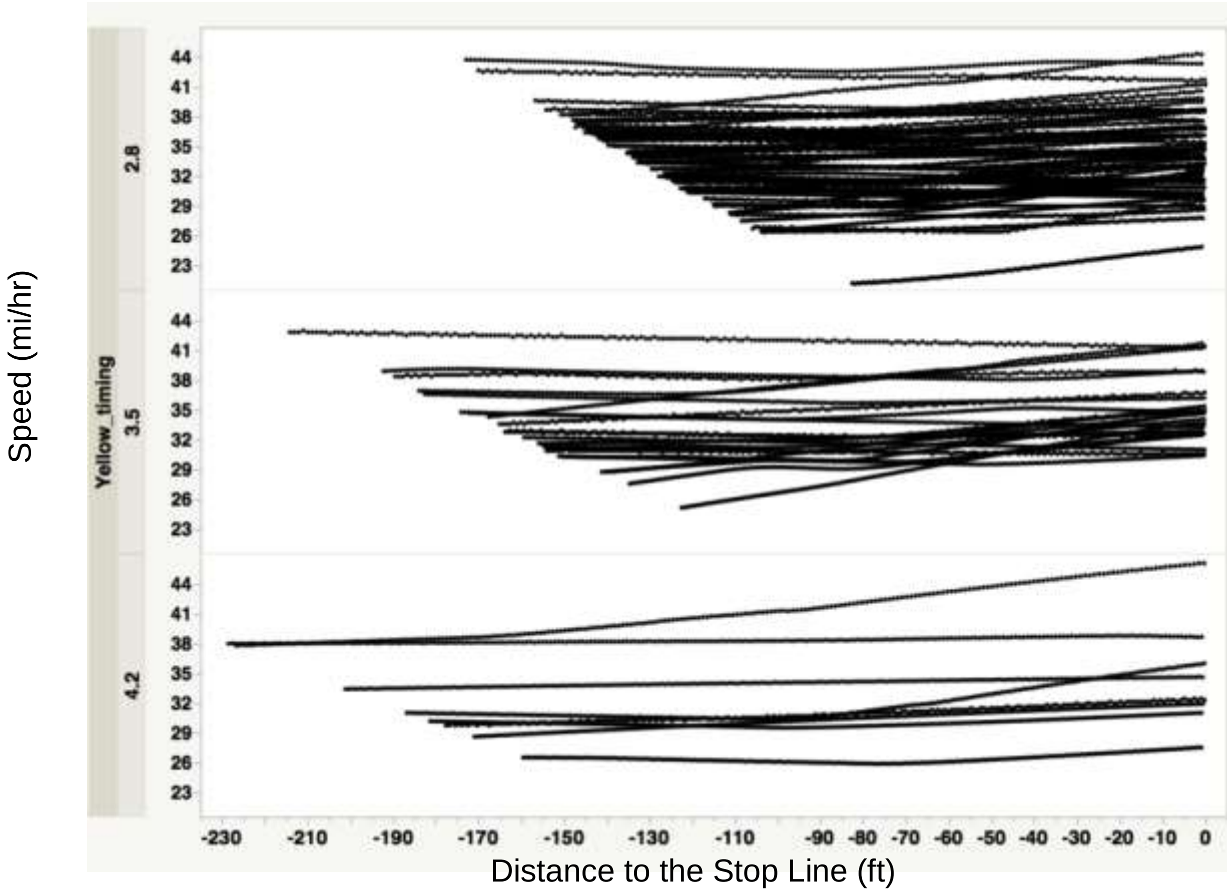
Note: The red circle is for 1 young male subject who ran into the opposing vehicle when that vehicle was turning.



