Investigating Critical Driver Behavioral Patterns during the Yellow Phase at Signalized Intersections

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***Abstract*— This paper presents the investigation results of driver behavioral patterns during a yellow phase, based on field observations of 1123 drivers at six signalized intersections of high accident frequency in Maryland. By classifying drivers at each intersection into aggressive pass, conservative stop, and normal groups based on their responses (i.e., stop or pass) and their distances to the stop line when the signal turns yellow, the statistical tests with the ordered-probit model clearly indicate the impacts of some critical factors on a driver's decision. Such factors include: average traffic flow speeds, traffic volume rate, the green split, the number of through and crossing lanes in the target approach, signal coordination, the difference between individual vehicle's approaching speed and average traffic flow speeds, individual driver's gender, age, and talking over cell phone or not, individual vehicle's type and model, and etc. The analysis results offer the basis for assessing the safety conditions at hazardous intersections, and for design of contra measures.**

I. INTRODUCTION

OVER the past decades, intersection related crashes constituted about 30 percent of the total accidents on Maryland state routes (e.g., 34% in 2002 and 35% in 2003). Among those, about 20 percent involved red-light-runnings, which caused either fatal rear-end or side-crash collisions [1]. A tremendous amount of resources have been invested in projects and programs to improve the safety and efficiency at signalized intersections. Despite the progress of those programs, significantly reduced traffic signal related crashes remain a challenging task. One of the main contributors to this dilemma is the lack of sufficient understanding on how individual factors as well as external traffic environments can ultimately have an impact on a driver's decision making process during the yellow phase [2][3].

In review of literature, Horst and Wilmink [4] indicated that such a process is governed by a multitude of factors, including driver attitude and emotional states, the crossing ability before the red phase, consequence of stopping and passing, interactions with other drivers, and the vehicle approaching speed. Their employed parameters were also adopted in later studies by Milazzo, et al. [5], Koppa [6], Shultz, et al. [7], BMI [8], and the Green Book [9]. In classifying driver responses during the yellow phase and identifying potential affecting factors, Shinar and Compton [10] observed more than 2000 drivers over a total of 72 hours at six intersections. Patten [11] investigated the impacts of mobile-phone usage on drivers from the perspective of cognitive workload and attention resource allocation. Caird et al. [12] used a driving simulator to measure the performance of 77 participants (older and younger drivers) when traffic signals changed from green to yellow. Liu, et al. [13] performed an extensive investigation of driver responses under different populations and vehicle characteristics. A study by El-Shawarby et al. [14] characterizes driver behavior at the onset of a yellow-phase transition on high-speed signalized intersection approaches using field data gathered from 60 test subjects. Most previous studies concluded that male drivers are more likely than female drivers in taking aggressive actions; senior drivers, in comparison with young drivers, are less likely to manifest aggressive driving patterns during a yellow-light phase; the presence of passengers was associated with lower rates of aggressive driving; and the likelihood of taking aggressive actions increases with the driver's value of time. It has also been recognized that a driver's response to a yellow-light phase may vary with some other factors such as talking on the phone or not talking on the phone. Despite the informative results provided by the previous studies, the following issues remain to be further addressed:

- Only the impact of individual driver related factors were investigated, however the impacts of other affecting factors such as signal control features, vehicle mechanical dynamics, intersection geometric features, and average traffic flow characteristics on driver behavior were not analyzed in a systematic way. Furthermore, the complex interactions between those factors and their collective impacts on drivers were not fully investigated;
- The data collection process of previous studies have either been conducted in a driving simulator or implemented through strictly controller field experiments. Driver behavior extracted from such environments could be biased and unrealistic without considering its interaction with surrounding traffic environment; and
- Due to the constraints of the sample size and the measurement method, the results of previous studies were not sufficient for definitely identifying key factors affecting driver behavior patterns in different driving

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populations.

