Characterization of Driving Behaviors Based on Field Observation of Intersection Left-Turn Across-Path Scenarios

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Abstract—There have been significant research and developments in recent years for intersection-safety solutions that are intended to alert drivers of hazardous situations by utilizing sensing, computing, and communication technologies. Since the effectiveness of intersection-safety systems depends strongly on driver perception and acceptance of the provided warning signal, the understanding of driver actions under the targeted scenario is a central research topic. One significant safety concern at intersections is the left-turn crossing-path scenarios, where a left-turning vehicle is confronted by oncoming traffic. This paper describes the analysis and synthesis of real-world data for such scenarios observed in field observations. Specifically, traffic interactions in left-turn across-path situations are evaluated to compare data from various intersections with different operation and traffic attributes. The analyzed data were characterized to gain insight into a time gap acceptance exhibited by a population of drivers. The knowledge of driving behaviors can provide the guidelines for future investigation as well as a knowledge basis for the selection of warning criteria to allow timely alerts to drivers in the intended safety applications.

Index Terms—Collision avoidance, driving behaviors, field observation, intersection crashes.

I. BACKGROUND

INTERSECTION collisions, particularly those with vehicles moving in crossing paths, are a major concern in roadway safety, since they often occur with significant speed differentials in the impact directions that lead to serious injuries or fatalities. In recent years, significant efforts have been devoted toward a safety research to reduce the numbers of crashes at intersections in several regions around the world [1]–[10]. A combination of newly developed and cost-reduced technologies can meaningfully reduce crashes if they are successfully implemented in intersection-decision-support (IDS) systems. This paper describes the IDS work carried out at California PATH for one of the most critical crash types: the left-turn across-path opposite-direction (LTAP-OD) situation [7], [8]. This is part of the overall research plan recently sponsored by Federal Highway Administration (FHWA) and several states in the U.S. [9], [10].

Fig. 1. Exemplar visual interface for left-turn warning.

Continuing efforts are now underway and expected to extend the operating concepts to integrate vehicle and infrastructure components and functions into cooperative intersection collision-avoidance systems (CICAS) [11].

An IDS/CICAS system requires the utilization of apparatus, including enhanced sensors, computer, and driver interface, on the existing infrastructure to provide drivers with advisory alerts. It will be noted here that warning and alert are loosely and interchangeably used within the discussions of this paper, although they may be interpreted quite differently from the human-factor perspective. For driver assistance, the IDS solutions may use a driver-infrastructure interface (DII), which conveys hazardous situations to drivers through a roadside sign. For example, the team at PATH has been experimenting with a DII illustrated in Fig. 1 for LTAP-OD warning. The sign only becomes active and is dynamically pulsed to draw drivers' attention. The activation of the DII is triggered by computing processors that determine if and when an alert signal is warranted by traffic conditions [12], [13].

The provision of an alert is not limited to infrastructure-based implementation only. Driver assistance can be implemented through a driver-vehicle interface (DVI), provided that the warning signal is communicated from roadside processors to the vehicle. The utilization of wireless communication for a data transmission is a central element in the research activities for the aforementioned CICAS project. Furthermore, the operational concepts of an intersection collision warning can be broadened considerably by allowing a two-way data exchange. By combining the available data from infrastructure and vehicle

sensors, a state map can be constructed [7], and warning decisions can be made more intelligently for intersection-safety applications. For example, in cases where the infrastructure sensors are unable to determine if a vehicle is in moving toward a turning maneuver, the activation of a turn signal detected on the vehicle data bus will be an additional information to process for an alert if necessary. Moreover, a vehicle-based application can be implemented with an adjustable-sensitivity feature that adapts to driver behaviors. These are examples of vehicle-infrastructure integration, which offers potential flexibility in the operating concepts.

The work described in this paper represents the analysis and synthesis of filed data gathered from several intersections for the investigation of driving behaviors. This is an extension of a prior work that involved the developments of apparatus and data-collection techniques [14]–[16] and methods for interpreting a driver time-gap selection [17], [18]. The results of this study provide a realistic understanding of driving behaviors and thus offer a solid foundation of knowledge base for the design of IDS and CICAS. Combined with human-factor experimental studies [19] and the use of a simulation model for scenario testing [20], the distribution of time- and distance-gap acceptance exhibited by drivers can help define the appropriate warning criteria to provide timely and effective alerts.

Section II contains a brief discussion on the motivation, approach, and limitation of the work described in this paper. In Section III, field-observation data are used to illustrate the analysis of traffic interactions in LTAP-OD scenarios. Descriptions of the data analysis and characterization were given in Section IV. A summary of the knowledge gained through this exercise and the implications for IDS/CICAS development and implementation are elaborated upon in Section V.

II. MOTIVATION, APPROACH, AND LIMITATION

One unique aspect of providing advisory alerts to drivers such as those proposed in IDS/CICAS applications is the wide spectrum of driver perception and reaction to the alert, which in turn dictates the effectiveness of the safety systems. It is essential that the advisory signal is generated in a timely fashion and communicated to the drivers with the least occurrences of false or nuisance alarms. However, it is impossible to satisfy this requirement for a large population of drivers, because each individual driver is likely to perceive traffic conditions differently and take risks according to his/her own judgment. An advisory warning issued under an objective assessment, which is based on a threat presented by opposing traffic, can only be designed to be satisfactory for most drivers. This is particularly true if the suggested warning is presented in the form of a driver-infrastructure interface.

Given the constraints in this challenging aspect of implementation, it is necessary to determine the appropriate warning thresholds that can sufficiently provide a timely alert to the driving public under a variety of traffic conditions and yet, at the same time, minimizes the potential of unnecessary nuisance or erroneous perception to the same population. For this purpose, the understanding of driving behaviors in a naturalistic setting will be extremely valuable in defining such warning thresholds.

In this context, the work described in this paper is a methodology of utilizing the field observation under real-world traffic conditions with an attempt to capture traffic patterns and associated driving behaviors that are exhibited by the driving public. The data collected from the field observation may be applicable for several types of intersection conflicts, but the main interest of this study is to further the understanding of LTAP-OD scenarios. LTAP-OD situations mostly happen in permissive and unprotected left-turn maneuvers where no designated left-turn phase is provided.

For clarification, several terms frequently used in such scenarios ought to be defined first. The vehicle that is turning left is called the subject vehicle (SV). The SV may face several opposing vehicles. The vehicle that is closest in time or distance and is most threatening is called the principal other vehicle (POV). A conflict occurs when an approaching POV is close in time or distance while an SV is turning.

Specifically, the discussions in this pare are intended for the exploration of the following issues.

1) How do we extract and interpret driving behaviors from the field-observation data?
2) What is the distribution of time and distance gap accepted by drivers making a left turn?
3) How is the distribution of gap acceptance influenced by intersection geometry, operation, and traffic attributes?
4) Can the characterization of field data provide useful inputs for the design of IDS/CICAS?

As will be explained in the following sections, affirmative and insightful answers can be given for questions 1) and 2). Preliminary conclusions can be made for questions 3) and 4), while meaningful and comprehensive answers will require further studies. More elaborated discussions of these issues are given in Section IV.

The field observation reported in this paper was considered an initial yet critical part of work in the overall scheme of the IDS project. The approach chosen was to explore data-collection methods under a variety of traffic conditions at candidate intersections. Instead of a permanent setup at the selected sites with an extensive and permanent instrumentation, the intention was to utilize a minimum set of equipment on a mobile platform that can be deployed at desired locations flexibly. Given these constraints, it should be noted that there were noticeable limitations during the course of data collection including the following.

1) The sensor-placement strategy was not thoroughly investigated to choose an optimal configuration or to assemble a set of multiple sensors for data fusion, and therefore, the setup did not allow full monitoring and tracking of all targets. For example, some targets were blocked by other vehicles in the traffic lanes and, therefore, might disappear from a radar or camera in some portions of their trajectories.
2) Since the radar sensor used in the mobile data-collection platform is based on the Doppler effect, stationary targets would disappear shortly after they arrived at the intersection and/or stopped for signals or other reasons.

3) Target detection and processing does not necessarily generate accurate measurements even with the reasonably good performance offered by the chosen radar sensor. Radar waves can reflect off different parts of a target, thus only providing approximate distance or speed. There are also occasional dropouts or erroneous identifications.

Despite the limitations described above, it was discovered during the analysis of collected data that the data-acquisition setup, albeit simplistic and minimal, yielded reasonably satisfactory results for the purpose of data evaluation. This is mainly due to the fact that the closest moving POV is most critical for SV driver decisions, and the POV is very likely to be successfully detected and tracked by the radar because they are often the leading vehicle in a stream of traffic and is not blocked. The analysis of radar data was supported by video images, which provided supplementary information; thus, results can be verified if the radar data became ambiguous or erroneous in certain situations.

III. Field-Observation Data Collection

As explained above, it is beneficial for the design and implementation of IDS by observing driving behaviors under a variety of traffic conditions and operation conditions; therefore, the field-observation sites are selected to allow as much diversity in relevant factors as possible among the locations. The potential relevant attributes, which are based on engineering judgment and intuition, include neighborhood settings (urban, suburban, rural), intersection operation features (traffic control, signal cycle, left-turn geometric layout), and traffic conditions (traffic volume, prevailing speed, pedestrian presence, etc.). Within the IDS project, the data collection was carried out at a number of intersections, with a selected few sufficient samples presented in this paper.

1) Shattuck and Hearst (in the city of Berkeley);
2) Chapin and El Camino Real (Burlingame);
3) Fifth Street and Brannan (San Francisco);
4) entrance into Del Monte Plaza from San Pablo Ave (Pinole).

The data collection at Shattuck and Hearst was conducted on three different dates with over 6 h of traffic data overall, while 2–3 h of data was collected at each of the other sites. Table I provides an overall comparison of the observation sites included in this paper and their associated parameters. The significance of intersection and traffic attributes is discussed below.

The results revealed by the analyzed data present recognizable patterns, and thus, the aggregate data are considered to constitute a statistically meaningful representation. This judgment is somehow subjective and deserves to be further quantified when additional field data become available. Nevertheless, the analysis of the LTAP-OD scenarios allows us to hypothesize the potential correlation between driving behaviors and intersection attributes, which in turn offers the guidelines for future field work.

Fig. 2 shows the data-acquisition setup at site A, an urban intersection in the downtown area of Berkeley, CA. As depicted,

TABLE I
INTERSECTION AND TRAFFIC CHARACTERISTICS OF FIELD OBSERVATION SITES

Observation Site ID	A	B	C	D
Location	Hearst /Shattuck, Berkeley	Chapin /El Camino Real, Burlingame	5th Street /Brannan, San Francisco	San Pablo Ave, Pinole
Urban/ Suburban	U	S	U	S
Traffic Control	Traffic Signal	Traffic Signal	Traffic Signal	None
Pedestrian Traffic Presence	Frequent	Few	Few	Few
Number of POV Mainline Lanes	2	2	2	2
Left-Turn Pocket For SV	Yes	No	No	Yes
Signal Cycle Length (seconds)	75	80	60	N/A
Green Phase Length (seconds)	34.5	55-65 (variable)	20	N/A
Amber Phase (seconds)	3.3	3.5	3.5	N/A
All-Red Phase (seconds)	2.0	0.5	0.5	N/A
POV Traffic Volume (POV vehicles per minute)	Medium, 10+	High, 20+	Medium, 10+	Medium, ~ 10
Prevalent POV Speed	9-14 m/sec (20-30 mi/h)	16-20 m/sec (35-45 mi/h)	9-14 m/sec (20-30 mi/h)	16-20 m/sec (35-45 mi/h)
Total Numbers of Observed LTAP-OD	226 (34+68+124)	226	112	81
LTAP-OD SV Traffic Volume (Average SV per hour)	30+	84+	42+	30+

this intersection has two lanes in the mainline traffic direction (Shattuck Ave) and a left-turn pocket lane for SV waiting to make left turns. There are also parking lanes on both sides of the street. The intersection is controlled by traffic signals, which have a signal cycle of 75 s during the hours of observation (late morning to early afternoon). During the observation hours, the average cruising-traffic speed was about 11 m/s (25 mi/h). There are frequent gaps available among the opposing traffic, which allow the SV to make its intended left turn. A curve is shown in Fig. 2 to represent the trajectory of a left-turn SV. A triangular area is used to show the coverage area of a radar sensor with the radar placement at the tip of the triangle. A circle is placed within the triangle as the crossing point of the left-turn trajectory. The circled spot is also considered to
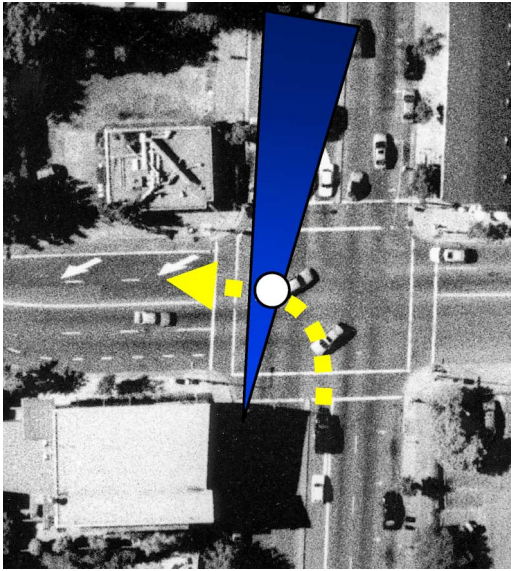
Fig. 2.   Depiction of the data-collection setup at site A.
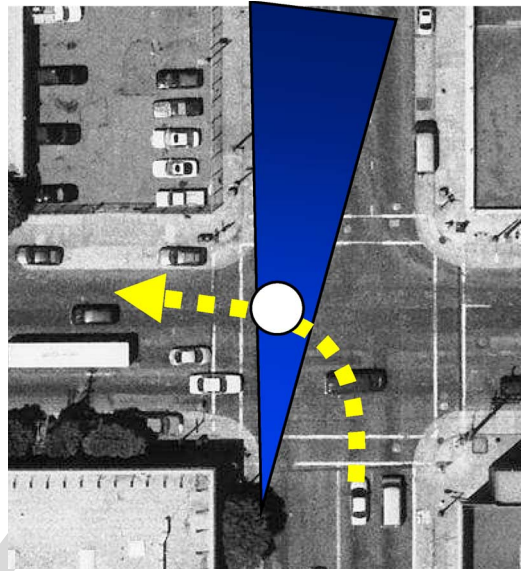

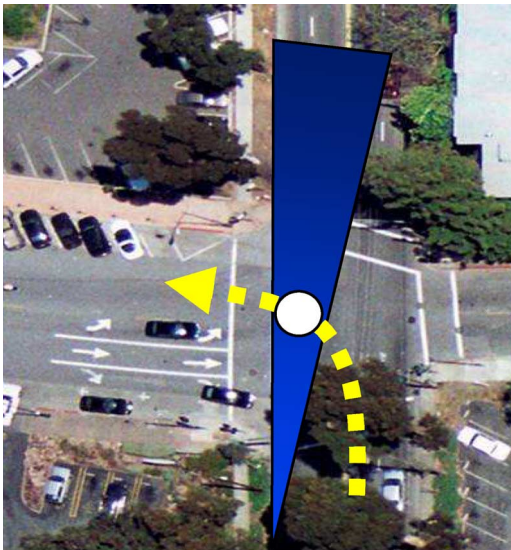
Fig. 4.   Data-collection setup at site C.

