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A color version of this report is available online at:
http://database.path.berkeley.edu/reports/index.cgi

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ABSTRACT

Currently, Federal and State governments are partnering with private industries and academia institutions to pursue the deployment of intersection decision support (IDS) and cooperative intersection collision avoidance systems (CICAS), which seek to combine infrastructure-based and vehicle-based functions to provide optimal solutions for roadway users. The overall (IDS) research plan was constructed to explore the requirements, tradeoffs assessment, and technology investigations necessary to define a Cooperative Intersection Collision Avoidance System. This report is the third report on the California PATH IDS research, and it focuses on two human factors studies which used the PATH instrumented Ford Taurus research vehicle to study driver behavior while making left turns.

The goal of the first study was to observe drivers' intersection approaches and left-turn maneuvers in a mostly naturalistic setting. Twenty-three drivers (both male and female and younger and older) were recruited to drive the instrumented vehicle 10 times around an 8-block course in the city of Berkeley, CA, making a total of 40 left turns per driver. The instrumented vehicle recorded driver actions, such as approach speed, brake activation, steering inputs, and limited estimates of oncoming vehicle gap (and lag) acceptance.

The goal of the second study at the California PATH Richmond Field Station (RFS) instrumented intersection was twofold. First, left-turn gap (or lag) acceptance was examined in an environment where gaps could be more accurately measured and tightly controlled. Second, the study introduced drivers to the concept of a left-turn Driver Infrastructure Interface (DII), a dynamic, no-left-turn sign, warning sign. Twenty drivers (both male and female and younger and older) were recruited to drive the instrumented vehicle through the RFS intersection 54 times with a single oncoming vehicle approaching. The vehicle approaches were timed to test the effects of different DII settings such as warning threshold onset timing on gap (lag) acceptance.

Key Words

Human Factors, Driver Behavior, Intersection Safety, LTAP-OD, Left Turn Driver Infrastructure Interface, DII, Cooperative Systems, ITS, Intelligent Transportation Systems, Active Safety, Crossing Path Collisions Crashes, Infrastructure Consortium

EXECUTIVE SUMMARY

Introduction

The Intersection Decision Support (IDS) project addressed the application of infrastructure-based and infrastructure-vehicle cooperative systems to address intersection safety. The Infrastructure Consortium (IC) was comprised of the US Department of Transportation (DOT), California DOT (Caltrans), Minnesota DOT, and Virginia DOT and their associated university research partners.

The project's three-year mission was to investigate key enabling technologies, conduct naturalistic driving data collection, perform driver modeling, develop an integrated IDS simulation approach, and look at the applicability of a large set of already- or nearly- available "commercial off the shelf" systems towards designing a Cooperative Intersection Collision Avoidance System (CICAS). The California PATH IDS research focused on the Left-Turn Across Path with Opposite Direction Traffic (LTAP-OD) crash type.

The ultimate goal of any intersection collision avoidance system is to reduce intersection crashes by providing drivers with information to support turning decisions. In order to accomplish this goal, any system intending to aid in LTAP-OD collision prevention must perform three functions:

1. Sense and track vehicle movements
2. Predict likely future vehicle states and potential conflict situations
3. Provide relevant information to the driver at the appropriate time

Past research detailed in previous IDS project reports had identified four potential driver-related causes of LTAP-OD crashes:

- Driver failure to judge safe time gaps correctly
- Driver failure to judge the speeds of closing vehicles
- Driver failure to see the oncoming vehicle (i.e., "looked but did not see")
- Obstruction of the driver's view by an opposing vehicle

Based on these assumptions of crash causes, the two human factors or driver behavior studies described in this report attempted to gain insights into what decisions are being made by drivers, when those decisions are being made, and what information drivers might be able to use to make better decisions. The specific human factors or driver behavior questions addressed during the IDS project (as described in this report) included the following:

1. How do drivers approach left-turn intersections (speed profiles, braking points)?
2. How long does it take drivers to traverse an intersection?
3. What "gaps" in the oncoming traffic are typically accepted or rejected?
4. When are decisions being made by the SV driver?
5. How can a conflict between the turning SV and POV be accurately predicted?