The research presented in this paper attempts to address the above issues from the following aspects:

- Collecting detailed information on the characteristics of drivers, roadway geometric features, congestion levels, average traffic flow speeds, vehicle dynamics, and vehicle types and performances through a specially designed video-based system;
- Classifying drivers into three groups: "aggressive", "conservative", and "normal", based on the critical distance to the stop line and their stop/go decision at the onset of yellow-phase transition;
- Employing a multi-stage, discrete statistical test for exploring the complex interrelations between a driver's response (i.e., discrete in nature) to an intersection yellow phase, his/her individual and vehicle's performance characteristics, traffic environments, and key intersection geometric features; and
- Proposing potential safety improvement strategies and measures for traffic safety practitioners, researchers, and authorities, grounded on a better understanding of those identified vital factors and their individual as well as collective influences on the behavior of driving populations.

II. DATA COLLECTION

With assistance from the Office of Traffic and Safety of Maryland State Highway Administration, this study selected six intersections (MD193 at MD201, MD650 at Metzerott Rd., Randolph Rd. at Glenallan Rd., MD410 at Belcrest Rd., MD410 at Adelphi Rd., and MD193 at Mission Dr.) for field data collection using a specially designed video-based system [15]. The key information associated with each intersection is shown in Table I.

TABLE I
SURVEY INTERSECTION CHARACTERISTICS

Intersections*	1	2	3	4	5	6
Cycle length (seconds)	150	150	120	150	150	150
Yellow phase duration (seconds)	4.5	5	4	4.5	5	5.5
Target approach green split	0.387 - 0.491	0.603	0.450 - 0.718	0.316	0.248	0.785
Speed limit (mph)	40	40	35	35	35	45
Number of through lanes in target approach	4	3	3	2	2	3
Number of cross lanes by the target approach	3	3	2	5	5	4
Coordination with next signal	Yes	No	Yes	Yes	No	No
Next signal visibility	Yes	No	Yes	Yes	No	No
Number of observations	292	360	77	128	150	116

*Intersection indices (1-6) refer to: MD193 at MD201, MD650 at Metzerott Rd., Randolph Rd. at Glenallan Rd., MD410 at Belcrest Rd., MD410 at Adelphi Rd., and MD193 at Mission Dr respectively.

A total of 56 near-side and far-side videos were collected, from which about more than 3000 samples were extracted. To ensure the data reliability, we compared each sample from the stop-line observers, near-side videos, and far-side videos. Only after the three sources are well matched, we then included this sample in the analysis dataset. Also, for some ambiguous characteristics such as driver age, we first classified the driving population into several age groups in our laboratory experiments and trained our field observers to have consistent classifications of various sample individuals. Such pre-training enables all field observers to produce the consistent results. Through the aforementioned procedure, only 1123 individual driver responses were finally accepted for use in the analysis. All collected variables are organized into the different groups for analysis as shown in Table II:

TABLE II
FIELD COLLECTED VARIABLES

Traffic environment related variables	
Cycle-based average traffic flow speed	AVGSPEED (mph)
Cycle-based lane flow rate	VOLUME (veh/hr/lane)
Vehicle in platoon or not	PLATOON (1 – Yes, 0 – No)
Green split	SPLIT
Lane position of the vehicle	MIDL (1 – inner lane, 0 – not inner lane)
Intersection related variables	
Yellow phase duration	YD (seconds)
Cycle length	CYCLE (seconds)
Number of through lanes	THRUL
Number of cross lanes	CROSSL
Speed limit sign posted or not	POST (1 – Yes, 0 – No)
Speed limit value	SPL (mph)
Signal coordinated or not	COOR (1 – Yes, 0 – No)
Individual vehicle dynamics variables	
Approaching speed when the yellow phase starts	I_SPEED (mph)
Percentage of vehicles above the average traffic flow speed	PER_ABOVE
Individual driver related variables	
Driver's gender	MALE (1 – Yes, 0 – No)
Driver's age (< 26 years old – Young, > 46 years old - SENIOR)	YOUNG (1 – Yes, 0 – No) SENIOR (1 – Yes, 0 – No)
Passenger in vehicle or not	PASSENGER (1 – Yes, 0 – No)
Driver on cell phone or not	PHONE (1 – Yes, 0 – No)
Individual vehicle related variables	
Vehicle is Sedan or not	SEDAN (1 – Yes, 0 – No)
Vehicle is SUV or not	SUV (1 – Yes, 0 – No)
Vehicle is Pick-up or not	PU (1 – Yes, 0 – No)
Vehicle is Sports car or not	SPORTCAR (1 – Yes, 0 – No)
Vehicle is Van or not	VAN (1 – Yes, 0 – No)
Vehicle is Truck or not	TRUCK (1 – Yes, 0 – No)
Vehicle is Bus or not	BUS (1 – Yes, 0 – No)
Vehicle is made in US or not	US (1 – Yes, 0 – No)
Vehicle is made in Japan or not	JAP (1 – Yes, 0 – No)
Vehicle is made in Europe or not	EUR (1 – Yes, 0 – No)
Vehicle is made in Korean or not	KOR (1 – Yes, 0 – No)
Dependent variables	
Driver's response patterns	GROUP (1 – conservative stop, 2 – normal, 3 – aggressive pass)