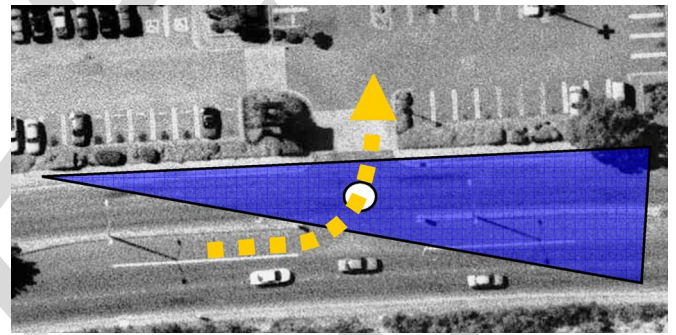Fig. 3.   Data-collection setup at site B.

Fig. 5.   Depiction of the data-collection setup at site D.

be the point or area of conflict, which will be used later for the calculation of vehicle arrival times so that a conflict can be predicted and evaluated. Similar markers and labels are also depicted in Figs. 3–5.

Fig. 3 shows the configuration at site B, a suburban area in the city of Burlingame, CA. At this location, due to the geometric constraints, there are no parking lanes or left-turn pockets. The intersection has a trapezoidal shape because of the angular connection and the nonequal widths of Chapin Ave on the two sides of El Camino Real. The main street (El Camino Real) is a major corridor with a consistently high volume of traffic at moderate to high speeds (16 to 20 m/s or 35–45 mi/h) throughout the day. The control of signals for traffic on Chapin is actuated so that a potentially longer green phase can be allocated for the traffic on El Camino Real. The green phase for the main road occupies 55–65 s out of the total 80 s in a cycle. There are frequent left-turning SV observed at the intersection

of El Camino Real and Chapin, where several commercial properties are located. The high volume of passing traffic has an effect on the SV maneuvers. Some drivers are enticed to creep forward or stop in the middle of the intersection in order to catch a gap more easily in the opposing traffic. Others are forced to wait until the end of the green phase before the left turn can be made.

Fig. 4 shows the observation setup for site C, an intersection in the city of San Francisco in an industrial neighborhood. There are two lanes of traffic and parking lanes on all directions of travel but no left-turn pockets. The left-turn SV on northbound Fifth Street turns onto westbound Brannan, which is a major street with relatively higher volumes of traffic. The green phase in the Fifth Street direction only uses 20 out of the 60 s of the signal cycle. The short green phase forces many SV to wait for their turns into the later part of the green or until the signal has turned amber or red. Traffic in the direction of opposing traffic or the POV typically moves at 9–14 m/s. The frequency of left-turn SV is higher than site A but lower than site B. A considerable portion of the POV traffic on the outside lane make right turns onto Brennan Street. Since California allows right turns during the red phase unless posted otherwise, a right-turning POV may appear to be moving toward a conflict with SV as both of them approach and enter the intersection.
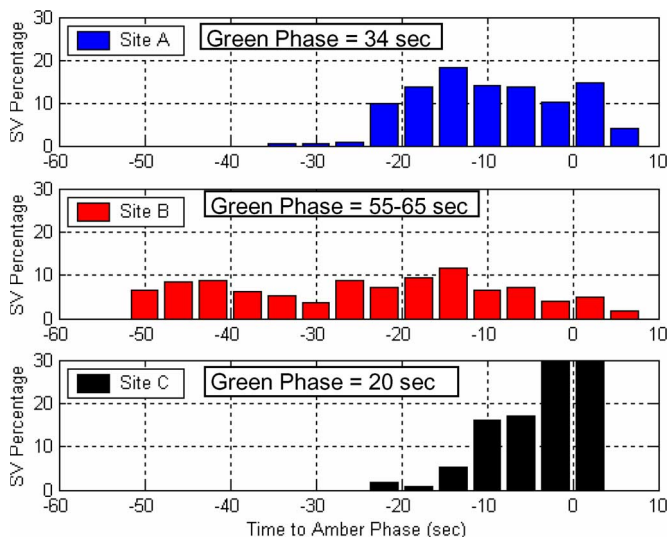
Fig. 6.   SV turning time in signal cycle at three observation sites.

Fig. 5 depicts the setting for LTAP-OD scenarios at a nonsignalized and atypical location in the city of Pinole, where vehicles entering and exiting from a shopping center face opposing traffic approaching from the right side of the picture. The straight-through traffic on the major roadway (San Pablo Avenue or State Route 123) typically moves at a relatively high speed of 16–20 m/s (35–45 mi/h). The traffic is very dense and heavy during the commute hours, but during our observation hours in the middle of the day, it was relatively light and sparse. The view of a driver making a left turn is partially obstructed due to a slight curve of the roadway and the trees planted on the median island.

Drivers anticipate and react to signal transitions at signalized intersections. Therefore, it is reasonable to hypothesize that the timing of left turn within the signal cycle may cause a difference in driving behaviors. For example, in the late stage of the green or amber phases, drivers may be tempted to rush their turns. Fig. 6 shows a comparison of a turning-time distribution from the three signalized intersections. Note that the signal-cycle lengths of the three sites are different. The green time is 34 s for site A, 55–65 s for site B, and 20 s for site C. The graph plots the time instant when the SV moves into the point of conflict relative to the beginning of the amber phase. A negative reading on the horizontal axis indicates that the turn occurs in green, and a positive reading implies turning in amber or early red phases. Each bar in the chart is shown for a 4-s interval. The values on the vertical axis are the percentage of SV turning at the corresponding time at the respective sites. The numbers for each site are normalized to be shown as a percentage of the total numbers of SV.

It is shown in Fig. 6 that the SV at sites A and B are evenly distributed across a large part of the green phase, but at site C, there is a high concentration at the end of green and into the amber and early red phases. The green phase at site C (San Francisco) is only 20-s long, thus forcing a very high percentage of late turns in the vicinity of the signal transition from green to amber. The discrepancies of such traffic characteristics

appear to be an important factor and should be noted for later data interpretation.

IV. FIELD DATA ANALYSIS AND INTERPRETATION

In order to synthesize data further for the purpose of this study, the LTAP-OD situations are first identified for review. This was accomplished with an automatic scan of radar data to identify the presence of SV targets and confirmed with a review of video data. From these identified samples, the interaction of SV–POV movements was further analyzed for interpretation.

A. Analysis of Vehicles Approaching an Intersection

When an SV makes a left turn, it is necessary for the SV driver to identify and accept a gap in traffic that is sufficient to complete the maneuver. The choice of a gap may be a "gap" between vehicles or a "lag" before the next POV arrives at the point of conflict. It is fair to assume that drivers typically judge the arrival time or the current distance of oncoming vehicles to decide whether it is safe to initiate a maneuver. Previous research also showed some evidence that such driver decisions can be a combination of time and distance gaps [21], [22].

For the analysis of traffic approaching an intersection, the time to intersection (T2I)[1] is a convenient measure of the closeness of a target vehicle. T2I is calculated by dividing the distance to intersection of a target vehicle by its current speed. The distance to intersection is often defined as the distance to the stop bar at the intersection. For the clarification of certain terminologies and to facilitate later discussions, a data set is used below to illustrate the variations of T2I for targets approaching during the different phases of the traffic signal.

The traffic in the POV direction within a traffic cycle (75 s) at site A is plotted in Fig. 7 with the instantaneous T2I of each vehicle versus time. The color bar and accompanying labels at the top of the chart indicate the signal phases during the cycle. There are two traffic lanes in this direction, and thus for lane differentiation, the data are denoted by ► (inside lane or lane 1) or ◄ (outside lane or lane 2). In the green phase in the first half of the signal cycle (34 s), multiple target vehicles are cruising toward the intersection at a relatively constant speed with their respective T2I decreases in a linear manner. As the signal transitions from green to amber, a target vehicle is seen slowing down and stopping with its T2I drops to a minimum value of about 2 s before increasing. The T2I of a stopping vehicle mostly follows this pattern because the decreasing speed yields a larger T2I, even though the distance to the intersection is decreasing as well. Behind the first stopping vehicle, several other vehicles also stop in the red phase. It can also be seen that the T2I of later arriving vehicles has greater minimum T2I values because they stop further from the stop bar.

For the analysis of LTAP-OD scenarios, it is important to observe the distance and speed of the POV when an SV left turn takes place. Therefore, it will be necessary to monitor the trajectory of a POV when an SV makes its turn. Furthermore,

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[1]T2I is used as the abbreviation for time to intersection instead of TTI because the latter may be confusing due to a widely recognized abbreviation for Texas Transportation Institute.
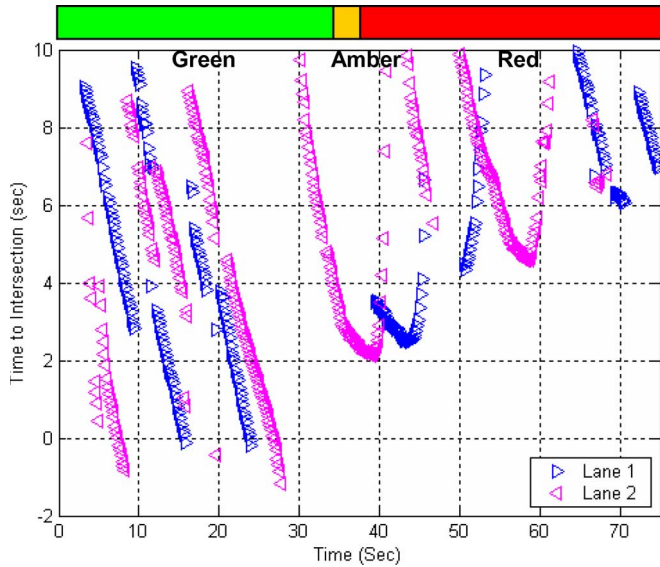
Fig. 7. Variations of T2I of vehicles approaching an intersection in a signal cycle.

if we calculate the POV T2I in a time window before and after the SV reaches the point of conflict, the closeness of the POV and, thus, the time gaps accepted by the SV in actual turns can be assessed.

After each SV target is identified from the radar data and confirmed by video review, the radar data is then scanned to check for the presence of a POV. The corresponding POV distance and speed are then used to monitor their trajectories relative to the turning motion of an SV. Two LTAP-OD examples are shown in Fig. 8(a) and (b) to illustrate the SV–POV encounters in a time window before and after the time instant when the SV reaches the point of conflict.

In Fig. 8(a), two opposing vehicles are approaching the intersection prior to the SV left turn. Initially, the vehicle on lane 2 is closer in time and is thus the POV by definition. At time = −3 s, the vehicle on lane 1 edges closer in time to the intersection and becomes the POV. At time = 0, the inside vehicle slows down, perhaps due to the appearance of the SV, and its T2I value remains flat for a second or so. Shortly after, the vehicle on lane 2 overtakes the other vehicle and becomes the POV again. This vehicle reaches the intersection when its T2I value becomes zero at about $t = 5$ s after the SV crosses the point of conflict.

In Fig. 8(b), besides the brief appearance of other vehicles at around $t = -6$, there is only one other vehicle present, and it by default, the POV. In this case, the SV left turn occurred during the signal transition from green to amber. The approaching POV was slowing down, perhaps due to the signal phase change or the presence of the SV. The POV T2I reaches a minimum value of 2 s right around $t = 0$, when the SV is at the point of conflict.