Method

Overview

This report describes two human factors experiments which recruited test participants to drive the PATH instrumented Ford Taurus research vehicle to study driver behavior while making left turns. In both studies, the test participants were considered to be driving the Subject Vehicle (SV) or the vehicle that was attempting to make a left turn. Oncoming vehicles, known as Principle Other Vehicles (POVs), were either other members of the general public (unaware of the study in progress) or driven by confederate PATH personnel.

The goal of the first study was to observe drivers' intersection approaches and left-turn maneuvers in a mostly naturalistic setting. The PATH instrumented vehicle was used to record driver actions, such as approach speed, brake activation, steering inputs, and limited estimates of oncoming vehicle gap (and lag) acceptance while making a series of left-turns on public roads in the city of Berkeley, CA.

The second study utilized both the PATH instrumented Ford Taurus research vehicle and the Richmond Field Station (RFS) instrumented intersection. Although this setting was less naturalistic, it allowed for left-turn gap (or lag) acceptance to examined in an environment where gaps could be more accurately measured and more tightly controlled. This second study also introduced drivers to the concept of a left-turn Driver Infrastructure Interface (DII), a dynamic, no-left-turn sign, warning sign.

Berkeley Instrumented Vehicle Field Test

Twenty-three drivers, age 25 to 75 (both male and female), drove an instrumented vehicle ten times around a 2-block by 4-block test route including four intersections, turning left at each intersection. Three of the intersections had left-turn pockets, and all of the intersections had a permissive green for left-turn movements. There are significant variations in gaps in oncoming traffic, presence of and distance to a lead vehicle and traffic signal phase. Each data collection lasted approximately 1.5 hours. The driving sessions were conducted at off-peak hours, either between 9:30 and 11 am or between 2 and 3:30 pm.

The instrumentation recorded drivers' manipulation of vehicles control (throttle, brake, and turn signal), vehicle motion (speed, acceleration, and position using DGPS), distance and relative velocity with front and on-coming traffic (radars), and video with a 5-channel recorder (driver's face, 3 front scenes, and rear scene). The DGPS and radar data were combined in order to render the SV and POV trajectories relative to the zone of conflict (ZOC), where the trajectories would collide. Traffic signal state was recorded manually through the post-processing of the instrumented vehicle's video recordings.

The resulting intersection approaches were categorized into four trajectories for analysis:

- Trajectory 1 (11.3%): SV drivers turned without stopping at the intersection.
- Trajectory 2 (28.4%): SV driver stops prior to the stop bar (typically due to arrival on a red phase) , and then proceeds to cross the intersection without stopping.
- Trajectory 3 (40.3%): SV driver stops prior to the stop bar, and then again in the intersection.
- Trajectory 4 (19.3%): SV driver does not stop prior to the stop bar, but does stop once in the intersection.

RFS Instrumented Intersection Experiment

Twenty drivers, age 20 to 84 (both male and female), were recruited to drive the instrumented vehicle (SV) through the RFS intersection 54 times with a single oncoming POV, both with and without the aid of a Driver Infrastructure Interface (DII) to aid the turning decision. Three factors were manipulated in this experiment: vehicle arrival (as measured by a predicted trailing buffer algorithm), warning presence (DII on versus DII off), and warning onset (the timing during the SV approach when the DII first illuminated).

The DII was a LED-based, looming, no-left-turn sign. It was mounted on the traffic signal pole, on the far-left corner of the intersection from the SV driver's point of view, and slightly below the pedestrian signal heads. The location used in this experiment was selected to keep the sign as close to the driver's focus of attention as possible during the intersection approach. The looming effect appeared to the driver as the expansion (by about 65 percent) and contraction of the outer red circle and inner red slash of the typical no-left-turn sign at a rate of about 2 Hz. The looming effect was used to attract attention to the sign while keeping the sign illuminated during the entire warning event (as opposed to simply flashing the sign which results in a cycle where the sign is not being shown even though the warning condition is still present).

The SV started each trial approximately 80 m from the intersection and reached a nominal speed of 20 mph during the approach. The POV started approximately 260 m from the intersection, and reached a nominal speed of 25 mph during the approach. During each approach, the driver was instructed to decide whether it was safe to turn in front of the approaching POV, and execute the maneuver if possible. After each trial, the drivers were asked two questions by the experimenter. First, they were asked, "Did you think there was enough time to turn in front of that car?" Responses fell into four categories:

1. Yes because the SV driver actually turned in front of the POV
2. The SV stopped but the driver felt that he could have turned
3. The SV stopped but might have turned if he was in a hurry
4. The SV stopped and the driver felt that there was not enough time to turn

Second, for trials where the DII was active, drivers were asked "When the DII warning came, did you feel it was early, late…?" Responses were coded on a scale of 1-5 with 1 being too early, 2 being a little early, 3 being just right, 4 being a little late, and 5 being too late.