III. METHODOLOGY

This study has collected a total of 1,123 observations of individual driver responses during the yellow phase at six intersections. For convenience of analysis, this study has first classified the driving population into three distinct patterns: "aggressive", "conservative", and "normal", based on their response during a yellow phase, and then evaluate the complex interrelations between different driver behavior patterns and associated factors.

A. Classification of Response Behaviors

Prior to the analysis of behavior related factors, this study needs to classify all observed driver decisions into three distinct groups: aggressive, normal, and conservative. The classification is based on the assumption that there exists a critical distance (d_c) perceived by a normal driver at each intersection when he/she notices the beginning of a yellow phase. A driver, if neither aggressive nor conservative, is most likely to take the stop action if his/her current location to the stop line (x_d) is longer than the perceived critical distance (d_c). By the same token, the driver may choose to pass the intersection during the yellow phase if his/her perceived d_c is longer than x_d. Note that such a critical distance d_c, is not directly observable from the field data (i.e., either $x_d < d_c$, or $x_d > d_c$) and it may vary with individual driver characteristics and surrounding conditions, such as intersection geometric features and traffic volume. Hence, this study has employed a discrete choice model for estimating the average d_c for driving populations at each intersection (see Table III).

TABLE III
THE ESTIMATED AVERAGE CRITICAL DISTANCE FOR THE DRIVING POPULATIONS AT EACH INTERSECTION

Surveyed Intersections	Yellow Duration(sec)	Cycle Length (sec)	Critical distance d_c (ft)
193@201	4.5	150	234ft
650@Metzerott	5	150	205ft
Randolph@Glenallan	4	120	269ft
410@Belcrest	4.5	150	200ft
410@Adelphi	5	150	177ft
193@Mission	5.5	150	278ft

TABLE IV
DISTRIBUTION OF DRIVING POPULATIONS AT INTERSECTIONS

Surveyed Intersections	Total Samples	Aggressive Pass	Normal	Conservative Stop
193@201	292	4% (13)	89%(260)	7% (19)
650@Metzerott	360	8% (28)	81%(292)	11% (40)
Randolph@Glenallan	77	8% (6)	84%(65)	6% (6)
410@Belcrest	128	5% (6)	90%(115)	5% (7)
410@Adelphi	150	7% (10)	83%(125)	10% (15)
193@Mission	116	8% (9)	84%(97)	8% (10)
Summary	1123	6% (72)	85%(954)	9% (97)

A detailed description of this estimation approach is not the focus of this paper, and is available elsewhere [16][17]. A summary of the definition for classification is shown below, and the resulting distribution of driving population at each intersection is shown in Table IV:

- Group 1: "Conservative stop" – Drivers who took the stop action even though they could have proceeded through the intersection during the yellow phase (i.e., the driver makes a stop even his/her distance to the stop line is less than the critical distance, d_c);
- Group 2: "Normal" – Drivers who took the stop action when $x_d > d_c$ or the pass action when $x_d < d_c$; and
- Group 3: "Aggressive pass" – Drivers who aggressively passed the intersection during the yellow phase even though they were quite far away ($x_d > d_c$).

B. *Statistical Analysis*

Since the dependent variables are discrete and ordered in nature, this study has employed the ordered-probit model [18] to investigate the impacts of associated variables on the resulting driving responses. The core concept of an ordered-probit model for a dependent variable of three classes can be presented with the following latent regression expression:

$$y^* = \beta' x + \varepsilon \quad 1)$$

Where, y^* is unobservable, its observable outcomes are:

$y = 1$ if $y^* \leq 0$

$y = 2$ if $0 < y^* \leq \mu_1$

$y = 3$ if $\mu_1 < y^*$

The unknown parameter μ_1, representing the boundaries between ordered responses will be estimated along with β (parameters for explanatory variables).