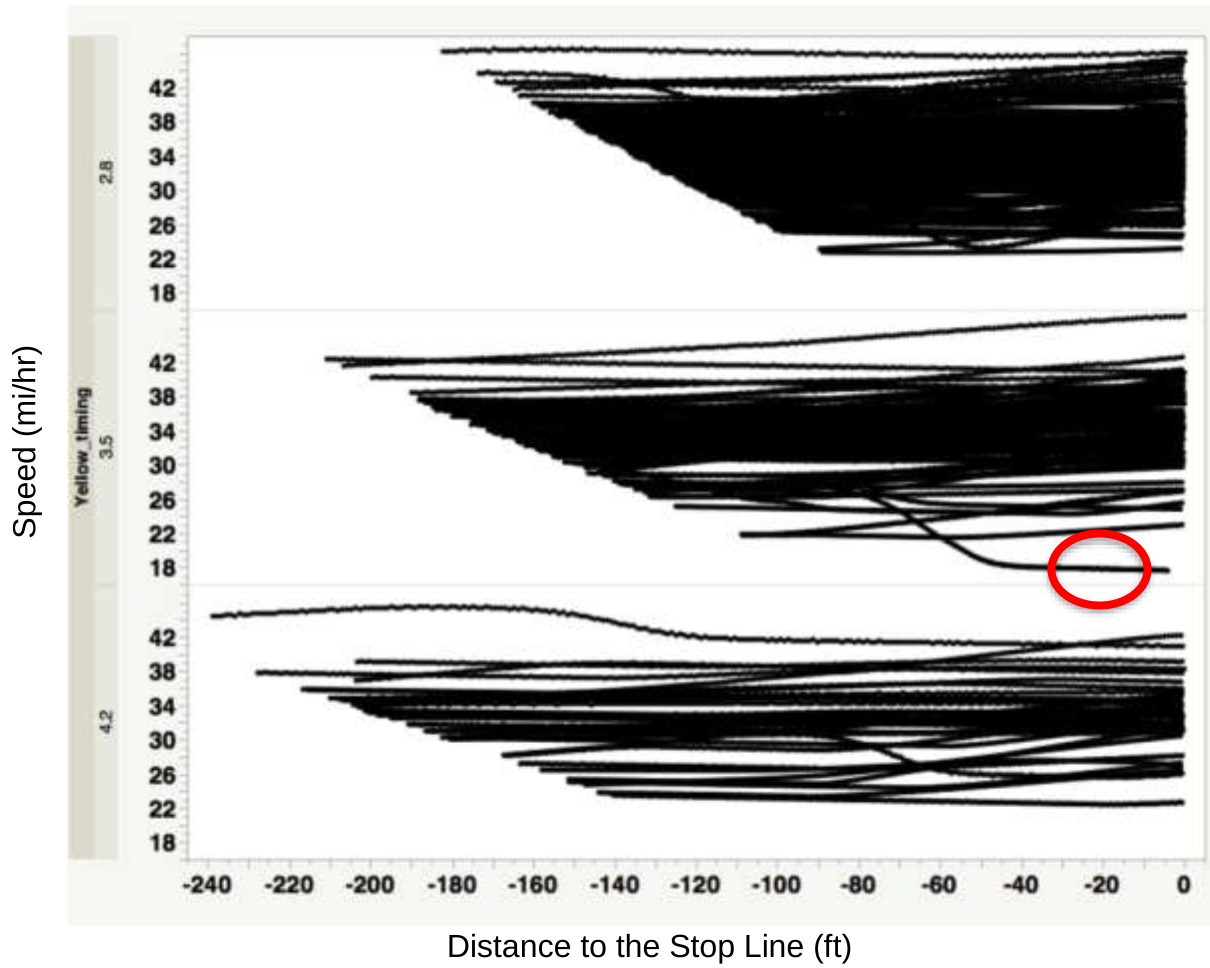
Appendix H7. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects by 2 Blocks
(Green Light, All Scenarios, When Departing Intersections)

Note: The red circle indicates 1 young male subject who collided with an opposing vehicle (LTAP/OD).

When departing the intersection at green light, subjects' behavior was either speeding up or remaining the current speed because potential risks at those intersections did not exist (Appendix H7).