Results

How do drivers approach left-turn intersections?

The Berkeley instrumented-vehicle field test found three interesting SV behaviors during the intersection approach if there is no lead vehicle causing interference:

1. The SV turns without stopping, dropping to a minimum speed between 5 and 7 m/s.
2. The SV slows to let a POV clear, dropping to a minimum speed between 2 and 4 m/s.
3. The SV must stop prior to or within the intersection to let the POV clear.

Typical approach speeds when entering the left-turn lane ranged from 9 to 13 m/s (20 to 30 mph), but the fastest typical turning speeds ranged from 5 to 7 m/s (11 to 15 mph). Approach and turning decision are also fluid and constantly being re-evaluated with an expectation of a change in conditions (e.g., the signal may change from green to amber). Drivers are, in essence, prepared to change their decision and stop at a moment's notice. Typical reaction time to an event such as a traffic signal change was observed to be fairly rapid, on the order of 0.4 seconds.

Similar observations were made during the RFS instrumented-intersection experiment, where the mean turning speed as the SV entered the intersection (when it turned without stopping) was within the same 5 and 7 m/s range that was found in the Berkeley instrumented-vehicle field test. In both studies it was very difficult to accurately predict from the SV approach speeds whether the driver intended turn or stop to let the POV clear.

How long does it take drivers to traverse an intersection?

The Berkeley instrumented-vehicle study examined the turning time, with results ranging from 5.2 to 7.8 seconds; however, the available measurement techniques to measure this parameter were not highly accurate. Nevertheless, the instrumented-vehicle study was able to conclude that neither age nor gender played a significant role in determining or predicting the turning time.

Although the RFS instrumented-intersection experiment was unable to directly measure turning time, it was noted that typical driver behaviors, variations in turning speed or trajectory (such as cutting the corner) when making a left turn, had the potential to introduce quite a bit of error (on the order of 0.7 seconds) into the predicted trailing buffer outcome.

Overall, the implications for IDS are positive. First, any prediction or warning algorithm does not need to take an individual driver's age or gender into account, which is good news given the relative difficulty in obtaining this information. Second, any warning or prediction algorithm will need to be tuned to its particular intersection installation, since turning times vary so widely among intersections. Further research is recommended to develop the quantitative basis for that tuning, based on intersection characteristics.

What "gaps" in the oncoming traffic are typically accepted or rejected?

The Berkeley instrumented-vehicle field test examined both accepted and rejected gaps for drivers approaching an intersection; however, it should be noted that the sample was limited to only those gaps in traffic randomly presented during the test. Thus, an accepted gap during the study does not necessarily coincide with the smallest acceptable gap, merely the first acceptable gap. Converting gaps to trailing buffers, the mean accepted trailing buffer resulting in a turn without a stop was 4.3 seconds (± 3 s), and the mean rejected trailing buffer resulting in a stop was 0.5 seconds (± 2.5 s), showing considerable overlap between the ranges of accepted and rejected gaps.

The RFS instrumented-intersection experiment examined both accepted and rejected gaps on an individual basis, presenting each driver with a series of gaps spanning from always rejected to always accepted. However, the study was conducted on a closed test track, without pedestrian traffic, with only one approaching POV, and with a permanently green signal for the SV and POV. These almost ideal and artificial conditions presented to the SV probably account for the fact that results showed a much narrower range, on the order of only 3 seconds of predicted trailing buffer, between gaps with 0 percent acceptance and gaps with 100 percent acceptance. The experimental conditions (as well as on-going questions about how exactly to compute "trailing buffer") also probably account for the fact that, overall, drivers were fairly aggressive in this study, finding a more than 50 percent turn rate when the predicted trailing buffer was just under a half-second, increasing to a 100 percent turn rate when the predicted trailing buffer was over 2 seconds.

When are decisions being made by the SV driver?