$\Pr ob(y=1) = cnorm(0 - \beta' x) - 0$

$\Pr ob(y=2) = cnorm(\mu_1 - \beta' x) - cnorm(0 - \beta' x)$

$\Pr ob(y=3) = 1 - cnorm(\mu_1 - \beta' x)$

The unobservable latent variable y^*, in the above model is the difference between the estimated distance to the stop line and the threshold value d_c, for a driver, the discrete dependent variable is a reflection of his/her response, which is: conservative stop, normal, or aggressive pass. The independent variables are all observable and potentially associated factors listed in Table II.

C. *Multi-stage Statistical Tests*

The statistical test with the ordered-probit model for all associated factors has been divided into three stages. The focus of Stage-I analysis is to identify critical traffic factors, which serve as the set of background variables for Stage-II and Stage-III analyses. Table V summarizes the test procedure for Stage I and Stage II analysis:

TABLE V
STATISTICAL TESTS PERFORMED IN STAGE-I AND STAGE-II

- **Stage-I:**
  - *Dependent variable – one of the following responses: “conservative stop”, “normal”, and “aggressive pass”*
  - *Independent variable set – AVGSPEED, VOLUME, PLATOON, SPLIT, and MIDL (Test 1)*
- **Stage-II:**
  - *Test 2 – significant background variables + yellow phase duration (YD)*
  - *Test 3 – significant background variables + cycle length (CYCLE)*
  - *Test 4 – significant background variables + number of through lanes (THRUL)*
  - *Test 5 – significant background variables + number of cross lanes (CROSSL)*
  - *Test 6 – significant background variables + speed limit sign being posted or not (POST)*
  - *Test 7 – significant background variables + speed limit value (SPL)*
  - *Test 8 – significant background variables + coordination with next intersection (COOR)*
  - *Test 9 – significant background variables + a vehicle’s approaching speed when the yellow starts (I_SPEED)*
  - *Test 10 – significant background variables + the difference (in percent) between each individual driver’s speed and the average traffic flow speed (PER_ABOVE)*
  - *Test 11 – significant background variables + male variable (MALE)*
  - *Test 12 – significant background variables + female variable (FEMALE)*
  - *Test 13 – significant background variables + young driver variable (YOUNG)*
  - *Test 14 – significant background variables + senior driver variable (SENIOR)*
  - *Test 15 – significant background variables + middle driver variable (MIDDLE)*
  - *Test 16 – significant background variables + variable for passengers or not (PASSENGER)*
  - *Test 17 – significant background variables + talking-on-phone variable (PHONE)*
  - *Test 18-24 – significant background variables + each of the vehicle type variables: (SEDAN, VAN, SUV, PU, SPORTCAR, TRUCK, BUS)*
  - *Test 25-28 – significant background variables + each of the vehicle made variables: (JAP, US, EUR, KOR)*

IV. ANALYSIS RESULTS AND FINDINGS

The results of Test-1 in Table VI show the impacts of Stage-I factors on a driver’s decision during the yellow phase. A positive and significant coefficient for the average traffic flow speed implies that the drivers are more likely to take aggressive passing actions in response to the observed yellow phase during the high-speed traffic conditions. This seems to justify the need to place speed enforcement at high-speed intersections so as to improve traffic safety. A negative coefficient for the traffic volume and green splits indicates that drivers tend to be self-restricted or constrained during the conditions of high volume or long green times, and are less likely to take the aggressive-pass action during the yellow phase.

Tests 2-8 shown in Table VI present the estimated impacts of intersection related factors on the response of drivers during the yellow phase. As expected, factors exhibited statistical significant signs include: the number of through and crossing lanes in the target approach, and signal coordination. A negative sign for the number of through lanes, THRUL (-.187), and a positive sign for the required crossing lanes, CROSSL (.112) imply that drivers in a major intersection approach of multiple lanes are more likely to take non-aggressive responses during a yellow phase. This may be due to the collective impacts of various factors, such as experiencing more volume (as reflected in the same estimation), having a longer green duration, and thus showing less desire to take the risk during the yellow phase. In contrast, drivers in the minor approach of a major-minor roadway intersection tend to be more aggressive to go through the intersection during the yellow phase.