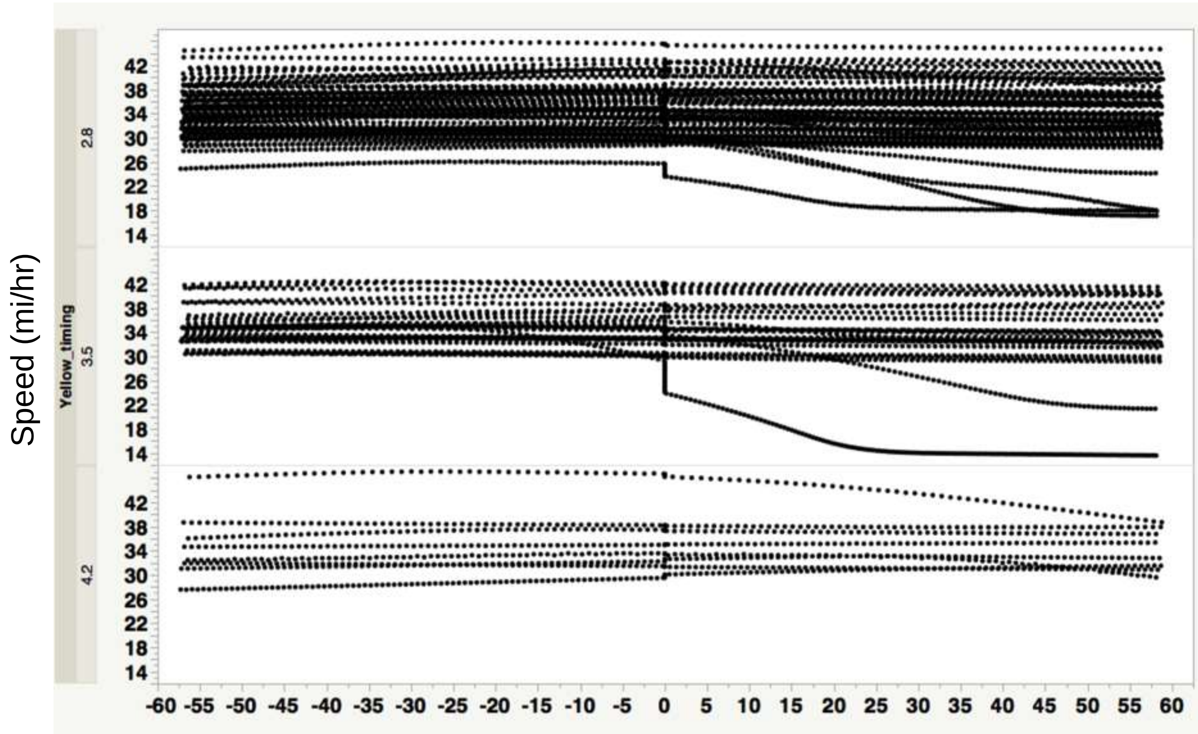


Appendix H8. Vehicle Speed as a Function of Distance to the Stop Line
for Each of the 24 Subjects
(Yellow Light, No Conflict, When Approaching Intersections, Subjects Ran Lights)