Both the Berkeley instrumented-vehicle field test and the RFS instrumented-intersection experiment examined the question of decision point. In the context of an IDS system, the decision point is one of the most critical elements as it directly dictates the timing or onset of any warning. In the field test, the concept of decision point was examined by contrasting the SV approach curves for cases where the SV turns without stopping and cases where the SV driver decides to stop for an approaching POV. In comparing these two conditions it was possible to discriminate between the two behaviors beginning approximately 17 m (or 2 seconds) from the stop bar. Given that a difference in the vehicle approach was already detectable at 2 seconds from the stop bar, it was expected that the decision to stop had already been made at least a half-second prior to then.

The RFS study further built upon these findings and experimentally tested DII warning onsets at 2, 3, and 4 seconds from the stop bar. Overall, the study surprisingly found that drivers were more or less insensitive to the warning point, which probably relates to the earlier conclusions regarding the fluidity of the decision point. The optimal warning point for all drivers was found to be around 3 seconds before the stop bar. There was also a slight age bias as older drivers didn't mind the warning being earlier and younger drivers didn't mind the warning being later.

Can a conflict between the turning SV and POV be accurately predicted and warned?

Overall, drivers in the RFS instrumented-intersection experiment were relatively receptive to the concept of a LTAP-OD DII, and the presence of a DII reduced the turn rate by an average of 20 percentage points (being more effective as the predicted trailing buffer decreased and less effective as the predicted trailing buffer increased). However, there are at least three issues which require further research before the implementation of any field operational test could be considered.

First, there are still significant questions regarding how, exactly, the trailing buffer should be calculated. While the trailing buffer measure appears to be correlated with turning rate, the formulas used to predict SV and POV arrival times still need some fine tuning due to questions regarding the tolerance of errors, variability, and SV aggressiveness.

Second, the question still remains about how to select the warning criteria. All of the studies in this section found overlapping ranges of accepted and rejected gaps. Although the gap acceptance rate increases as the trailing buffer increases, there was no natural cut-off point or obvious policy on which to base the warning criteria. Fortunately, drivers tended to agree with the DII alert more as the warning criteria was set at lower trailing buffers. In effect, the presence of the DII not only deterred drivers from making a turn, but it also influenced their opinion as to what constituted an unsafe condition.

Third and finally, there were significant differences among intersections in parameters such as turning time, traffic volumes and available gaps, and approach speeds. More research is needed to determine if an LTAP-OD alert algorithm will need to be fine-tuned to its intersection and to provide the foundation for defining handbook guidelines for the alert parameters.

LIST OF TABLES AND FIGURES

1.0 INTRODUCTION

Overview of the IDS Research Program

The Intersection Decision Support (IDS) project addressed the application of infrastructure-based and infrastructure-vehicle cooperative systems to address intersection safety. The Infrastructure Consortium (IC) was comprised of the US Department of Transportation (DOT), California DOT (Caltrans), Minnesota DOT, and Virginia DOT and their associated university research partners.

The project's three-year mission was to investigate key enabling technologies, conduct naturalistic driving data collection, perform driver modeling, develop an integrated IDS simulation approach, and look at the applicability of a large set of already- or nearly- available "commercial off the shelf" systems toward meeting IDS requirements. One key output of this research was the conceptualization and initial feasibility testing of several intersection collision avoidance countermeasures which primarily made use of roadside-mounted dynamic message signs to communicate information to the drivers approaching the intersection.

Three intersection collision types were investigated by the IC with each of the states taking the lead on a particular problem. The Virginia DOT investigated the problem of Straight Crossing Path (SCP) collisions, such as those that occur when a driver violates a stop sign or stop signal. The Minnesota DOT investigated the problem of Left Turn Across Path with Lateral Direction (LTAP-LD) traffic. This type of collision often occurs with deadly consequences in more rural areas where a driver must make a left turn from a stop sign onto a major highway where the cross-traffic is not required to stop (and is often traveling at substantial speed). Finally, the California DOT, in partnership with California PATH, investigated the problem of Left Turn Across Path with Opposite Direction (LTAP-OD) traffic. This type of collision frequently occurs in urban areas where a driver has a permissive, but not protected left turn signal, and must use their own judgment as to whether or not there is enough time to turn left in front of an oncoming vehicle.