TABLE VI
ESTIMATION RESULTS OF TEST 1 - 8

Parameter Coefficient [P value] (Sample Size)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
C	3.426 [<.001]	3.779 [<.001]	4.248 [<.001]	4.889 [<.001]	4.191 [<.001]	3.432 [<.001]	4.381 [<.001]	3.470 [<.001]
AVGSPEED [+]	.0382 [<.001]	.0392 [<.001]	.0401 [<.001]	.0346 [<.001]	.0440 [<.001]	.0385 [<.001]	.0388 [<.001]	.0365 [<.001]
VOLUME[-]	-.307E-02 [<.001]	-.307E-02 [<.001]	-.309E-02 [<.001]	-.325E-02 [<.001]	-.331E-02 [<.001]	-.307E-02 [<.001]	-.311E-02 [<.001]	-.321E-02 [<.001]
SPLIT[-]	-2.199 [<.001]	-2.261 [<.001]	-2.217 [<.001]	-1.804 [<.001]	-2.226 [<.001]	-2.227 [<.001]	-2.643 [<.001]	-2.309 [<.001]
MIDL[-] (570)	-.247 [.213]							
PLATOON[-] (268)	-.521 [.408]							
YD[+]		.0725 [.643]						
CYCLE[-]			-.508-02 [.422]					
THRUL[-]				-.187 [.009]				
CROSSL[+]					.112 [.003]			
POST[-] (497)						-.0174 [.863]		
SPL[-]							-.0289 [.198]	
COOR[+] (497)								.228 [.019]

Also revealed is the good signal coordination (COOR) between adjacent intersections tends to make drivers take aggressive actions during the yellow phase. This may be due to the deficiency of traditional signal progression models to take driver behavior and safety related issues into account. Most studies on signal progression try to focus on maximizing the operational efficiency of intersections, but not to minimize the total number of vehicles trapped in the dilemma zones or to minimize the total number of potential aggressive driving maneuvers. Other factors such as the yellow phase duration, the cycle length, and posted speed limit do not exhibit any significant impact on a driver’s decision making during a yellow phase among those available sample observations.

Table VII-VIII reports the estimated results of individual and vehicle related factors on a driver’s response during the yellow phase. Tests 9-10 are focused on investigating the impact due to an individual vehicle’s approaching speed, while tests 11-15 are mainly on evaluating the response differences due to the gender and age factors. Also included in the evaluation are the impacts due to having passengers and talking over the cell-phone (through Tests 16-17), vehicle types (Tests 18-24), and vehicle made (Tests 25-28). Although the estimated relations are not consistent across all six observed intersections, their statistical indications have revealed the following interesting behavioral patterns:

- Drivers having their approaching speeds higher than the average flow speed are more likely to behave aggressively when encountering a yellow phase (PER_ABOVE: 4.160/p-value < 0.1, see Test 10 in Table VII);
- Male drivers are more likely to take aggressive actions when approaching the yellow phase (MALE: .652, see Test 11 in Table VII);
- Female drivers tend to take conservative actions when approaching the yellow phase (FEMALE: -.652/p-value < 0.1, see Test 12 in Table VII);
- Young drivers tend to take aggressive actions when

approaching the yellow phase (YOUNG: .925/p-value < 0.1, see Test 13 in Table VII), but senior drivers are more likely to be conservative (SENIOR: -.977/p-value < 0.1, see Test 14 in Table VII);

- Drivers talking on phone tend to take conservative actions when approaching the yellow phase (PHONE: -1.087/p-value < 0.1, see Test 17 in Table VII);
- Drivers in vans tend to take conservative actions when approaching the yellow phase (VAN: -.851/p-value < 0.1, see Test 19 in Table VIII);
- Drivers in sports cars tend to take aggressive actions when approaching the yellow phase (SPORTCAR: 1.263/p-value < 0.1, see Test 22 in Table VIII); and
- Drivers in Japan made cars exhibited the pattern of taking aggressive decisions during the yellow phase (JAPAN: .666/p-value < 0.1,see Test 25 in Table VIII);