As shown by the two examples above, the SV and POV trajectories relative to the point of conflict can be evaluated in a period of potential interaction. The proximity of POV relative to an SV in a LTAP-OD situation can now be objectively compared with a common method. The procedure explained above will be the essential tool used throughout the remainder of this paper for all intersections. Aside from the T2I measure,
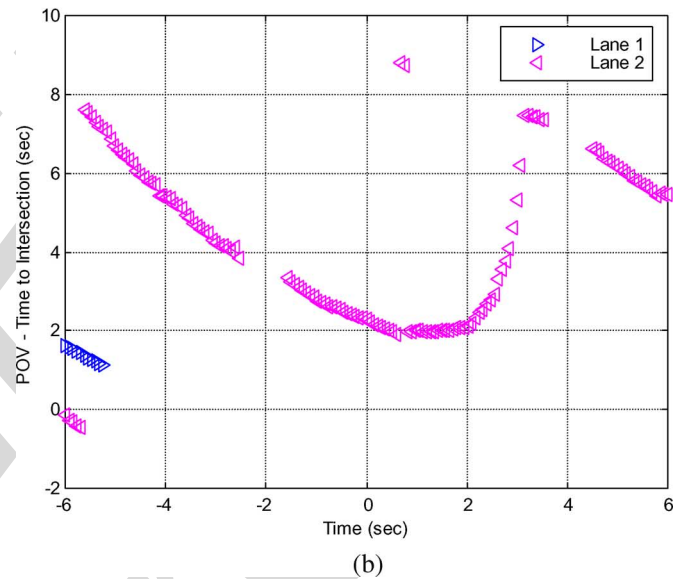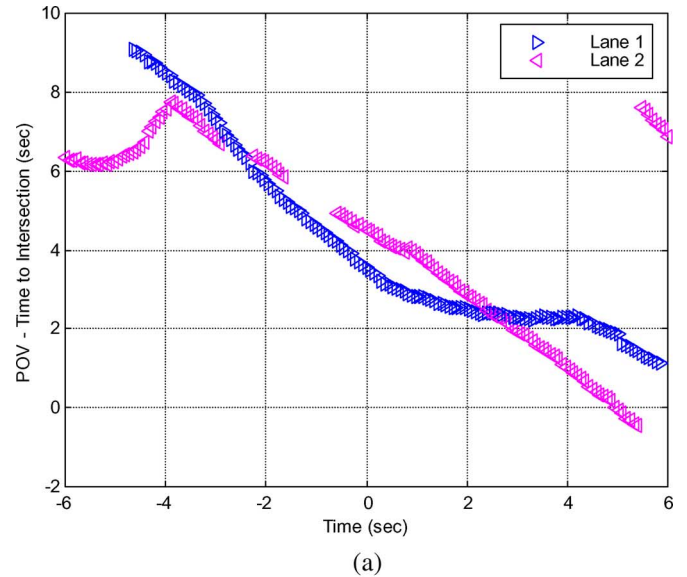

Fig. 8. (a) POV-T2I versus SV detection time—example 1. (b) POV-T2I versus SV detection time—example 2.

it is believed that a distance to intersection (D2I) may also be an important factor in a driver's consideration for the judgment of oncoming traffic. Many aspects of analysis in the following sections can be applied to D2I as well, but the discussions and illustrations will only be shown for T2I to avoid being repetitive.

Upon further examination of field-observation sites, it is noticed that the geometric layout of intersections are very different, and therefore, the stop-bar position relative to the point of conflict varies significantly, as shown in Figs. 2–5. It is reasoned that the perceived closeness of oncoming traffic relative to the point of conflict, instead of the stop bar, is more important for drivers' gap acceptance. This is especially true for large-size intersections. Therefore, the calculation of the POV proximity is adjusted by using the time to point of conflict (T2POC). Similar to T2I, T2POC is the estimated arrival time of a vehicle by dividing the current distance to the point of conflict (D2POC) of a target vehicle by its instantaneous speed.

By the use of T2POC, a conflict can be represented by the relative arrival times of SV and POV at the point of conflict.

It should be further noted that the term, time to conflict, adopted herein has a completely different meaning from the conventional use of TTC; TTC is usually used to denote the time to collision, which is calculated, for example, by dividing the space between two vehicles by the speed differential in a vehicle-following situation.

B. Description of LTAP-OD Scenarios by SV–POV Interaction

The same procedure of the data analysis described above can be followed for all SV cases to identify the characteristics of time acceptance at multiple locations. When data were presented as an aggregate representation of a large number of drivers, it enables us to compare the driving behaviors at each site under different traffic conditions and to compare the differences among multiple sites.
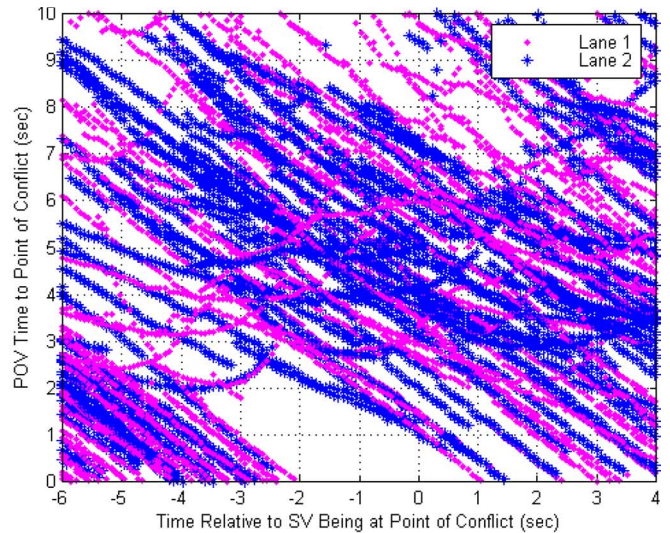
Fig. 9(a) is a chart generated from a 2-hr data set from site A. It is a composite chart with a total of 68 left-turning SV. Fig. 9(a) is constructed in the following manner.

1) For each SV, the POV T2POC is plotted in the time window of -6 and $+4$ s around $t = 0$ when SV arrives at the point of conflict.
2) A plot similar to the examples in Fig. 8 is repeated for all 68 turning SV.
3) The POV may be in either of the two lanes. If there are multiple vehicles approaching, only the one with the smallest T2POC is plotted.
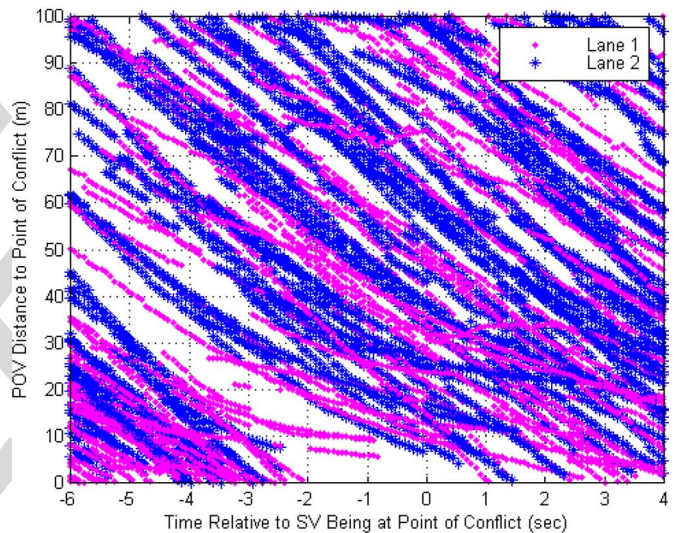
Fig. 9(b) is similarly constructed for the D2POC.

Fig. 9(a) and (b) provides intuitive yet revealing phenomena of SV–POV interaction. Some explanations and comments are given as follows.

1) If a POV cruises toward the intersection at a constant speed, its T2POC curve will be a straight line with a down slope of -1 in Fig. 9(a).
2) If a POV slows down, the slope of its T2POC trajectory will decrease in absolute values as can be seen in some examples in their corresponding T2POC and D2POC curves.
3) A few POV targets are found to slow down or stop as they get very close to the point of conflict. This is particularly visible for a couple of cases at the center bottom of the Fig. 9(b). The POV is slowing down due to the presence of a turning SV or signal transition.
4) Often, there is a previously passing POV before the SV turns. These POV cross the point of conflict before SV arrival at time $= 0$. A cluster of POV pass through prior to $t = -2$ in Fig. 9(a).
5) The two-second period of a passing POV before an SV arrives at the point of conflict, which is described in 4), is called the leading buffer.
6) For the majority of cases, POV does not arrive until two seconds after SV crosses the point of conflict. If the arrival times of SV and POV are close to each other, as indicated by several cases in Fig. 9(a) with POV T2POC crossing near time $= +1$, then there is a potential conflict or hazard.

(a)

(b)

Fig. 9. (a) POV-T2POC versus time relative to SV crossing POC (Data 12/11/03). (b) POV-D2POC versus time relative to SV crossing POC (Data 12/11/03).

7) The time period between the passing of SV and the subsequent arrival of POV at the point of conflict, which is mentioned in 6), is referred to as the trailing buffer.
8) The shorter the trailing buffer, the greater the risk is for the LTAP-OD scenario. The trailing buffer is also indicative of the aggressiveness of SV drivers in their decision to turn.
9) A time gap is clearly evident in Fig. 9(a). The gap is bordered by the leading and trailing buffer, but it is also visible in a channel in the chart that angles backward in time to the upper left of the graph. There is a sparse POV presence in the channel. The reason for the existence of a gap and a channel extended backward in time is obvious because a decision to make the turn is made a few seconds before the SV arrives at the point of conflict. This is a significant point to note because the timing of
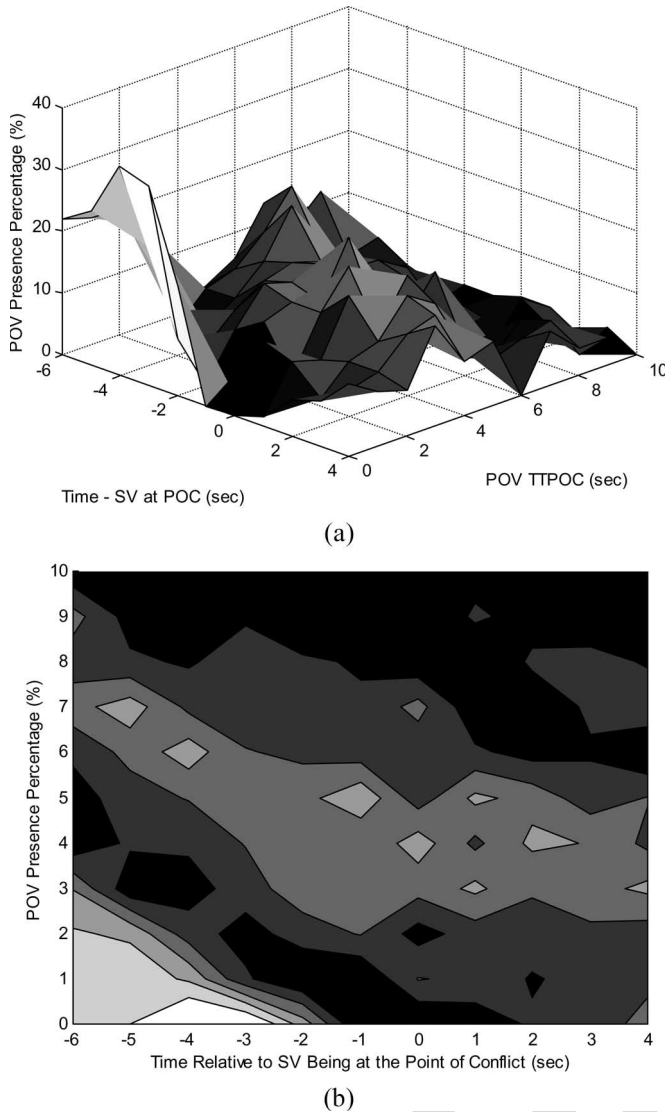
(a)

(b)

Fig. 10.   (a) Three-dimensional view of POV presence with respect to SV arrival. (b) Two-dimensional view of POV presence with respect to SV arrival.

warning in IDS/CICAS must be related to the time of driver decision.

If the graph of Fig. 9(a) is divided into a grid of 1-s intervals in both directions, and the number of POV presence within each grid is counted, a distribution plot of the POV can be generated. Fig. 10(a) shows a three-dimensional plot of this distribution. The vertical reading is calculated by dividing the number of POV by the total number of SV and expressed in the percentage of cases where an SV is encountering a POV at the respective grids in time.

In Fig. 10(a), a high peak is present on the left side of the chart, which shows the cluster of previously passing vehicles that correspond to those in the triangular area at the lower left corner in Fig. 9(a). The peak at the central portion of the chart is indicative of the intensity of oncoming POV faced by SV as the SV makes its turn. The valley between the two peaks reveals the time gap and channel as mentioned in Fig. 9(a), which are accepted by the SV to make the left turn.

The three-dimensional plot of Fig. 10(a) can also be projected onto a two-dimensional contour plot, shown in Fig. 10(b), which offers an alternative visualization of the SV–POV encounters. A more intense or lighter-color area in Fig. 10(b) means that the POV is present for a higher percentage of cases. Conversely, a darker area means that the presence of the POV is sparse or less frequent. Fig. 10(a) and (b) conveys a quantified representation of the same data in Fig. 9(a).

The shape and form of the gaps are influenced by traffic conditions and intersection attributes. These graphs provide useful visualization tools for data comparison. Due to the space limitation, the results generated from other data sets will not be shown, but they all show similar patterns with variations in intensity distribution. To allow a comparison of such driving behaviors under varying traffic conditions and in different intersection settings, further quantitative analysis is needed.

C. Data Utilization and Characterization for Different Traffic Conditions and at Different Intersections

Once the approach of data analysis is chosen, they can be similarly applied to data sets from various traffic and intersection conditions. The data can then be synthesized to gain an insight into the data of relevant traffic and roadway factors that may influence the driving behaviors. For example, one may wish to compare the percentage of SV turning with POV arriving with a short trailing buffer at different sites. Also, one may choose to utilize the field data from different sites to check if the distribution of accepted time gaps shows any significant variation due to varying traffic conditions.