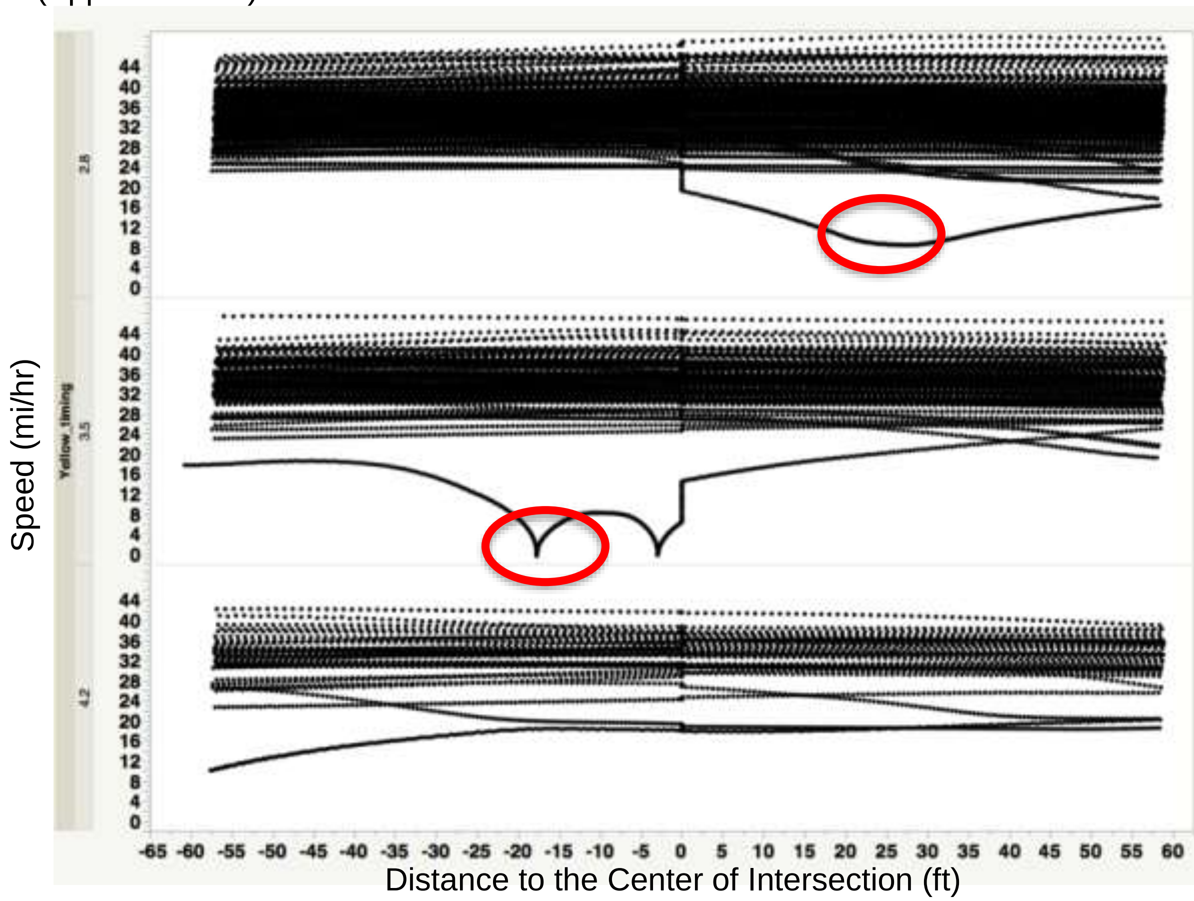
Appendix H9. Vehicle Speed as a Function of Distance to the Stop Line for Each of the 24 Subjects (Yellow Light, No Conflict, Other Traffic Had Maneuvers, When Approaching Intersections, Subjects Ran Lights)
Note: The red circle indicated 1 older male subject who decelerated for a vehicle to the left with its left-turn signal on.

For the intersections without conflict, after entering the intersection, some subjects slowed down for unknown reasons (Appendix H10). All these were older subjects (4 male and 2 female). When the yellow light changed at 4.2 s before the stop line (bottom of Appendix H10), the speed did change.