TABLE VII
ESTIMATION RESULTS OF STAGE-II ANALYSIS (TEST 9 - 17)

Parameter Coefficient [P value] (Sample Size)	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17
C	2.639 [<.001]	2.720 [<.001]	3.202 [<.001]	3.854 [<.001]	3.217 [<.001]	3.676 [<.001]	3.579 [<.001]	3.529 [<.001]	3.795 [<.001]
AVGSPEED[+]	.0343 [<.001]	.0348 [<.001]	.0401 [<.001]	.0401 [<.001]	.0423 [<.001]	.0394 [<.001]	.0391 [<.001]	.0376 [<.001]	.0416 [<.001]
VOLUME[-]	-.302E-02 [<.001]	-.303E-02 [<.001]	-.321E-02 [<.001]	-.321E-02 [<.001]	-.323E-02 [<.001]	-.310E-02 [<.001]	-.310E-02 [<.001]	-.307E-02 [<.001]	-.328E-02 [<.001]
SPLIT[-]	-1.672 [<.001]	-1.639 [<.001]	-2.210 [<.001]	-2.210 [<.001]	-2.435 [<.001]	-2.299 [<.001]	-2.237 [<.001]	-2.230 [<.001]	-2.326 [<.001]
I_SPEED[+]	.113 [<.001]								
PER_ABOVE[+]		4.160 [<.001]							
MALE[+] (750)			.652 [.063]						
FEMALE[-] (373)				-.652 [.063]					
YOUNG[+] (591)					.925 [.004]				
SENIOR[-] (163)						-.977 [.083]			
MIDDLE[-] (369)							-.326 [.259]		
PASSENGER[-] (192)								-.609 [.378]	
PHONE[-] (118)									-1.087 [.039]

TABLE VIII
ESTIMATION RESULTS OF STAGE-II ANALYSIS (TEST 18 - 28)

Parameter Coefficient [P value] (Sample Size)	Test 18	Test 19	Test 20	Test 21	Test 22	Test 23	Test 24	Test 25	Test 26	Test 27	Test 28
C	3.411 [<.001]	3.587 [<.001]	3.476 [<.001]	3.390 [<.001]	3.326 [<.001]	3.437 [<.001]	3.425 [<.001]	3.214 [<.001]	3.548 [<.001]	3.512 [<.001]	3.460 [<.001]
AVGSPEED[+]	.0383 [<.001]	.0368 [<.001]	.0384 [<.001]	.0386 [<.001]	.0357 [<.001]	.0384 [<.001]	.0383 [<.001]	.0381 [<.001]	.0378 [<.001]	.0387 [<.001]	.0387 [<.001]
VOLUME[-]	-.308E-02 [<.001]	-.308E-02 [<.001]	-.308E-02 [<.001]	-.303E-02 [<.001]	-.297E-02 [<.001]	-.306E-02 [<.001]	-.307E-02 [<.001]	-.303E-02 [<.001]	-.307E-02 [<.001]	-.304E-02 [<.001]	-.304E-02 [<.001]
SPLIT[-]	-2.207 [<.001]	-2.144 [<.001]	-2.226 [<.001]	-2.195 [<.001]	-2.026 [<.001]	-2.199 [<.001]	-2.201 [<.001]	-2.183 [<.001]	-2.182 [<.001]	-2.193 [<.001]	-2.223 [<.001]
SEDAN[+] (540)	.0378 [.667]										
VAN[-] (150)		-.851 [.021]									
SUV[-] (225)			-.222 [.316]								
PU[+] (94)				.609 [.221]							
SPORTCAR[+] (81)					1.263 [.009]						
TRUCK[-] (26)						-.246 [.693]					
BUS (7)							.1123 [.855]				
JAP[+] (445)								.666 [.021]			
US[-] (559)									-.252 [.541]		
EUR[-] (80)										-.725 [.354]	
KOR[-] (39)											-.734 [.187]