Summary of Prior Work

A series of three reports were written (including this one) on the results of the California IDS research program. The first report ([1]Chen, et al., 2005) was an interim report which described the research progress to that date. In that report the following topics were discussed:

- An analysis of frequency of the various intersections crash types in the state of California as compared to the frequency of those crash types in U.S. overall.
- The results of a literature review examining the human factors or, in this case, driver errors which have been proposed as potential root causes for intersection crashes.
- The results of the work to conceptualize, design, build, and demonstrate a prototype LTAP-OD intersection collision avoidance countermeasure.

To summarize the highlights of this report, it was estimated that 42.7 percent of crashes in the U.S. are related to intersections, and 27.5 percent of the intersection crossing path crashes fall into the category known as LTAP-OD ([2]Najim, Smith, and Smith, 2001). After examining the various factors such as speed, intersection signalization, and driver age, it was found that most of these types of crashes occurred at moderate speeds, at signalized intersections, and with older drivers being somewhat overrepresented in LTAP-OD crashes.

Based on the literature review, driver errors, such as failure to see crucial information (e.g., obstruction of view, driver distraction) or failure to correctly judge available information (e.g., misjudged speed of or distance to another vehicle), were the most frequently identified causal factor in LTAP-OD crashes. Furthermore, when performing left-turn maneuvers, drivers may be subject to several biases in gap acceptance behavior, resulting in shorter gaps being accepted as the speed of the oncoming POV increases.

These conclusion lead to the design of an IDS LTAP-OD countermeasure system architecture consisting primarily of a sensor suite to detect potential crossing path collisions and a Driver Infrastructure Interface (DII) which provided for communication with the driver. As described in the report, the initial DII was conceptualized as a dynamic, looming, no-left-turn sign. The dynamic aspect of the sign referred to the fact that it would illuminate as the SV approached the intersection only when there was a potential conflict with an approaching POV.

The second report ([3]Misener, et al., 2007) constituted the final IDS project report which described the overall systems engineering research performed during the project. In that report the following topics were discussed:

- A methodology and the results of several radar-based field observations
- A methodology and the results of several video-based field observations
- The results of a series of laboratory experiments to fine tune various parameters related to the DII looming effect
- The results of the effort to locate and test a number Commercial Off-The-Shelf (COTS) technologies and devices which could potentially be used to fulfill the sensing requirements needed by an IDS LTAP-OD countermeasure system
- The system architecture conceptualization, functional requirements, performance specifications, and algorithm design considerations for an IDS LTAP-OD countermeasure system

The field data collections performed during the IDS project fell into two categories: roadside observations (covered in previous report as listed above) and instrumented vehicle studies (to be described later in this current report). The roadside observations were taken at six intersections in northern California, which had varying characteristics, geometries, and traffic volumes. At each location, radar and video recording devices were set up to capture several hours of left-turn SV and straight-through POV movements. The data collected using this method appears in two separate analyses: one primarily based on the radar data and the other primarily based on a frame-by-frame video analysis. Given that these intersection-based methods were quite complimentary to the vehicle-based methods described later in this report, a summary of the results of the prior intersection-based studies has been integrated into the summary and conclusions section of this report where the results for similar research questions have been compared and contrasted across methods.

Human Factors Research Goals

The ultimate goal of an intersection collision avoidance system is to reduce intersection crashes by providing drivers with information to support turning decisions. In order to accomplish this goal, any system intending to aid in LTAP-OD collision prevention must perform three functions:

1. Sense and track vehicle movements
2. Predict likely future vehicle states and potential conflict situations
3. Provide relevant information to the driver at the appropriate time

While the many challenges with the vehicle sensing aspects of this project have already been described in the previous IDS reports, the second two tasks, predicting potential conflicts and communicating the appropriate information to the driver in a timely manner, are highly dependent on the understanding of driver left-turn behavior. The study of driver behavior in this report attempted to gain insights into what decisions are being made by drivers, when those decisions are being made, and what information drivers might be able to use to make better decisions. The specific human factors or driver behavior questions addressed during the IDS project include the following:

1. How do drivers approach left-turn intersections (speed profiles, braking points)?
2. How long does it take drivers to traverse an intersection?
3. What "gaps" in the oncoming traffic are typically accepted or rejected?
4. When are decisions being made by the SV driver?
5. Can a conflict between the turning SV and POV be accurately predicted and warned?