For a comparison of signalized intersections with distinct traffic attributes, the data from sites A, B, and C are analyzed further. Fig. 11 shows a comparison of the distribution of POV arrival times after the SV has crossed the point of conflict. The graph is generated by counting the numbers of POV passing through the point of conflict in every 1-s intervals and plotting the cumulative percentage curves of each of the three sites. The percentage is normalized by dividing the number of POV by the total SV number.

For the purpose of discussions, let us define a conflict that warrants the issuance of warning to be a situation when the trailing buffer is less than 2 s. The data depicted in Fig. 11 indicate that there is a difference in the percentage of left-turn cases. For example, site C appears to have the highest ratio, which is followed by site B, and site A possesses the lowest ratio. This ratio can be interpreted as the level of aggressiveness of SV turning maneuvers for a site.

There are at least a couple of possible explanations for this contrast in the ratios for these sites. The driver group at one site may indeed be more aggressive than the other sites, for a reason such as driver demographics. On the other hand, the traffic patterns at a particular site may distort the observed phenomenon and cause a shift in the distribution for a site. For example, we have explained in Section III that there are a large number of right-turning POV at site C, and they are frequently on a trajectory that appears to be approaching a conflict with the left-turning SV. Under these conditions, however, the SV drivers are likely to recognize that the situations were not
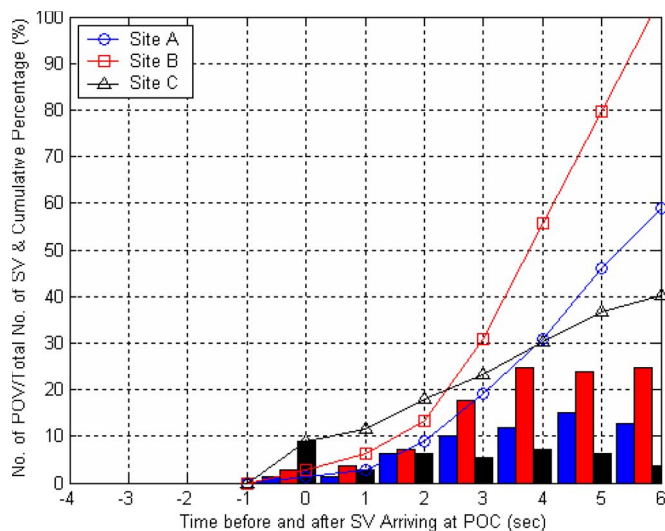
Fig. 11. Distribution of POV arrival after SV crossing POC for sites A, B, and C.

Fig. 12. Distribution of accepted POV time gap at sites A, B, and C.

threatening as both vehicles move relatively slow, and the right-turning vehicle may further slow down as they come to a position to turn. In other words, the SV driver assumes that the risks are not necessarily high and chooses to make an informed decision to initiate the turn. This is one exemplar situation that driver perception should be taken into account in the selection of warning criteria.

The three curves in Fig. 11, from $t = +2$ to $t = +6$, show different trends as site C increases slowly while site B rises rapidly. In this chart, a curve with greater values implies that the traffic is more intense as a higher percentage of SV encounters the POV moving through and arriving at the point of conflict. This partially reflects the consistently high-volume POV traffic at site B than other sites. Additionally, a large number of SV turned near the end of the green phase and in the amber phase at site C, as revealed in Fig. 6. This resulted in a smaller number of POV arriving after the SV finishes its turn, because the POV traffic would have been stopped for the red phase afterward. If the SV traffic is forced to turn mostly at the end of green or in the amber phase, there will be a limited knowledge that can be gained on time gap acceptance, because drivers are operating under the conditions that the POV traffic will stop for a signal transition. This point highlights the importance of conducting field observations, because a direct and realistic investigation can really help the understanding of a traffic phenomenon.

One aspect of turning behaviors that is not fully addressed in the representation of data given in Fig. 11 is the traffic dynamics that have occurred from the time of the SV driver decision to the instant of POV arriving at the point of conflict. The decision point is at least several seconds before the SV reaches the point of conflict. During this time period, the trajectories of SV and POV may have changed over time. The distribution of the POV arrival as shown in Fig. 11 is not necessarily indicative of the risks perceived by the drivers at the time of decision.

A method of utilizing field data to estimate drivers' time gap acceptance was suggested [17], [23]. By projecting the POV future arrival times from a time window when the driver decision is made before the actual turn, the distribution of
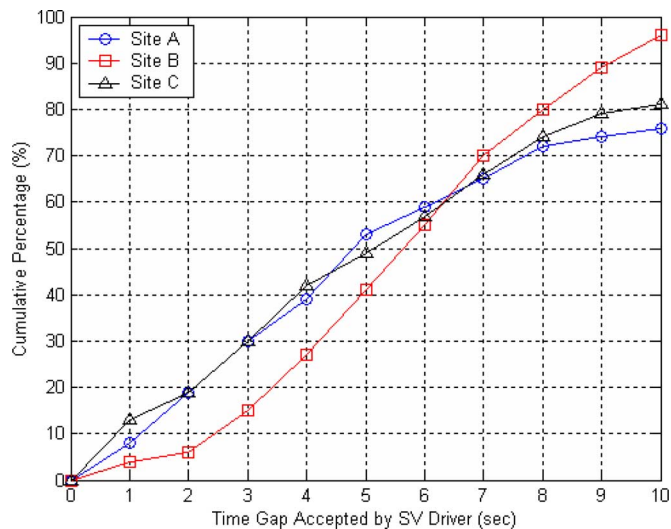
POV encountered by all drivers can be aggregately counted to derive a time gap acceptance curve. The driver-decision time is estimated by the average turning time and the perception time needed to take into account his/her own judgment of the traffic conditions. For example, a perception period of 1 s is used in the estimation of gap acceptance with reference to a related work [24]. A synthesis of data from multiple observation sites can be used to construct an aggregate model of driver time-acceptance behaviors. Fig. 12 plots the cumulative percentage of the POV time gap accepted by drivers from sites A, B, and C. The graph shows that the distribution is similar in range and shape.

Recent relevant work has utilized the same field-observation data to examine the circumstances of potential conflicts to further categorize the effects of intersection and traffic attributes on driving behaviors [25]. This topic deserves more extensive field observation and further in-depth investigation. However, a preliminary characterization can be concluded as follows.

1) Pedestrians can be a significant factor in urban environment, such as site A. The presence of a pedestrian causes disturbances to vehicle trajectories and leads to higher risks at times.
2) In high-speed dense-traffic environment, such as site B, potential conflicts frequently occur.
3) The turning scenarios in late green or amber phases, such as those at site C, are typically nonthreatening and commonly assumed so by SV drivers, because POV is expected to stop for the upcoming red signal, despite the movements initially appear to be hazardous.
4) On average, about 20%–40% of all left-turn maneuvers in the field data can be classified as potential conflicts that lead to a projected or actual short-trailing buffer. These apparent near miss or close encounters are the situations that warrant the issuance of warning.

V. SUMMARY AND CONCLUSION

Field observation was carried out to collect real-world traffic data for the study of intersection safety. Data were collected

at multiple locations to encompass a variety of geometric and operational conditions. The experimental setup and the procedures for analyzing and visualizing the traffic patterns and driving behaviors were thoroughly discussed. The subsequent analysis of data as explained in this paper demonstrates that a considerable information can be extracted and synthesized for the understanding of driving behaviors. In particular, the gap acceptance in LTAP-OD scenarios are examined to evaluate if there are recognizable patterns that indicate the effects of traffic attributes and intersection characteristics.

The availability of field data and the associated methodology constitute a foundation of knowledge for assessing the critical design parameters for safety countermeasures. For example, the lengths of signal phases seem to have a major influence on the distribution of gap acceptance. The vehicle speed and volume can cause a difference in the risk-taking behaviors of drivers. Pedestrian presence appears to be a significant factor in urban environment. The understanding of these issues provides guidelines for selecting a set of explanatory variables for more in-depth work in human-factor studies and warning criteria for safety applications.

The data-collection work presented herein was carried out in an *ad hoc* manner, which can certainly benefit from a more systematic approach with enhanced data-acquisition equipment. The encouraging results from this study also justify the further use of field observation in future work. With comprehensive filed observation and data collection, the outcome of these studies will provide significant insights into driving behaviors. Since the effectiveness of an IDS/CICAS solution is highly dependent on the driver perception and response to the issued warning, the knowledge of driving behaviors in a real-world setting is an excellent baseline for selecting warning criteria. The linkage of field observation to sensing, processing, and human-factor evaluation of suggested safety countermeasures remains topics of future studies.

ACKNOWLEDGMENT

REFERENCES

[1] T. Oda and T. Tajima, "Driving safety support system for senior society," in *Proc. ITS World Congress*, Toronto, ON, Canada, Oct. 1999. CD-ROM.

[2] A. Maeoka, "Supporting the safety of driving at the signalized intersections," in *Proc. IEEE Intell. Veh. Symp.*, Tokyo, Japan, May 2001, pp. 227–232.

[3] M. Hopstock, D. Ehmanns, and H. Spannheimer, "Development of advanced assistance systems for intersection safety," in *Proc. 9th Int. Conf. AMAA*, Berlin, Germany, Mar. 2005. CD-ROM.

[4] K. C. Fuerstenberg, "A new European approach for intersection safety—The EC project INTERSAFE," in *Proc. 8th Int. IEEE Conf. Intell. Transp. Syst.*, Vienna, Austria, Sep. 13–16, 2005, pp. 343–347.

[5] M. Schulze, G. Noecker, and K. Boehm, "PReVENT: A European program to improve active safety," in *Proc. 5th Int. Conf. Intell. Transp. Syst. Telecommun.*, Brest, France, Jun. 2005. CD-ROM.

[6] R. A. Ferlis, "Analysis of an infrastructure collision avoidance concept for straight crossing path crashes at signalized intersections," in *Proc. Annu. Meeting Transp. Res. Board*, Washington, DC, Jan. 2001, pp. 85–91.

[7] M. Zennaro and J. A. Misener, "A 'State Map' architecture for safe intelligent intersections," in *Proc. 13th Annu. Meeting Intell. Transp. Soc. Amer.*, Minneapolis, MN, May 19–22, 2003. CD-ROM.

[8] J. A. Misener, D. Ragland, X. Q. Wang, and T. E. Cohn, "Toward a smarter, safer intersection: Application of intelligent countermeasures to the intersection crash problem," in *Proc. ITS World Congr.*, Madrid, Spain, Nov. 2003. CD-ROM.

[9] J. D. Chovan *et al.*, *Examination of intersection, left turn across path crashes and potential IVHS countermeasures*. Washington, DC: Natl. Highway Traffic Safety Administration, 1994.

[10] J. S. Wang and R. Knipling, *Intersection crossing path crashes: Problem size assessment and statistical description*. Washington, DC: Natl. Highway Traffic Safety Administration, 1994.

[11] *US DOT CICAS Program*. [Online]. Available: http://www.its.dot.gov/cicas/

[12] *US DOT Update on Intelligent Vehicles and Intersections*. [Online]. Available: http://www.tfhrc.gov/pubrds/04jan/08.htm

[13] *California PATH Research Featured*. [Online]. Available: http://www.path.berkeley.edu/PATH/Research/Featured/032703/IDSforWeb.html

[14] C.-Y. Chan *et al.*, "Threat assessment of traffic moving toward a signal-controlled intersection," in *Proc. IEEE Intell. Veh. Symp.*, Parma, Italy, Jun. 2004, pp. 931–936.

[15] C.-Y. Chan and B. Bougler, "Evaluation of cooperative roadside and vehicle-based data collection for assessing intersection conflicts," in *Proc. IEEE Intell. Veh. Symp.*, Las Vegas, NV, Jun. 2005, pp. 165–170.

[16] S. E. Shladover *et al.*, "Measuring intersection turning behavior to support design of an intersection collision warning system," in *Proc. ITS World Congr.*, Nagoya, Japan, Oct. 2004. CD-ROM.

[17] C.-Y. Chan *et al.*, "Observations of driver time-gap acceptance at intersections in left-turn across-path opposite direction scenarios," presented at the Transportation Research Board Ann. Meeting, Washington, DC, 2005, Paper No. 05-2159. to appear in Transportation Research Record.

[18] D. Ragland *et al.*, "Impact of pedestrian presence on movement of left-turning vehicles: Method, preliminary results & possible use in intersection decision support," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2005, Paper No. 05-2199.

[19] D. Cody, "Analysis of field test data in an instrumented vehicle: Descriptions of left-turn maneuvers for intersection safety countermeasure design," presented at the TRB Annu. Meeting, 2005, Paper No. 05-2255. CD-ROM.

[20] S. E. Shladover *et al.*, "Design of alert criteria for an intersection decision support (IDS) system," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2005, Paper No. 05-2516. to appear in Transportation Research Record.

[21] L. Staplin, "Simulator and Field Measures of Driver Age Differences in Left-Turn Gap Judgments," in *Proc. 74th Annu. Meeting Transp. Res. Board*, 1995, pp. 49–55. Transportation Research Record No.1485.

[22] J. Alexander, P. Barham, and I. Black, "Factors influencing the probability of an incident at a junction: Results from an interactive driving simulator," *Accident Anal. Prev.*, vol. 34, no. 6, pp. 779–792, Nov. 2002.

[23] D. Ragland *et al.*, "Gap acceptance for vehicles turning left across oncoming traffic: Implications for intersection decision support," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2006, Paper No. 06-2696.

[24] P. L. Olson, "Driver Perception-Response time," in *Chapter 3 in Human Factors in Traffic Safety*, R. E. Dewar and P. L. Olson, Eds. Tucson, AZ: Lawyers and Judges, 2002.

[25] C.-Y. Chan, "Observation of left-turn conflicts at signalized intersections and design of gap-assistance systems in urban environment," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2006, Paper No. 06-0119.