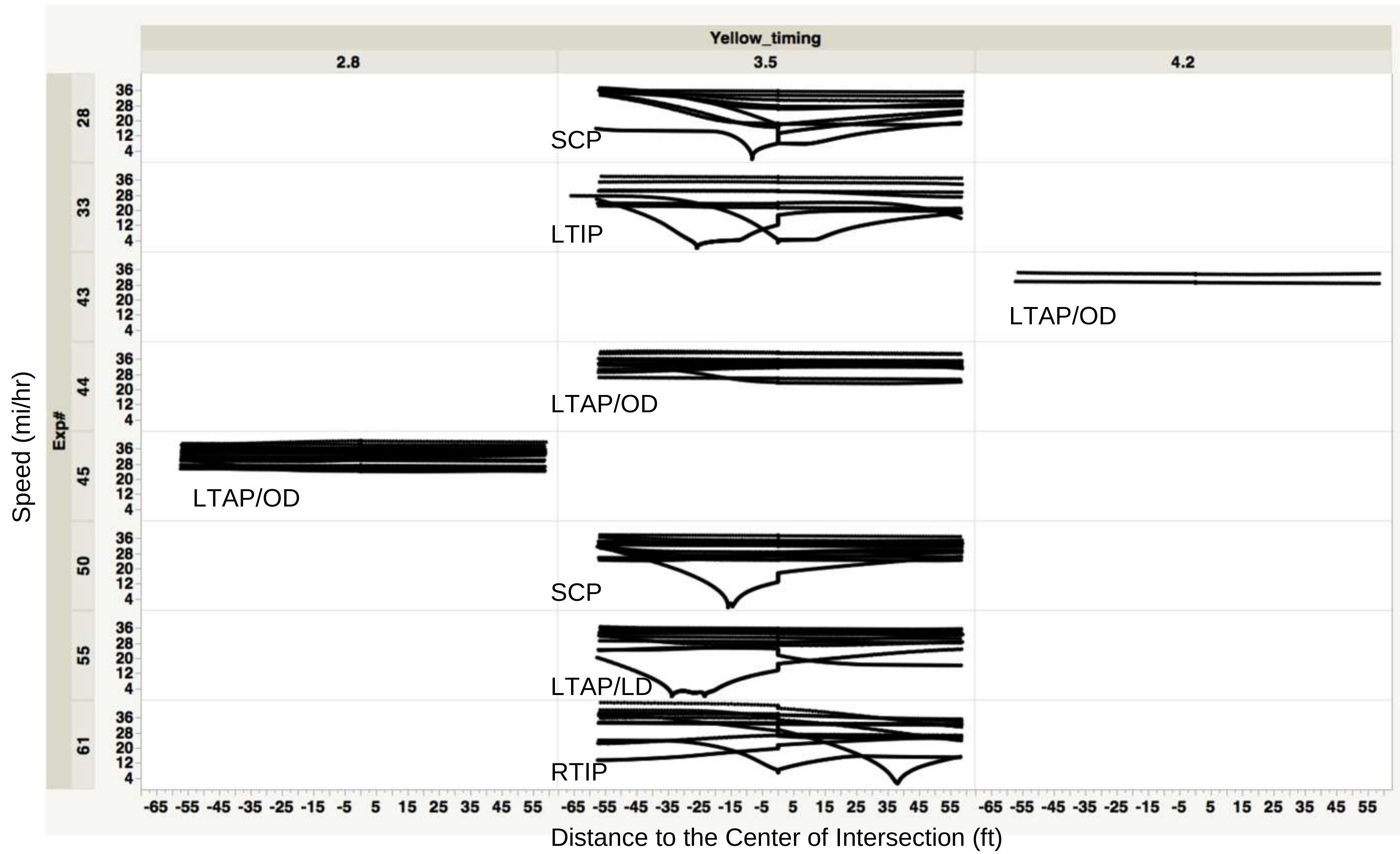
Appendix H10. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects
(Running Yellow Lights with No Conflicts)

When traffic had maneuvers, all subjects had consistent performance except an older male (Appendix H11).



Appendix H11. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects
(Running Yellow Lights with No Conflicts, Other Traffic Had Maneuvers)