Summary Driver Behavior Study Methodologies Used in IDS

The two driver behavior data collections detailed in this report were based on the use of the PATH instrumented Ford Taurus research vehicle. Drivers were recruited for one of two separate experiments: a field test in the city of Berkeley or a controlled experiment at the Richmond Field Station (RFS) instrumented intersection. The goal of the field test was to observe the SV driver's left-turn approach and execution behavior in a naturalistic setting, while the study conducted at the RFS intersection provided a controlled setting and allowed for the addition of an experimental Driver Infrastructure Interface (DII), a dynamic, no-left-turn, warning sign.

Each of the IDS data collection techniques could be characterized as having both advantages and disadvantages. The roadside observations (described in a previous report) allowed the study of vehicle-based traffic flow at several diverse intersections, capturing left-turn movements in their most naturalistic form. However, the data that were collected using this method lacked detail on the SV approach and a microscopic view of the driver actions. The field study performed with the instrumented vehicle provided a very microscopic view of the driver actions, such as approach speed, brake activation, and steering inputs, but sacrificed some of the naturalistic qualities (as the drivers were aware that they were being observed) and some of the external traffic measurement capabilities (due to sensor limitations on a moving platform). Finally, the study at the highly instrumented RFS intersection provided for excellent measurement and control of both the SV and POV movements, but could arguably be biased as the setting (a single POV on a closed test track) was the most contrived scenario and carried the most risk of creating unnatural driving behaviors.

At each stage of the project, the design of one study was cross-checked with the preliminary results of the other studies. Thus, the range of DII onset timings tested at the Richmond Field Station were based on the results of the Berkeley field test. Similarly, the preliminary data collected in the Berkeley field test and at the Richmond Field Station were cross-checked with results of the roadside observations to make sure that the SV driving behavior looked normal, and that the influences of observation were minimal. While, individually, each data collection method has its own strengths and weaknesses, the combination of studies provides a strong foundation towards the understanding of driver left-turn behavior.

2.0 BERKELEY INSTRUMENTED VEHICLE FIELD TEST

Written by Delphine Cody and Bénédicte Bougler

2.1 Research Questions

This section describes the preliminary results from the Berkeley instrumented-vehicle field test study which was intended to describe how drivers approach left turns in a near naturalistic setting. In this study volunteer drivers were recruited to drive California PATH's instrumented vehicle in real traffic conditions in order to:

1. To provide a description of driver behavior when reaching an intersection with permissive green for making a left turn, with a focus on the difference between a driver who stops to let on-coming traffic clear the intersection and a driver who does not stop before the turn.
2. To have a better understanding of gap acceptance in the presence of on-coming traffic when drivers turn without stopping.

Based on a literature review conducted and detailed in an earlier report, we identified the following issues and needs:

- Elderly drivers seem to use a set distance to accept or reject a gap, independently of on-coming traffic speed.
- For the situation where drivers[1] do not stop for on-coming traffic prior to turn, he range of accepted gap when the SV does not stop is comprised between 3 to 8 seconds from where the trajectories of the SV and POV intersect. Any gap beyond 8 seconds is accepted and the rate of acceptance of gaps in-between 3 to 8 is proportional to the increase of the gap size.

These points lead to the following need for supporting the design of the intersection decision support system:

- Do drivers base their decision based on time or distance to intersection? In other words,

[1] In the remaining of this report, the driver intending to make a left turn will be referred to as subject vehicle, or SV, and the on-coming vehicles will be called principal other vehicles or POV.

would a driver consider that if a vehicle is within a certain distance from the intersection, it is a no go situation whatever the speed of this on-coming vehicle.

- The 5 second range is big in terms of input for an intersection decision support system. Therefore, there is a need to understand the distribution of accepted gaps between this range and to identify factors influencing drivers decision for this specific situation.
- Assessment of driver's decision point for turning in front of vehicle or waiting for a vehicle to clear the intersection.

In order to provide input for the design of the intersection decision support, one of the data collection paradigms chosen was to conduct a field study. This method allows to observe the three components of the system driver/infrastructure (here intersections) /vehicle/traffic and identify which factors are relevant to investigate in more details.