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Characterization of Driving Behaviors Based on Field Observation of Intersection Left-Turn Across-Path Scenarios

Ching-Yao Chan, *Member, IEEE*

Abstract—There have been significant research and developments in recent years for intersection-safety solutions that are intended to alert drivers of hazardous situations by utilizing sensing, computing, and communication technologies. Since the effectiveness of intersection-safety systems depends strongly on driver perception and acceptance of the provided warning signal, the understanding of driver actions under the targeted scenario is a central research topic. One significant safety concern at intersections is the left-turn crossing-path scenarios, where a left-turning vehicle is confronted by oncoming traffic. This paper describes the analysis and synthesis of real-world data for such scenarios observed in field observations. Specifically, traffic interactions in left-turn across-path situations are evaluated to compare data from various intersections with different operation and traffic attributes. The analyzed data were characterized to gain insight into a time gap acceptance exhibited by a population of drivers. The knowledge of driving behaviors can provide the guidelines for future investigation as well as a knowledge basis for the selection of warning criteria to allow timely alerts to drivers in the intended safety applications.

Index Terms—Collision avoidance, driving behaviors, field observation, intersection crashes.

I. BACKGROUND

INTERSECTION collisions, particularly those with vehicles moving in crossing paths, are a major concern in roadway safety, since they often occur with significant speed differentials in the impact directions that lead to serious injuries or fatalities. In recent years, significant efforts have been devoted toward a safety research to reduce the numbers of crashes at intersections in several regions around the world [1]–[10]. A combination of newly developed and cost-reduced technologies can meaningfully reduce crashes if they are successfully implemented in intersection-decision-support (IDS) systems. This paper describes the IDS work carried out at California PATH for one of the most critical crash types: the left-turn across-path opposite-direction (LTAP-OD) situation [7], [8]. This is part of the overall research plan recently sponsored by Federal Highway Administration (FHWA) and several states in the U.S. [9], [10].
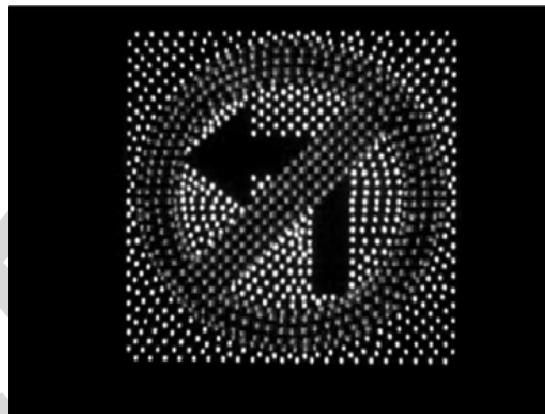
Fig. 1. Exemplar visual interface for left-turn warning.

Continuing efforts are now underway and expected to extend the operating concepts to integrate vehicle and infrastructure components and functions into cooperative intersection collision-avoidance systems (CICAS) [11].

An IDS/CICAS system requires the utilization of apparatus, including enhanced sensors, computer, and driver interface, on the existing infrastructure to provide drivers with advisory alerts. It will be noted here that warning and alert are loosely and interchangeably used within the discussions of this paper, although they may be interpreted quite differently from the human-factor perspective. For driver assistance, the IDS solutions may use a driver-infrastructure interface (DII), which conveys hazardous situations to drivers through a roadside sign. For example, the team at PATH has been experimenting with a DII illustrated in Fig. 1 for LTAP-OD warning. The sign only becomes active and is dynamically pulsed to draw drivers' attention. The activation of the DII is triggered by computing processors that determine if and when an alert signal is warranted by traffic conditions [12], [13].

The provision of an alert is not limited to infrastructure-based implementation only. Driver assistance can be implemented through a driver-vehicle interface (DVI), provided that the warning signal is communicated from roadside processors to the vehicle. The utilization of wireless communication for a data transmission is a central element in the research activities for the aforementioned CICAS project. Furthermore, the operational concepts of an intersection collision warning can be broadened considerably by allowing a two-way data exchange. By combining the available data from infrastructure and vehicle

sensors, a state map can be constructed [7], and warning decisions can be made more intelligently for intersection-safety applications. For example, in cases where the infrastructure sensors are unable to determine if a vehicle is in moving toward a turning maneuver, the activation of a turn signal detected on the vehicle data bus will be an additional information to process for an alert if necessary. Moreover, a vehicle-based application can be implemented with an adjustable-sensitivity feature that adapts to driver behaviors. These are examples of vehicle-infrastructure integration, which offers potential flexibility in the operating concepts.

The work described in this paper represents the analysis and synthesis of filed data gathered from several intersections for the investigation of driving behaviors. This is an extension of a prior work that involved the developments of apparatus and data-collection techniques [14]–[16] and methods for interpreting a driver time-gap selection [17], [18]. The results of this study provide a realistic understanding of driving behaviors and thus offer a solid foundation of knowledge base for the design of IDS and CICAS. Combined with human-factor experimental studies [19] and the use of a simulation model for scenario testing [20], the distribution of time- and distance-gap acceptance exhibited by drivers can help define the appropriate warning criteria to provide timely and effective alerts.

Section II contains a brief discussion on the motivation, approach, and limitation of the work described in this paper. In Section III, field-observation data are used to illustrate the analysis of traffic interactions in LTAP-OD scenarios. Descriptions of the data analysis and characterization were given in Section IV. A summary of the knowledge gained through this exercise and the implications for IDS/CICAS development and implementation are elaborated upon in Section V.

II. MOTIVATION, APPROACH, AND LIMITATION

One unique aspect of providing advisory alerts to drivers such as those proposed in IDS/CICAS applications is the wide spectrum of driver perception and reaction to the alert, which in turn dictates the effectiveness of the safety systems. It is essential that the advisory signal is generated in a timely fashion and communicated to the drivers with the least occurrences of false or nuisance alarms. However, it is impossible to satisfy this requirement for a large population of drivers, because each individual driver is likely to perceive traffic conditions differently and take risks according to his/her own judgment. An advisory warning issued under an objective assessment, which is based on a threat presented by opposing traffic, can only be designed to be satisfactory for most drivers. This is particularly true if the suggested warning is presented in the form of a driver-infrastructure interface.

Given the constraints in this challenging aspect of implementation, it is necessary to determine the appropriate warning thresholds that can sufficiently provide a timely alert to the driving public under a variety of traffic conditions and yet, at the same time, minimizes the potential of unnecessary nuisance or erroneous perception to the same population. For this purpose, the understanding of driving behaviors in a naturalistic setting will be extremely valuable in defining such warning thresholds.

In this context, the work described in this paper is a methodology of utilizing the field observation under real-world traffic conditions with an attempt to capture traffic patterns and associated driving behaviors that are exhibited by the driving public. The data collected from the field observation may be applicable for several types of intersection conflicts, but the main interest of this study is to further the understanding of LTAP-OD scenarios. LTAP-OD situations mostly happen in permissive and unprotected left-turn maneuvers where no designated left-turn phase is provided.

For clarification, several terms frequently used in such scenarios ought to be defined first. The vehicle that is turning left is called the subject vehicle (SV). The SV may face several opposing vehicles. The vehicle that is closest in time or distance and is most threatening is called the principal other vehicle (POV). A conflict occurs when an approaching POV is close in time or distance while an SV is turning.

Specifically, the discussions in this pare are intended for the exploration of the following issues.

1) How do we extract and interpret driving behaviors from the field-observation data?
2) What is the distribution of time and distance gap accepted by drivers making a left turn?
3) How is the distribution of gap acceptance influenced by intersection geometry, operation, and traffic attributes?
4) Can the characterization of field data provide useful inputs for the design of IDS/CICAS?

As will be explained in the following sections, affirmative and insightful answers can be given for questions 1) and 2). Preliminary conclusions can be made for questions 3) and 4), while meaningful and comprehensive answers will require further studies. More elaborated discussions of these issues are given in Section IV.

The field observation reported in this paper was considered an initial yet critical part of work in the overall scheme of the IDS project. The approach chosen was to explore data-collection methods under a variety of traffic conditions at candidate intersections. Instead of a permanent setup at the selected sites with an extensive and permanent instrumentation, the intention was to utilize a minimum set of equipment on a mobile platform that can be deployed at desired locations flexibly. Given these constraints, it should be noted that there were noticeable limitations during the course of data collection including the following.

1) The sensor-placement strategy was not thoroughly investigated to choose an optimal configuration or to assemble a set of multiple sensors for data fusion, and therefore, the setup did not allow full monitoring and tracking of all targets. For example, some targets were blocked by other vehicles in the traffic lanes and, therefore, might disappear from a radar or camera in some portions of their trajectories.
2) Since the radar sensor used in the mobile data-collection platform is based on the Doppler effect, stationary targets would disappear shortly after they arrived at the intersection and/or stopped for signals or other reasons.

3) Target detection and processing does not necessarily generate accurate measurements even with the reasonably good performance offered by the chosen radar sensor. Radar waves can reflect off different parts of a target, thus only providing approximate distance or speed. There are also occasional dropouts or erroneous identifications.

Despite the limitations described above, it was discovered during the analysis of collected data that the data-acquisition setup, albeit simplistic and minimal, yielded reasonably satisfactory results for the purpose of data evaluation. This is mainly due to the fact that the closest moving POV is most critical for SV driver decisions, and the POV is very likely to be successfully detected and tracked by the radar because they are often the leading vehicle in a stream of traffic and is not blocked. The analysis of radar data was supported by video images, which provided supplementary information; thus, results can be verified if the radar data became ambiguous or erroneous in certain situations.

III. Field-Observation Data Collection

As explained above, it is beneficial for the design and implementation of IDS by observing driving behaviors under a variety of traffic conditions and operation conditions; therefore, the field-observation sites are selected to allow as much diversity in relevant factors as possible among the locations. The potential relevant attributes, which are based on engineering judgment and intuition, include neighborhood settings (urban, suburban, rural), intersection operation features (traffic control, signal cycle, left-turn geometric layout), and traffic conditions (traffic volume, prevailing speed, pedestrian presence, etc.). Within the IDS project, the data collection was carried out at a number of intersections, with a selected few sufficient samples presented in this paper.

1) Shattuck and Hearst (in the city of Berkeley);
2) Chapin and El Camino Real (Burlingame);
3) Fifth Street and Brannan (San Francisco);
4) entrance into Del Monte Plaza from San Pablo Ave (Pinole).

The data collection at Shattuck and Hearst was conducted on three different dates with over 6 h of traffic data overall, while 2–3 h of data was collected at each of the other sites. Table I provides an overall comparison of the observation sites included in this paper and their associated parameters. The significance of intersection and traffic attributes is discussed below.

The results revealed by the analyzed data present recognizable patterns, and thus, the aggregate data are considered to constitute a statistically meaningful representation. This judgment is somehow subjective and deserves to be further quantified when additional field data become available. Nevertheless, the analysis of the LTAP-OD scenarios allows us to hypothesize the potential correlation between driving behaviors and intersection attributes, which in turn offers the guidelines for future field work.

Fig. 2 shows the data-acquisition setup at site A, an urban intersection in the downtown area of Berkeley, CA. As depicted,

TABLE I
INTERSECTION AND TRAFFIC CHARACTERISTICS OF
FIELD OBSERVATION SITES

Observation Site ID	A	B	C	D
Location	Hearst /Shattuck, Berkeley	Chapin /El Camino Real, Burlingame	5th Street /Brannan, San Francisco	San Pablo Ave, Pinole
Urban/ Suburban	U	S	U	S
Traffic Control	Traffic Signal	Traffic Signal	Traffic Signal	None
Pedestrian Traffic Presence	Frequent	Few	Few	Few
Number of POV Mainline Lanes	2	2	2	2
Left-Turn Pocket For SV	Yes	No	No	Yes
Signal Cycle Length (seconds)	75	80	60	N/A
Green Phase Length (seconds)	34.5	55-65 (variable)	20	N/A
Amber Phase (seconds)	3.3	3.5	3.5	N/A
All-Red Phase (seconds)	2.0	0.5	0.5	N/A
POV Traffic Volume (POV vehicles per minute)	Medium, 10+	High, 20+	Medium, 10+	Medium, ~ 10
Prevalent POV Speed	9-14 m/sec (20-30 mi/h)	16-20 m/sec (35-45 mi/h)	9-14 m/sec (20-30 mi/h)	16-20 m/sec (35-45 mi/h)
Total Numbers of Observed LTAP-OD	226 (34+68+124)	226	112	81
LTAP-OD SV Traffic Volume (Average SV per hour)	30+	84+	42+	30+

this intersection has two lanes in the mainline traffic direction (Shattuck Ave) and a left-turn pocket lane for SV waiting to make left turns. There are also parking lanes on both sides of the street. The intersection is controlled by traffic signals, which have a signal cycle of 75 s during the hours of observation (late morning to early afternoon). During the observation hours, the average cruising-traffic speed was about 11 m/s (25 mi/h). There are frequent gaps available among the opposing traffic, which allow the SV to make its intended left turn. A curve is shown in Fig. 2 to represent the trajectory of a left-turn SV. A triangular area is used to show the coverage area of a radar sensor with the radar placement at the tip of the triangle. A circle is placed within the triangle as the crossing point of the left-turn trajectory. The circled spot is also considered to
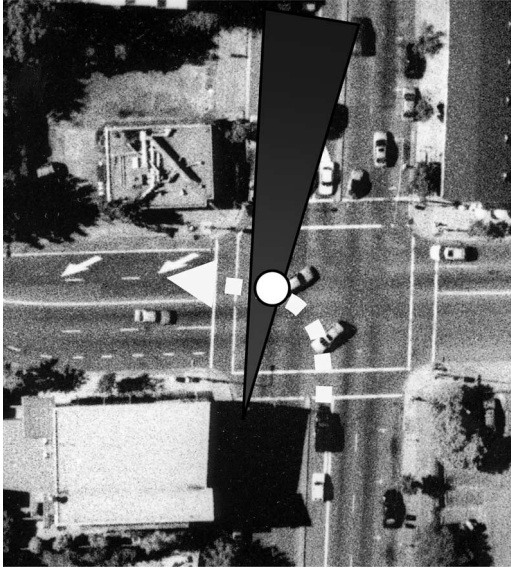
Fig. 2.   Depiction of the data-collection setup at site A.
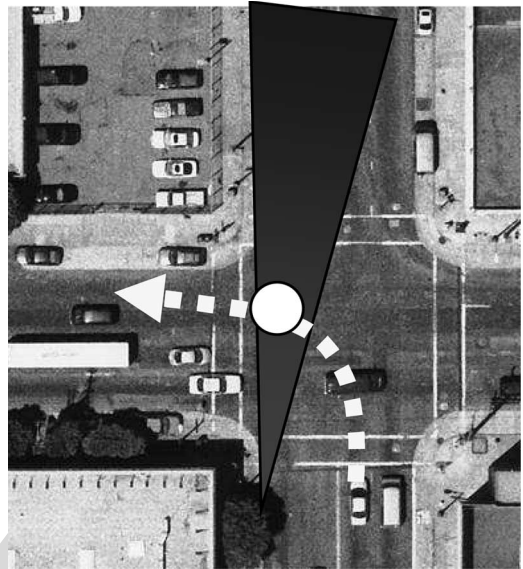