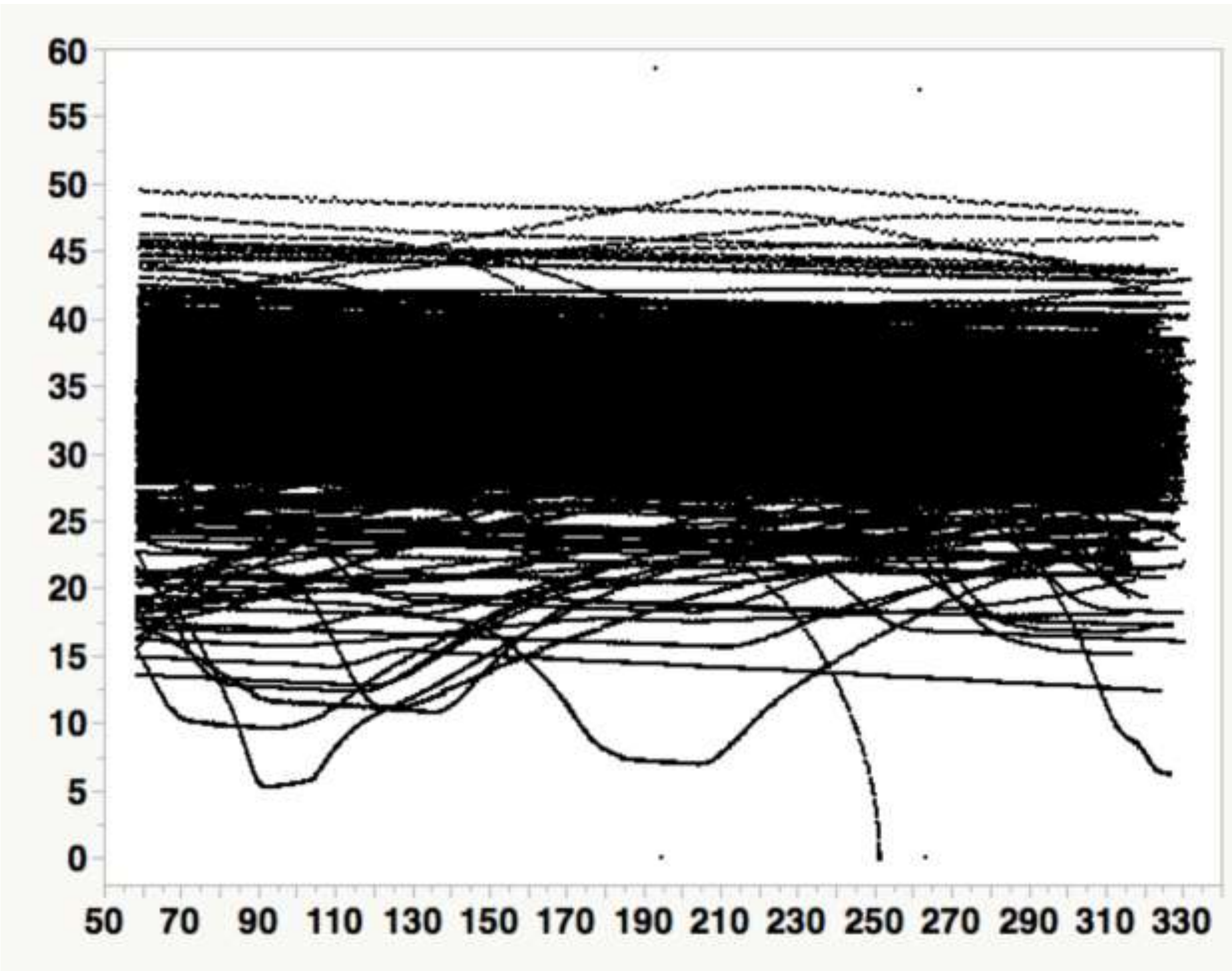
Note: The red circles indicate an older male who decelerated after passing through the center of the intersection for the 2.8 s yellow duration and stopped the vehicle twice for 3.5 s yellow duration.