Stage-III analysis, shown in Table IX, is designed to explore the compound impacts of individual and vehicle related factors on a driver's behavior. It is noticeable that some factors, shown insignificant during individual tests in Stage-II, reveal significant collective impacts on a driver's response during the yellow phase. For examples, the numbers of passengers that exhibit a negative but insignificant sign when the test is based on all samples, shows different and significant relations when the samples were divided by gender. As indicated in Table IX, female drivers tend to be conservative when having passengers (FEMALE*PASSENGER: -1.057/p-value <0.1), but not for male drivers. Similar discrepancies also exist between young and senior drivers with passengers. Some of critical behavioral patterns revealed in Table IX are listed as follows:

- Young female drivers tend to take aggressive actions when approaching the yellow phase, while senior and middle-age female drivers tend to take conservative actions under the same situation (see tests 45-47);
- Female drivers talking over phone tend to take conservative actions when approaching the yellow phase, but not male drivers (see tests 33 and 49);
- Female van-drivers tend to take conservative actions when approaching the yellow phase, but not male drivers(see tests 35 and 51);
- Male drivers in SUVs tend to take aggressive actions when approaching the yellow phase, but not female drivers (see tests 36 and 52); and
- Female and young drivers in sports cars tend to take aggressive actions when approaching the yellow phase (see tests 54 and 66);

TABLE IX
RESULTS OF THE STAGE III ANALYSIS (COMPOUND VARIABLES)

Test #	Variables	Coef.	P-Value	Test #	Parameters	Coef.	P-Value
29	MALE*YOUNG	.787	[<.001]	64	YOUNG*SUV	.199	[.185]
30	MALE*SENIOR	-.433	[.005]	65	YOUNG*PU	.916	[<.001]
31	MALE*MIDDLE	.107	[.314]	66	YOUNG*SPORTCAR	1.551	[<.001]
32	MALE*PASSENGER	.249	[.170]	67	YOUNG*TRUCK	.509	[.426]
33	MALE*PHONE	.643	[.154]	68	YOUNG*BUS	.127	[.913]
34	MALE*SEDAN	.028	[.774]	69	YOUNG*JAP	.822	[<.001]
35	MALE*VAN	.237	[.126]	70	YOUNG*US	.361	[.001]
36	MALE*SUV	.707	[<.001]	71	YOUNG*EUR	.059	[.820]
37	MALE*PU	.613	[.035]	72	YOUNG*KOR	.046	[.904]
38	MALE*SPORTCAR	.984	[<.001]	73	SENIOR*PASSENGER	-1.023	[<.001]
39	MALE*TRUCK	-.246	[.393]	74	SENIOR*PHONE	-1.041	[<.001]
40	MALE*BUS	-.104	[.876]	75	SENIOR*SEDAN	-.424	[.018]
41	MALE*JAP	.705	[<.001]	76	SENIOR*VAN	-1.648	[<.001]
42	MALE*US	.166	[.074]	77	SENIOR*SUV	-1.469	[<.001]
43	MALE*EUR	.293	[.221]	78	SENIOR*PU	.150	[.658]
44	MALE*KOR	.610	[.369]	79	SENIOR*SPORTCAR	.207	[.730]
45	FEMALE*YOUNG	.272	[.022]	80	SENIOR*TRUCK	-.604	[.379]
46	FEMALE*SENIOR	-1.394	[<.001]	81	SENIOR*BUS	-.105	[.928]
47	FEMALE*MIDDLE	-.934	[<.001]	82	SENIOR*JAP	-.329	[.153]
48	FEMALE*PASSENGER	-1.057	[<.001]	83	SENIOR*US	-.756	[<.001]
49	FEMALE*PHONE	-1.200	[<.001]	84	SENIOR*EUR	-1.579	[<.001]
50	FEMALE*SEDAN	-.028	[.817]	85	SENIOR*KOR	-1.638	[<.001]
51	FEMALE*VAN	-1.615	[<.001]	86	MIDDLE*PASSENGER	-.318	[.050]
52	FEMALE*SUV	-1.419	[<.001]	87	MIDDLE*PHONE	-1.108	[<.001]
53	FEMALE*PU	.089	[.957]	88	MIDDLE*SEDAN	-.068	[.594]
54	FEMALE*SPORTCAR	1.343	[<.001]	89	MIDDLE*VAN	-1.097	[<.001]
55	FEMALE*BUS	-.162	[.922]	90	MIDDLE*SUV	-.14E-02	[.993]
56	FEMALE*JAP	-.169	[.182]	91	MIDDLE*PU	.129	[.676]
57	FEMALE*US	-.837	[<.001]	92	MIDDLE*SPORTCAR	-.128	[.744]
58	FEMALE*EUR	-.996	[.047]	93	MIDDLE*TRUCK	-.399	[.271]
59	FEMALE*KOR	-.780	[.004]	94	MIDDLE*BUS	-.244	[.795]
60	YOUNG*PASSENGER	-.331	[.110]	95	MIDDLE*JAP	-.180	[.203]
61	YOUNG*PHONE	.569	[.237]	96	MIDDLE*US	-.424	[<.001]
62	YOUNG*SEDAN	.233	[.024]	97	MIDDLE*EUR	-.668	[.011]
63	YOUNG*VAN	.130	[.508]	98	MIDDLE*KOR	-.599	[.087]