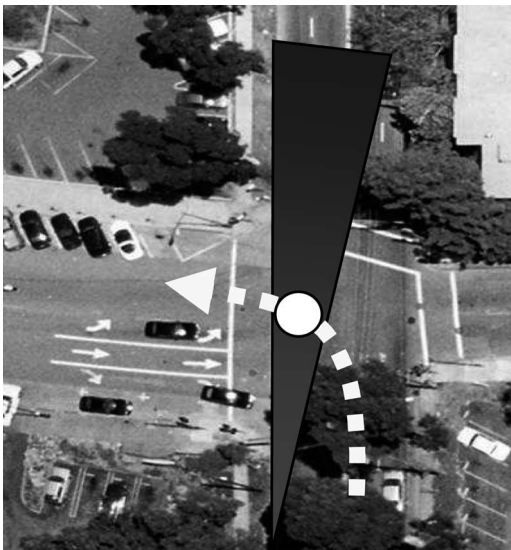Fig. 4.   Data-collection setup at site C.

Fig. 3.   Data-collection setup at site B.

Fig. 5.   Depiction of the data-collection setup at site D.

be the point or area of conflict, which will be used later for the calculation of vehicle arrival times so that a conflict can be predicted and evaluated. Similar markers and labels are also depicted in Figs. 3–5.

Fig. 3 shows the configuration at site B, a suburban area in the city of Burlingame, CA. At this location, due to the geometric constraints, there are no parking lanes or left-turn pockets. The intersection has a trapezoidal shape because of the angular connection and the nonequal widths of Chapin Ave on the two sides of El Camino Real. The main street (El Camino Real) is a major corridor with a consistently high volume of traffic at moderate to high speeds (16 to 20 m/s or 35–45 mi/h) throughout the day. The control of signals for traffic on Chapin is actuated so that a potentially longer green phase can be allocated for the traffic on El Camino Real. The green phase for the main road occupies 55–65 s out of the total 80 s in a cycle. There are frequent left-turning SV observed at the intersection

of El Camino Real and Chapin, where several commercial properties are located. The high volume of passing traffic has an effect on the SV maneuvers. Some drivers are enticed to creep forward or stop in the middle of the intersection in order to catch a gap more easily in the opposing traffic. Others are forced to wait until the end of the green phase before the left turn can be made.

Fig. 4 shows the observation setup for site C, an intersection in the city of San Francisco in an industrial neighborhood. There are two lanes of traffic and parking lanes on all directions of travel but no left-turn pockets. The left-turn SV on northbound Fifth Street turns onto westbound Brannan, which is a major street with relatively higher volumes of traffic. The green phase in the Fifth Street direction only uses 20 out of the 60 s of the signal cycle. The short green phase forces many SV to wait for their turns into the later part of the green or until the signal has turned amber or red. Traffic in the direction of opposing traffic or the POV typically moves at 9–14 m/s. The frequency of left-turn SV is higher than site A but lower than site B. A considerable portion of the POV traffic on the outside lane make right turns onto Brennan Street. Since California allows right turns during the red phase unless posted otherwise, a right-turning POV may appear to be moving toward a conflict with SV as both of them approach and enter the intersection.
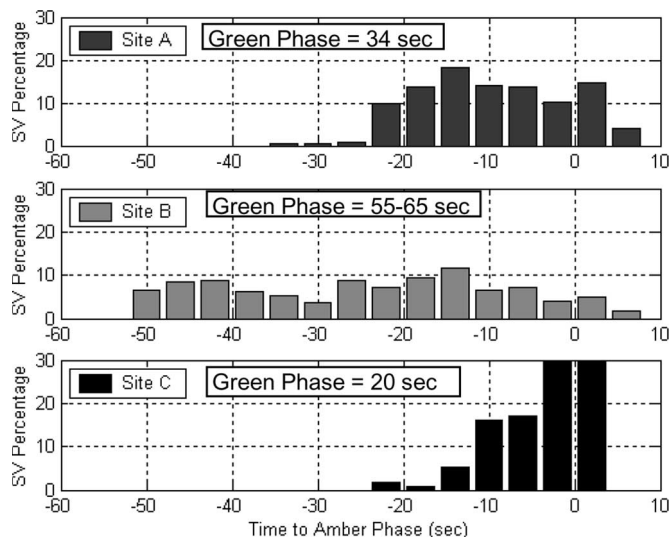
Fig. 6.   SV turning time in signal cycle at three observation sites.

Fig. 5 depicts the setting for LTAP-OD scenarios at a nonsignalized and atypical location in the city of Pinole, where vehicles entering and exiting from a shopping center face opposing traffic approaching from the right side of the picture. The straight-through traffic on the major roadway (San Pablo Avenue or State Route 123) typically moves at a relatively high speed of 16–20 m/s (35–45 mi/h). The traffic is very dense and heavy during the commute hours, but during our observation hours in the middle of the day, it was relatively light and sparse. The view of a driver making a left turn is partially obstructed due to a slight curve of the roadway and the trees planted on the median island.

Drivers anticipate and react to signal transitions at signalized intersections. Therefore, it is reasonable to hypothesize that the timing of left turn within the signal cycle may cause a difference in driving behaviors. For example, in the late stage of the green or amber phases, drivers may be tempted to rush their turns. Fig. 6 shows a comparison of a turning-time distribution from the three signalized intersections. Note that the signal-cycle lengths of the three sites are different. The green time is 34 s for site A, 55–65 s for site B, and 20 s for site C. The graph plots the time instant when the SV moves into the point of conflict relative to the beginning of the amber phase. A negative reading on the horizontal axis indicates that the turn occurs in green, and a positive reading implies turning in amber or early red phases. Each bar in the chart is shown for a 4-s interval. The values on the vertical axis are the percentage of SV turning at the corresponding time at the respective sites. The numbers for each site are normalized to be shown as a percentage of the total numbers of SV.

It is shown in Fig. 6 that the SV at sites A and B are evenly distributed across a large part of the green phase, but at site C, there is a high concentration at the end of green and into the amber and early red phases. The green phase at site C (San Francisco) is only 20-s long, thus forcing a very high percentage of late turns in the vicinity of the signal transition from green to amber. The discrepancies of such traffic characteristics

appear to be an important factor and should be noted for later data interpretation.

IV. FIELD DATA ANALYSIS AND INTERPRETATION

In order to synthesize data further for the purpose of this study, the LTAP-OD situations are first identified for review. This was accomplished with an automatic scan of radar data to identify the presence of SV targets and confirmed with a review of video data. From these identified samples, the interaction of SV–POV movements was further analyzed for interpretation.

A. Analysis of Vehicles Approaching an Intersection

When an SV makes a left turn, it is necessary for the SV driver to identify and accept a gap in traffic that is sufficient to complete the maneuver. The choice of a gap may be a "gap" between vehicles or a "lag" before the next POV arrives at the point of conflict. It is fair to assume that drivers typically judge the arrival time or the current distance of oncoming vehicles to decide whether it is safe to initiate a maneuver. Previous research also showed some evidence that such driver decisions can be a combination of time and distance gaps [21], [22].

For the analysis of traffic approaching an intersection, the time to intersection (T2I)[1] is a convenient measure of the closeness of a target vehicle. T2I is calculated by dividing the distance to intersection of a target vehicle by its current speed. The distance to intersection is often defined as the distance to the stop bar at the intersection. For the clarification of certain terminologies and to facilitate later discussions, a data set is used below to illustrate the variations of T2I for targets approaching during the different phases of the traffic signal.

The traffic in the POV direction within a traffic cycle (75 s) at site A is plotted in Fig. 7 with the instantaneous T2I of each vehicle versus time. The color bar and accompanying labels at the top of the chart indicate the signal phases during the cycle. There are two traffic lanes in this direction, and thus for lane differentiation, the data are denoted by ▶ (inside lane or lane 1) or ◀ (outside lane or lane 2). In the green phase in the first half of the signal cycle (34 s), multiple target vehicles are cruising toward the intersection at a relatively constant speed with their respective T2I decreases in a linear manner. As the signal transitions from green to amber, a target vehicle is seen slowing down and stopping with its T2I drops to a minimum value of about 2 s before increasing. The T2I of a stopping vehicle mostly follows this pattern because the decreasing speed yields a larger T2I, even though the distance to the intersection is decreasing as well. Behind the first stopping vehicle, several other vehicles also stop in the red phase. It can also be seen that the T2I of later arriving vehicles has greater minimum T2I values because they stop further from the stop bar.

For the analysis of LTAP-OD scenarios, it is important to observe the distance and speed of the POV when an SV left turn takes place. Therefore, it will be necessary to monitor the trajectory of a POV when an SV makes its turn. Furthermore,

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[1]T2I is used as the abbreviation for time to intersection instead of TTI because the latter may be confusing due to a widely recognized abbreviation for Texas Transportation Institute.
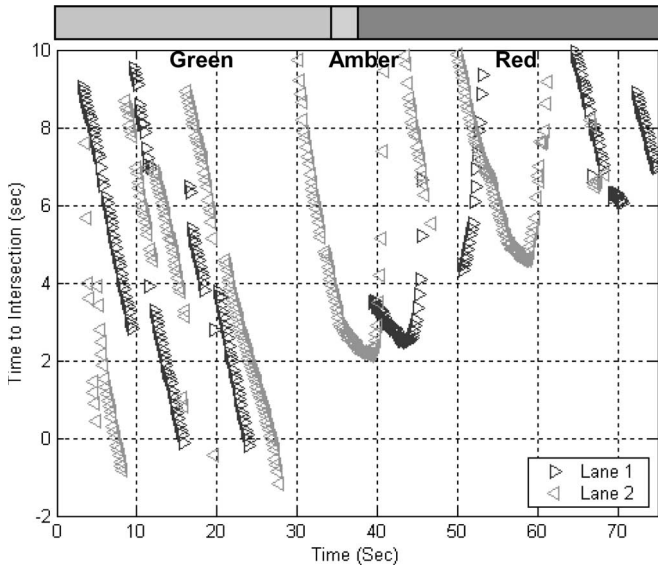
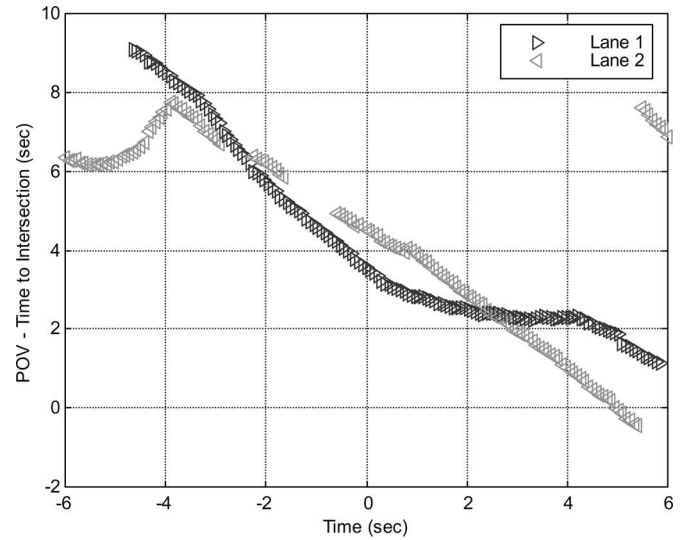Fig. 7. Variations of T2I of vehicles approaching an intersection in a signal cycle.

if we calculate the POV T2I in a time window before and after the SV reaches the point of conflict, the closeness of the POV and, thus, the time gaps accepted by the SV in actual turns can be assessed.