This report contains four main sections. In the first section, the methodology applied for the field test is provided, with a description of the field test protocol, a description of the vehicle used for collection data and the data that were collected, and the description of the sample of driver who participated to the study. In the second section, the data reduction is detailed. This section is composed of two subsections. In the first one, we describe how the sensor and radar data are filtered. In the second, we present how a subsequent set of data was created from video files and how we derived the variables used for the analyses from the collected data. The third section presents the data analysis and is composed of two subsections. In the first one, we provide a description of the driver behavior when the driver intending to turn left reaches the intersection, and will illustrate how speed profile could be used in order to assess the beginning and end of the decision zone. In the second subsection, we describe how the lag and gap acceptance is a closed loop process for the situation of a SV moving toward the intersection and offer a list of factors influencing the lag/gap acceptance process. We conclude this report with a discussion of the data presented, the next data analysis steps, and the next research steps.

2.2 Method

Overview

This section is composed of three sub-sections. The first one describes the protocol used for the field test. The second subsection details the data collection system and illustrates the vehicle used for the data collection as well as the data collected at that time. Finally, the last part describes the sample of volunteer drivers who participated to the study.

Field Test Protocol

The field test was conducted on a 2 block by 4 block test route located in the downtown section of the City of Berkeley (see Figure 2-1). The subjects drove the California PATH instrumented vehicle (see Figure 2-2) approximately 6 miles from the PATH research facility to Berkeley, and then drove around the test loop 10 times (counterclockwise), turning left at each of the 4 intersections (numbered 1 through 4 in Figure 2-1). Of the four repeated left turns around the block, the first three intersections have left turn pockets, but intersection 4 only had a single shared lane for left turns and straight through (right turns used the parking lane). None of the test route intersections had protected left turn phases. One peculiarity of the first intersection (turning left from southbound Martin Luther King Ave. on eastbound University Ave.) was that the green phase for the oncoming traffic began earlier than it did for the direction of travel used in this study (to allow for a protected left turn phase for the oncoming traffic).

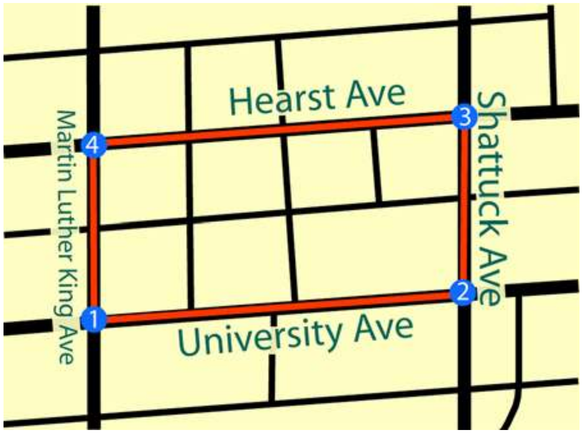


Figure 2-1. Berkeley observation site.

The repetition around the block allows observing the same driver at the same set of intersections with varying traffic conditions. There are significant variations in gaps in oncoming traffic, presence of and distance to a lead vehicle and traffic signal phase. Each data collection lasted approximately 1.5 hours. The driving sessions were conducted at off-peak hours, either between 9:30 and 11 am or between 2 and 3:30 pm.

Instrumented Vehicle Description and Collected Data

The instrumented vehicle used for the data collection was a Ford Taurus, model year 2000. This vehicle is instrumented with a suit of sensors (see Figure 2-2 below) in order to record the drivers' interaction with the vehicle and the front driving scene.