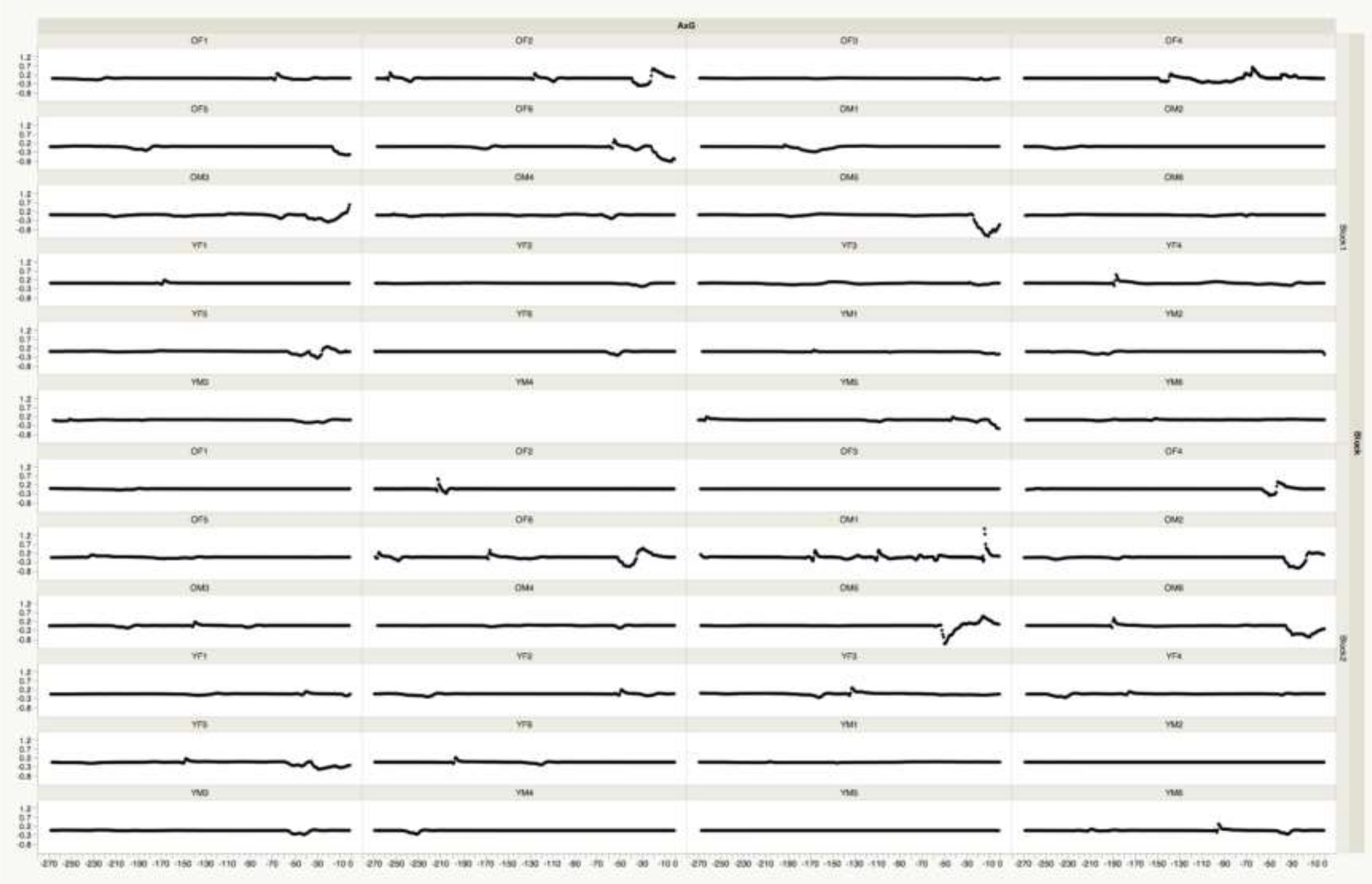
Appendix H12. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects (Running Yellow Lights with Conflicts)

For the intersections with LTAP/OD conflicts, speeds through the intersection were constant. Subjects slowed down for other conflicts (Appendix H12). At Int-28 (SCP from the left), more subjects decelerated than Int-50 (SCP from the right) because the right vehicle crossed subject vehicle path earlier, even before subjects entered the intersection. For RTIP, subjects adjusted their speed to maintain the gap to the vehicle coming from the right, which became the lead vehicle after merging, so deceleration occurred after the center of the intersection.