After each SV target is identified from the radar data and confirmed by video review, the radar data is then scanned to check for the presence of a POV. The corresponding POV distance and speed are then used to monitor their trajectories relative to the turning motion of an SV. Two LTAP-OD examples are shown in Fig. 8(a) and (b) to illustrate the SV–POV encounters in a time window before and after the time instant when the SV reaches the point of conflict.
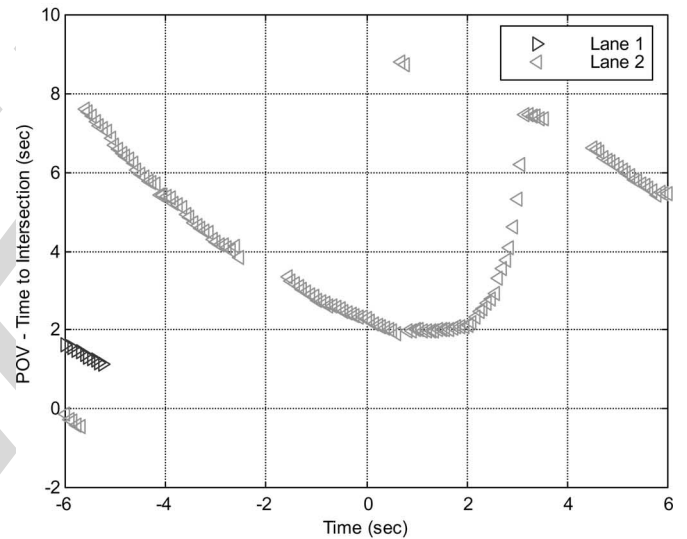
In Fig. 8(a), two opposing vehicles are approaching the intersection prior to the SV left turn. Initially, the vehicle on lane 2 is closer in time and is thus the POV by definition. At time $= -3$ s, the vehicle on lane 1 edges closer in time to the intersection and becomes the POV. At time $= 0$, the inside vehicle slows down, perhaps due to the appearance of the SV, and its T2I value remains flat for a second or so. Shortly after, the vehicle on lane 2 overtakes the other vehicle and becomes the POV again. This vehicle reaches the intersection when its T2I value becomes zero at about $t = 5$ s after the SV crosses the point of conflict.

In Fig. 8(b), besides the brief appearance of other vehicles at around $t = -6$, there is only one other vehicle present, and it by default, the POV. In this case, the SV left turn occurred during the signal transition from green to amber. The approaching POV was slowing down, perhaps due to the signal phase change or the presence of the SV. The POV T2I reaches a minimum value of 2 s right around $t = 0$, when the SV is at the point of conflict.

As shown by the two examples above, the SV and POV trajectories relative to the point of conflict can be evaluated in a period of potential interaction. The proximity of POV relative to an SV in a LTAP-OD situation can now be objectively compared with a common method. The procedure explained above will be the essential tool used throughout the remainder of this paper for all intersections. Aside from the T2I measure,

(a)

(b)

Fig. 8. (a) POV-T2I versus SV detection time—example 1. (b) POV-T2I versus SV detection time—example 2.

it is believed that a distance to intersection (D2I) may also be an important factor in a driver's consideration for the judgment of oncoming traffic. Many aspects of analysis in the following sections can be applied to D2I as well, but the discussions and illustrations will only be shown for T2I to avoid being repetitive.

Upon further examination of field-observation sites, it is noticed that the geometric layout of intersections are very different, and therefore, the stop-bar position relative to the point of conflict varies significantly, as shown in Figs. 2–5. It is reasoned that the perceived closeness of oncoming traffic relative to the point of conflict, instead of the stop bar, is more important for drivers' gap acceptance. This is especially true for large-size intersections. Therefore, the calculation of the POV proximity is adjusted by using the time to point of conflict (T2POC). Similar to T2I, T2POC is the estimated arrival time of a vehicle by dividing the current distance to the point of conflict (D2POC) of a target vehicle by its instantaneous speed.

By the use of T2POC, a conflict can be represented by the relative arrival times of SV and POV at the point of conflict.

It should be further noted that the term, time to conflict, adopted herein has a completely different meaning from the conventional use of TTC; TTC is usually used to denote the time to collision, which is calculated, for example, by dividing the space between two vehicles by the speed differential in a vehicle-following situation.

B. Description of LTAP-OD Scenarios by SV–POV Interaction

The same procedure of the data analysis described above can be followed for all SV cases to identify the characteristics of time acceptance at multiple locations. When data were presented as an aggregate representation of a large number of drivers, it enables us to compare the driving behaviors at each site under different traffic conditions and to compare the differences among multiple sites.
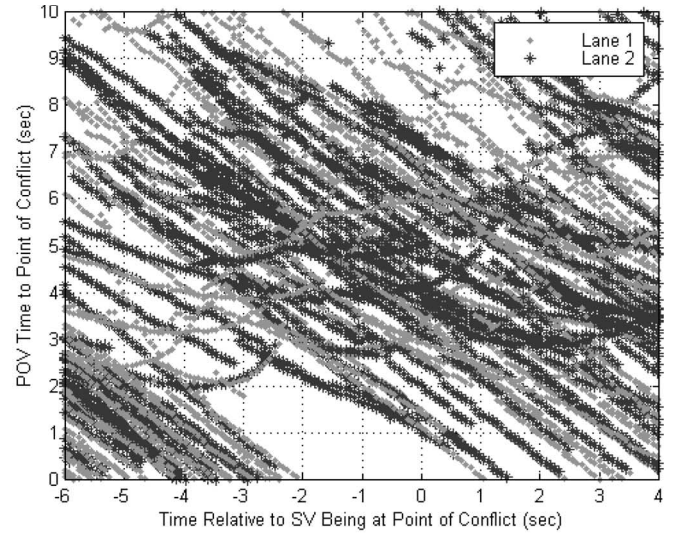
Fig. 9(a) is a chart generated from a 2-hr data set from site A. It is a composite chart with a total of 68 left-turning SV. Fig. 9(a) is constructed in the following manner.

1) For each SV, the POV T2POC is plotted in the time window of -6 and $+4$ s around $t = 0$ when SV arrives at the point of conflict.
2) A plot similar to the examples in Fig. 8 is repeated for all 68 turning SV.
3) The POV may be in either of the two lanes. If there are multiple vehicles approaching, only the one with the smallest T2POC is plotted.
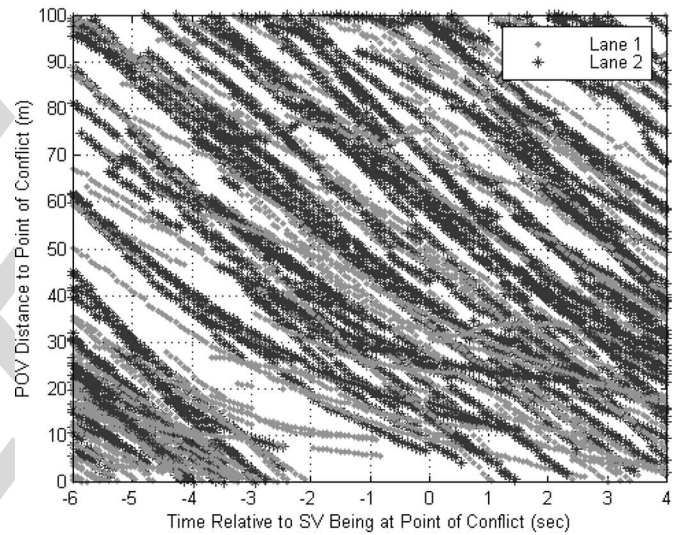
Fig. 9(b) is similarly constructed for the D2POC.

Fig. 9(a) and (b) provides intuitive yet revealing phenomena of SV–POV interaction. Some explanations and comments are given as follows.

1) If a POV cruises toward the intersection at a constant speed, its T2POC curve will be a straight line with a down slope of -1 in Fig. 9(a).
2) If a POV slows down, the slope of its T2POC trajectory will decrease in absolute values as can be seen in some examples in their corresponding T2POC and D2POC curves.
3) A few POV targets are found to slow down or stop as they get very close to the point of conflict. This is particularly visible for a couple of cases at the center bottom of the Fig. 9(b). The POV is slowing down due to the presence of a turning SV or signal transition.
4) Often, there is a previously passing POV before the SV turns. These POV cross the point of conflict before SV arrival at time $= 0$. A cluster of POV pass through prior to $t = -2$ in Fig. 9(a).
5) The two-second period of a passing POV before an SV arrives at the point of conflict, which is described in 4), is called the leading buffer.
6) For the majority of cases, POV does not arrive until two seconds after SV crosses the point of conflict. If the arrival times of SV and POV are close to each other, as indicated by several cases in Fig. 9(a) with POV T2POC crossing near time $= +1$, then there is a potential conflict or hazard.

(a)

(b)

Fig. 9. (a) POV-T2POC versus time relative to SV crossing POC (Data 12/11/03). (b) POV-D2POC versus time relative to SV crossing POC (Data 12/11/03).

7) The time period between the passing of SV and the subsequent arrival of POV at the point of conflict, which is mentioned in 6), is referred to as the trailing buffer.
8) The shorter the trailing buffer, the greater the risk is for the LTAP-OD scenario. The trailing buffer is also indicative of the aggressiveness of SV drivers in their decision to turn.
9) A time gap is clearly evident in Fig. 9(a). The gap is bordered by the leading and trailing buffer, but it is also visible in a channel in the chart that angles backward in time to the upper left of the graph. There is a sparse POV presence in the channel. The reason for the existence of a gap and a channel extended backward in time is obvious because a decision to make the turn is made a few seconds before the SV arrives at the point of conflict. This is a significant point to note because the timing of
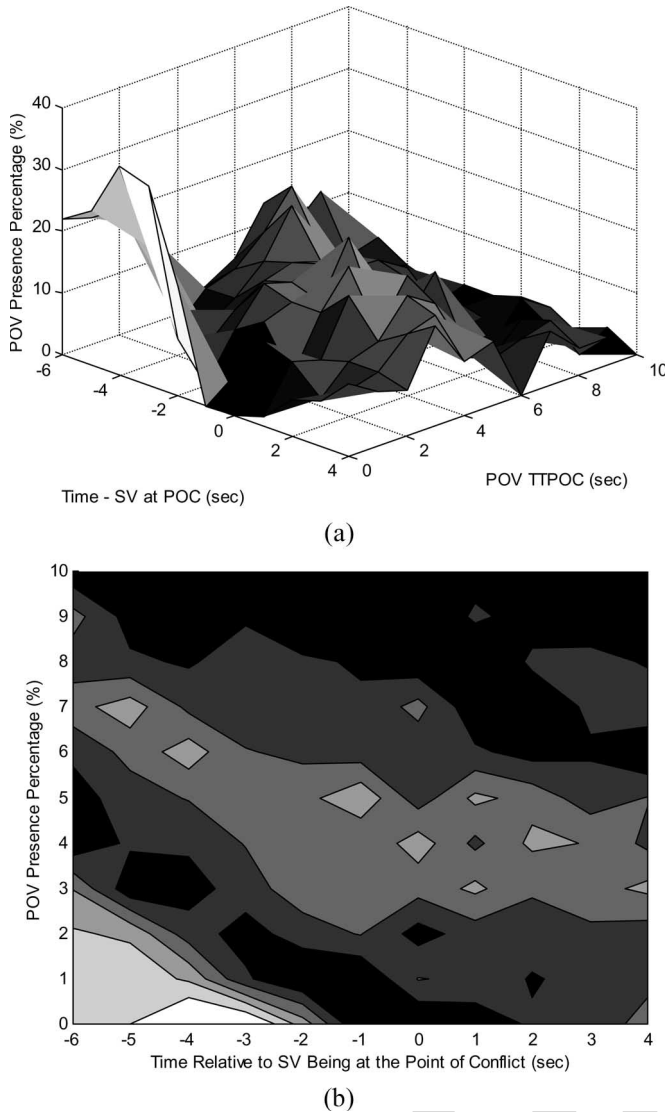
(a)

(b)

Fig. 10.   (a) Three-dimensional view of POV presence with respect to SV arrival. (b) Two-dimensional view of POV presence with respect to SV arrival.

warning in IDS/CICAS must be related to the time of driver decision.

If the graph of Fig. 9(a) is divided into a grid of 1-s intervals in both directions, and the number of POV presence within each grid is counted, a distribution plot of the POV can be generated. Fig. 10(a) shows a three-dimensional plot of this distribution. The vertical reading is calculated by dividing the number of POV by the total number of SV and expressed in the percentage of cases where an SV is encountering a POV at the respective grids in time.

In Fig. 10(a), a high peak is present on the left side of the chart, which shows the cluster of previously passing vehicles that correspond to those in the triangular area at the lower left corner in Fig. 9(a). The peak at the central portion of the chart is indicative of the intensity of oncoming POV faced by SV as the SV makes its turn. The valley between the two peaks reveals the time gap and channel as mentioned in Fig. 9(a), which are accepted by the SV to make the left turn.

The three-dimensional plot of Fig. 10(a) can also be projected onto a two-dimensional contour plot, shown in Fig. 10(b), which offers an alternative visualization of the SV–POV encounters. A more intense or lighter-color area in Fig. 10(b) means that the POV is present for a higher percentage of cases. Conversely, a darker area means that the presence of the POV is sparse or less frequent. Fig. 10(a) and (b) conveys a quantified representation of the same data in Fig. 9(a).

The shape and form of the gaps are influenced by traffic conditions and intersection attributes. These graphs provide useful visualization tools for data comparison. Due to the space limitation, the results generated from other data sets will not be shown, but they all show similar patterns with variations in intensity distribution. To allow a comparison of such driving behaviors under varying traffic conditions and in different intersection settings, further quantitative analysis is needed.

C. Data Utilization and Characterization for Different Traffic Conditions and at Different Intersections

Once the approach of data analysis is chosen, they can be similarly applied to data sets from various traffic and intersection conditions. The data can then be synthesized to gain an insight into the data of relevant traffic and roadway factors that may influence the driving behaviors. For example, one may wish to compare the percentage of SV turning with POV arriving with a short trailing buffer at different sites. Also, one may choose to utilize the field data from different sites to check if the distribution of accepted time gaps shows any significant variation due to varying traffic conditions.