V. POTENTIAL APPLICATIONS

The empirical information presented in this paper offers some valuable information for understanding the complex interrelations between the decision of drivers and all contribution factors. More importantly, with some additional modeling work, traffic safety engineers can design effective strategies to counter dilemma zone related accidents and estimate the distribution of dilemma zones. For instance, one can:

- Enhance traditional signal timing models for possible reduction of aggressive driving related factors identified in this study without much loss of operational efficiency;

- Propose driver education guidelines based on the behavioral findings in this study to depress aggressive maneuvers during the yellow phase;
- Develop a driver response classification and prediction module to support the dilemma zone protection system; and
- Construct an index of traffic safety for each intersection based on the distribution of driving populations and all critical factors identified in this study and local specific observations. Responsible traffic agencies can then apply this index to prioritize the resources for safety improvement and design effective policies.

VI. CONCLUSIONS AND RECOMMENDATIONS

This study has observed the behavior of 1123 drivers in response to an encountered yellow phase and their surrounding traffic conditions at six signalized intersections. The comprehensive field data obtained with a reliable system offers the basis for this study to rigorously profile driver behavioral patterns and analyze the impacts of various behavioral and environmental factors. Through extensive field observations and statistical analyses, this study has reached the following tentative conclusions:

- Driving populations at most signalized intersections, based on their responses during the yellow phase, can be classified into three distinct groups: aggressive, normal, and conservative;
- A variety of factors may affect a driver's decision on taking an aggressive or a conservative action during the yellow phase. Examples of factors include: average traffic flow speed, green splits, traffic volume, signal coordination, number of approach lanes, talking on the phone or not, vehicle type, age, and gender;
- The speed of a vehicle approaching the intersection in comparison with the average flow speed seems to be the best indicator for identifying the aggressive level of a driver;
- The intersection geometric features may affect a driver's response to the encountered yellow phase. For example, drivers on the minor street are more likely to take an aggressive pass decision during a yellow phase due to the allocated short green phase;
- A coordinated signal system may encourage drivers to take an aggressive passing decision during the yellow phase;
- Multiple behavioral variables could have significant compound impact on a driver's response during the yellow phase. For example, male drivers in SUVs tend to take aggressive actions when approaching the yellow phase, but not female drivers; and
- Understanding the distribution of different driving behavioral patterns and the critical contributing factors is essential for researchers and responsible agencies to design of improvement strategies at signalized intersections.

It should be mentioned that all above reported findings are exploratory in nature and much remains to be extended due to the complex interactions between drivers, their experienced traffic conditions, and the large number of potentially related factors. Further research along the followings lines will be essential:

- Conducting comprehensive speed profile analyses with appropriate traffic sensors at all major intersections plagued by accidents so as to verify the distribution of driving populations;
- Performing an in-depth driving population classification for intersections experiencing a high accident frequency with the video-based approach developed in this study;
- Refining the set of contributing variables proposed in this study, and estimate the distribution of various driver responses to the yellow-light phase with more data from intersections of different geometric features and driving populations;
- Performing extensive analyses on compound impacts of multiple behavioral variables for identifying various driver behavioral patterns; and
- Applying all the research findings to develop a set of intersection safety evaluation models, and test their effectiveness in identifying underlying factors that degrade the quality of traffic safety at intersections of high crash frequency.

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