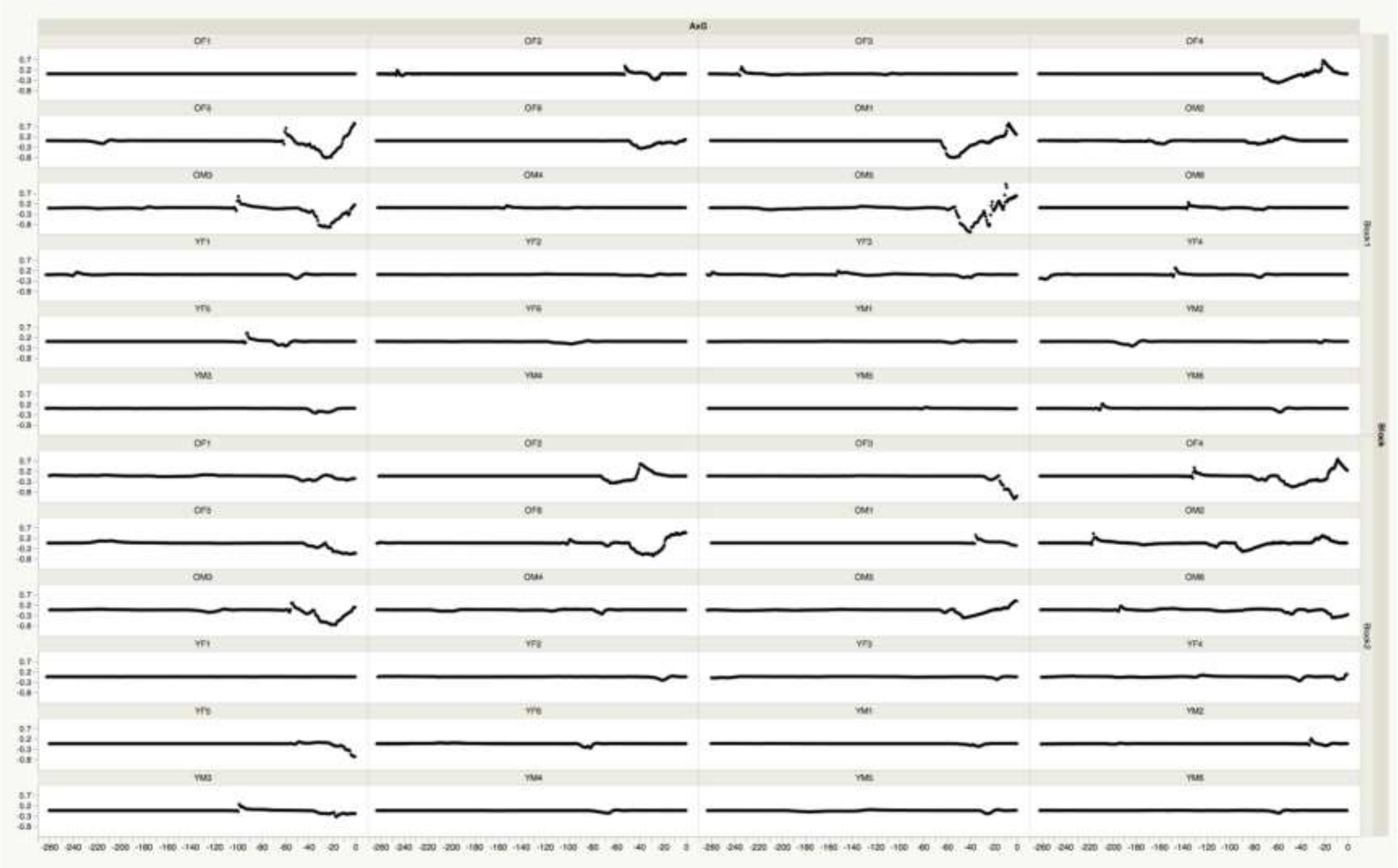
If subjects had run the yellow light, the maneuvers and conflicts associated with other vehicles would usually have no effect to the speed when departing from the intersection. Subjects would slow down (1) when subjects were requested to stop if the last intersection was passed and (2) to maintained a safe gap to the lead vehicle. Appendix H13 shows the speed profile for all intersections. For most cases, the speed did not change as the distance from the center of the just-passed intersection increased. Some older subjects slowed down for unknown reasons.



Appendix H13. Vehicle Speed as a Function of Distance to the Center of Intersection for Each of the 24 Subjects
(Yellow Light, All Scenarios, When Departing Intersections, Subjects Ran Lights)



Appendix H14. Jerk When Approaching the Intersection by Subject (Green Light, LTAP/OD)



Appendix H15. Jerk When Approaching the Intersection by Subject (Green Light, RTIP)