For a comparison of signalized intersections with distinct traffic attributes, the data from sites A, B, and C are analyzed further. Fig. 11 shows a comparison of the distribution of POV arrival times after the SV has crossed the point of conflict. The graph is generated by counting the numbers of POV passing through the point of conflict in every 1-s intervals and plotting the cumulative percentage curves of each of the three sites. The percentage is normalized by dividing the number of POV by the total SV number.

For the purpose of discussions, let us define a conflict that warrants the issuance of warning to be a situation when the trailing buffer is less than 2 s. The data depicted in Fig. 11 indicate that there is a difference in the percentage of left-turn cases. For example, site C appears to have the highest ratio, which is followed by site B, and site A possesses the lowest ratio. This ratio can be interpreted as the level of aggressiveness of SV turning maneuvers for a site.

There are at least a couple of possible explanations for this contrast in the ratios for these sites. The driver group at one site may indeed be more aggressive than the other sites, for a reason such as driver demographics. On the other hand, the traffic patterns at a particular site may distort the observed phenomenon and cause a shift in the distribution for a site. For example, we have explained in Section III that there are a large number of right-turning POV at site C, and they are frequently on a trajectory that appears to be approaching a conflict with the left-turning SV. Under these conditions, however, the SV drivers are likely to recognize that the situations were not
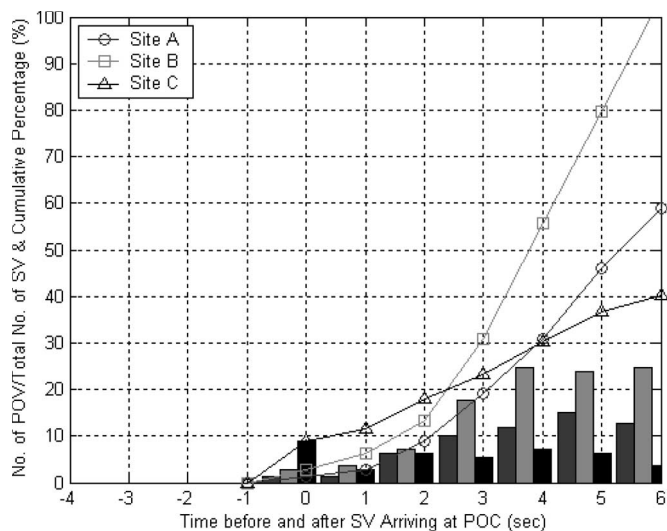
Fig. 11. Distribution of POV arrival after SV crossing POC for sites A, B, and C.

Fig. 12. Distribution of accepted POV time gap at sites A, B, and C.

threatening as both vehicles move relatively slow, and the right-turning vehicle may further slow down as they come to a position to turn. In other words, the SV driver assumes that the risks are not necessarily high and chooses to make an informed decision to initiate the turn. This is one exemplar situation that driver perception should be taken into account in the selection of warning criteria.

The three curves in Fig. 11, from $t = +2$ to $t = +6$, show different trends as site C increases slowly while site B rises rapidly. In this chart, a curve with greater values implies that the traffic is more intense as a higher percentage of SV encounters the POV moving through and arriving at the point of conflict. This partially reflects the consistently high-volume POV traffic at site B than other sites. Additionally, a large number of SV turned near the end of the green phase and in the amber phase at site C, as revealed in Fig. 6. This resulted in a smaller number of POV arriving after the SV finishes its turn, because the POV traffic would have been stopped for the red phase afterward. If the SV traffic is forced to turn mostly at the end of green or in the amber phase, there will be a limited knowledge that can be gained on time gap acceptance, because drivers are operating under the conditions that the POV traffic will stop for a signal transition. This point highlights the importance of conducting field observations, because a direct and realistic investigation can really help the understanding of a traffic phenomenon.

One aspect of turning behaviors that is not fully addressed in the representation of data given in Fig. 11 is the traffic dynamics that have occurred from the time of the SV driver decision to the instant of POV arriving at the point of conflict. The decision point is at least several seconds before the SV reaches the point of conflict. During this time period, the trajectories of SV and POV may have changed over time. The distribution of the POV arrival as shown in Fig. 11 is not necessarily indicative of the risks perceived by the drivers at the time of decision.

A method of utilizing field data to estimate drivers' time gap acceptance was suggested [17], [23]. By projecting the POV future arrival times from a time window when the driver decision is made before the actual turn, the distribution of
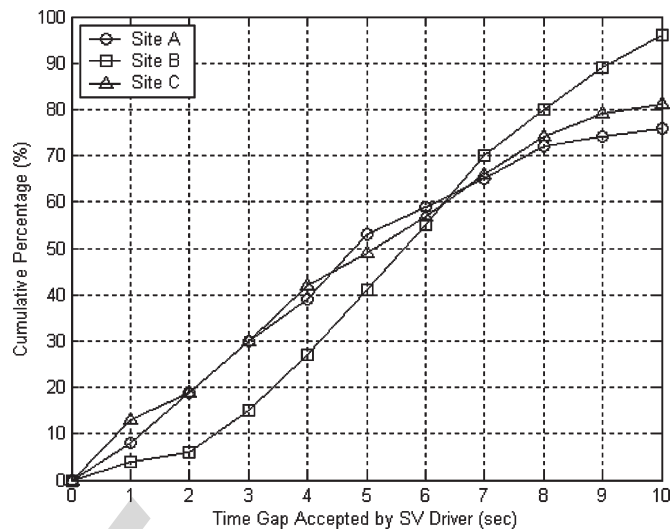
POV encountered by all drivers can be aggregately counted to derive a time gap acceptance curve. The driver-decision time is estimated by the average turning time and the perception time needed to take into account his/her own judgment of the traffic conditions. For example, a perception period of 1 s is used in the estimation of gap acceptance with reference to a related work [24]. A synthesis of data from multiple observation sites can be used to construct an aggregate model of driver time-acceptance behaviors. Fig. 12 plots the cumulative percentage of the POV time gap accepted by drivers from sites A, B, and C. The graph shows that the distribution is similar in range and shape.

Recent relevant work has utilized the same field-observation data to examine the circumstances of potential conflicts to further categorize the effects of intersection and traffic attributes on driving behaviors [25]. This topic deserves more extensive field observation and further in-depth investigation. However, a preliminary characterization can be concluded as follows.

1) Pedestrians can be a significant factor in urban environment, such as site A. The presence of a pedestrian causes disturbances to vehicle trajectories and leads to higher risks at times.
2) In high-speed dense-traffic environment, such as site B, potential conflicts frequently occur.
3) The turning scenarios in late green or amber phases, such as those at site C, are typically nonthreatening and commonly assumed so by SV drivers, because POV is expected to stop for the upcoming red signal, despite the movements initially appear to be hazardous.
4) On average, about 20%–40% of all left-turn maneuvers in the field data can be classified as potential conflicts that lead to a projected or actual short-trailing buffer. These apparent near miss or close encounters are the situations that warrant the issuance of warning.

V. SUMMARY AND CONCLUSION

Field observation was carried out to collect real-world traffic data for the study of intersection safety. Data were collected

at multiple locations to encompass a variety of geometric and operational conditions. The experimental setup and the procedures for analyzing and visualizing the traffic patterns and driving behaviors were thoroughly discussed. The subsequent analysis of data as explained in this paper demonstrates that a considerable information can be extracted and synthesized for the understanding of driving behaviors. In particular, the gap acceptance in LTAP-OD scenarios are examined to evaluate if there are recognizable patterns that indicate the effects of traffic attributes and intersection characteristics.

The availability of field data and the associated methodology constitute a foundation of knowledge for assessing the critical design parameters for safety countermeasures. For example, the lengths of signal phases seem to have a major influence on the distribution of gap acceptance. The vehicle speed and volume can cause a difference in the risk-taking behaviors of drivers. Pedestrian presence appears to be a significant factor in urban environment. The understanding of these issues provides guidelines for selecting a set of explanatory variables for more in-depth work in human-factor studies and warning criteria for safety applications.

The data-collection work presented herein was carried out in an *ad hoc* manner, which can certainly benefit from a more systematic approach with enhanced data-acquisition equipment. The encouraging results from this study also justify the further use of field observation in future work. With comprehensive filed observation and data collection, the outcome of these studies will provide significant insights into driving behaviors. Since the effectiveness of an IDS/CICAS solution is highly dependent on the driver perception and response to the issued warning, the knowledge of driving behaviors in a real-world setting is an excellent baseline for selecting warning criteria. The linkage of field observation to sensing, processing, and human-factor evaluation of suggested safety countermeasures remains topics of future studies.

REFERENCES

[1] T. Oda and T. Tajima, "Driving safety support system for senior society," in *Proc. ITS World Congress*, Toronto, ON, Canada, Oct. 1999. CD-ROM.

[2] A. Maeoka, "Supporting the safety of driving at the signalized intersections," in *Proc. IEEE Intell. Veh. Symp.*, Tokyo, Japan, May 2001, pp. 227–232.

[3] M. Hopstock, D. Ehmanns, and H. Spannheimer, "Development of advanced assistance systems for intersection safety," in *Proc. 9th Int. Conf. AMAA*, Berlin, Germany, Mar. 2005. CD-ROM.

[4] K. C. Fuerstenberg, "A new European approach for intersection safety—The EC project INTERSAFE," in *Proc. 8th Int. IEEE Conf. Intell. Transp. Syst.*, Vienna, Austria, Sep. 13–16, 2005, pp. 343–347.

[5] M. Schulze, G. Noecker, and K. Boehm, "PReVENT: A European program to improve active safety," in *Proc. 5th Int. Conf. Intell. Transp. Syst. Telecommun.*, Brest, France, Jun. 2005. CD-ROM.

[6] R. A. Ferlis, "Analysis of an infrastructure collision avoidance concept for straight crossing path crashes at signalized intersections," in *Proc. Annu. Meeting Transp. Res. Board*, Washington, DC, Jan. 2001, pp. 85–91.

[7] M. Zennaro and J. A. Misener, "A 'State Map' architecture for safe intelligent intersections," in *Proc. 13th Annu. Meeting Intell. Transp. Soc. Amer.*, Minneapolis, MN, May 19–22, 2003. CD-ROM.

[8] J. A. Misener, D. Ragland, X. Q. Wang, and T. E. Cohn, "Toward a smarter, safer intersection: Application of intelligent countermeasures to the intersection crash problem," in *Proc. ITS World Congr.*, Madrid, Spain, Nov. 2003. CD-ROM.

[9] J. D. Chovan *et al.*, *Examination of intersection, left turn across path crashes and potential IVHS countermeasures*. Washington, DC: Natl. Highway Traffic Safety Administration, 1994.

[10] J. S. Wang and R. Knipling, *Intersection crossing path crashes: Problem size assessment and statistical description*. Washington, DC: Natl. Highway Traffic Safety Administration, 1994.

[11] *US DOT CICAS Program*. [Online]. Available: http://www.its.dot.gov/cicas/

[12] *US DOT Update on Intelligent Vehicles and Intersections*. [Online]. Available: http://www.tfhrc.gov/pubrds/04jan/08.htm

[13] *California PATH Research Featured*. [Online]. Available: http://www.path.berkeley.edu/PATH/Research/Featured/032703/IDSforWeb.html

[14] C.-Y. Chan *et al.*, "Threat assessment of traffic moving toward a signal-controlled intersection," in *Proc. IEEE Intell. Veh. Symp.*, Parma, Italy, Jun. 2004, pp. 931–936.

[15] C.-Y. Chan and B. Bougler, "Evaluation of cooperative roadside and vehicle-based data collection for assessing intersection conflicts," in *Proc. IEEE Intell. Veh. Symp.*, Las Vegas, NV, Jun. 2005, pp. 165–170.

[16] S. E. Shladover *et al.*, "Measuring intersection turning behavior to support design of an intersection collision warning system," in *Proc. ITS World Congr.*, Nagoya, Japan, Oct. 2004. CD-ROM.

[17] C.-Y. Chan *et al.*, "Observations of driver time-gap acceptance at intersections in left-turn across-path opposite direction scenarios," presented at the Transportation Research Board Ann. Meeting, Washington, DC, 2005, Paper No. 05-2159. to appear in Transportation Research Record.

[18] D. Ragland *et al.*, "Impact of pedestrian presence on movement of left-turning vehicles: Method, preliminary results & possible use in intersection decision support," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2005, Paper No. 05-2199.

[19] D. Cody, "Analysis of field test data in an instrumented vehicle: Descriptions of left-turn maneuvers for intersection safety countermeasure design," presented at the TRB Annu. Meeting, 2005, Paper No. 05-2255. CD-ROM.

[20] S. E. Shladover *et al.*, "Design of alert criteria for an intersection decision support (IDS) system," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2005, Paper No. 05-2516. to appear in Transportation Research Record.

[21] L. Staplin, "Simulator and Field Measures of Driver Age Differences in Left-Turn Gap Judgments," in *Proc. 74th Annu. Meeting Transp. Res. Board*, 1995, pp. 49–55. Transportation Research Record No.1485.

[22] J. Alexander, P. Barham, and I. Black, "Factors influencing the probability of an incident at a junction: Results from an interactive driving simulator," *Accident Anal. Prev.*, vol. 34, no. 6, pp. 779–792, Nov. 2002.

[23] D. Ragland *et al.*, "Gap acceptance for vehicles turning left across on-coming traffic: Implications for intersection decision support," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2006, Paper No. 06-2696.

[24] P. L. Olson, "Driver Perception-Response time," in *Chapter 3 in Human Factors in Traffic Safety*, R. E. Dewar and P. L. Olson, Eds. Tucson, AZ: Lawyers and Judges, 2002.

[25] C.-Y. Chan, "Observation of left-turn conflicts at signalized intersections and design of gap-assistance systems in urban environment," presented at the Transportation Research Board Annu. Meeting, Washington, DC, 2006, Paper No. 06-0119.

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