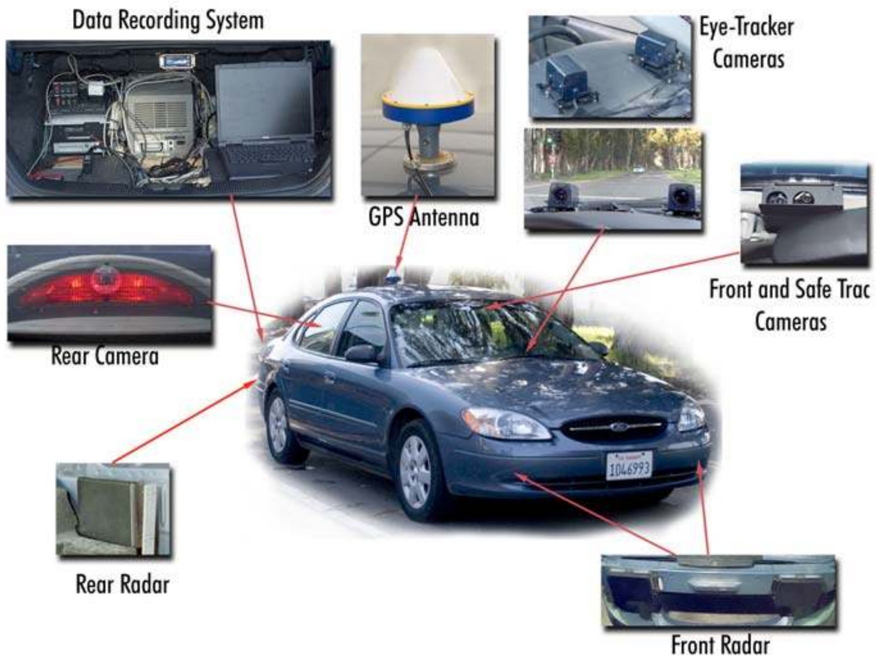


Figure 2-2. California PATH instrumented vehicle.

The data recorded about the vehicle control, which will be referred to as engineering data in the rest of this document, were as follows:

- Steering angle, expressed in degrees, 360 represents a full turn of the steering wheel and the number of degrees keeps on increasing. The 0 is when the steering wheel is in a straight position, positive values indicate the driver is steering to the left and negative values that the driver is steering to the right,
- Brake pedal, on or off, measured by the onset of the brake light,
- Turn signal, on or off, measured by the onset of the turn light,
- Throttle, percentage of depression,
- Accelerometers,
- Differential GPS,
- Two EVT-300 radars directed at the forward vehicles (lead and on-coming). These radars have a 12 degree field of view and detect target in a range of a 150 meters from the antenna. The radars antenna were located on the right and left side of the front bumper.

The video data was collected with a set of cameras pointed at the forward, side and rear of the vehicle, and also at the driver (see Figure 2-3 on next page).

- The three other scenes and the driver's face are recorded on a second channel with a four to one video splitter. In Figure 2-3a, the left top image is the front left side of the vehicle, the top right is the front right of the vehicle, the image on the bottom left is the rear of the vehicle and the image on the bottom right is the driver's face.
- The forward scene is recorded on a single channel (Figure 2-3b)

a) Quad Split Image

b) Forward Scene

Figure 2-3. View from video cameras mounted in the vehicle.

A titler is used in order to print the time that is recorded for the engineering data in the video files. This allows verifying the accuracy of the synchronization between video and engineering files.

The engineering data are recorded at 13 Hz and the video is collected at 30 fps. The video and engineering files are synchronized post data collection in 1 minute folder. The GPS data is used to automatically select the section of data corresponding to the approach and crossing of each of the chosen intersection. These data were also used in order to compute the driver's traveled path (see next section for detail).

Because the traffic signals of the three of the intersections are timed, drivers often encountered the same pattern of phases for one data collection. The pattern was as follows:

- Intersections 1: green for the first run and red for the remainder of the trial
- Intersections 2 & 3: green or red (there was a difference between morning and afternoon and also based on the traffic density)
- Intersection 4: almost systematically red

Test Participants

A total of 23 volunteers participated in the experiment and were distributed in three age groups: 25 to 35, 45 to 55 and 65 to 75. The initial goal was to have 10 participants for each group, balanced on gender. Unfortunately, we did not have time to run all of the middle age and older drivers. Table 2-1 below shows the characteristics of the sample:

Table 2-1. Sample characteristics.

Group		n	Age[2] (Years)	Years Driving	Yearly mileage[3]		
					< 5,000	5,000 - 10,000	> 10,000
Younger	Male	5	30.0 (2.5)	13.0 (3.0)	1	2	2
	Female	5	29.4 (3.5)	9.8 (5.3)	2	3	-
Middle Age	Male	3	49.3 (3.2)	31.6 (4.7)	-	1	2
	Female	3	51.6 (2.1)	34.0 (3.6)	1	1	1
Older	Male	4	69.8 (4.1)	52.0 (2.3)	-	3	1
	Female	3	66.6 (2.9)	42.6 (8.0)	3	-	-

These characteristics were collected via a questionnaire that drivers filled out at the end of the test drive. The sample is fairly homogeneous in terms of age and years driven by age group and gender. The yearly mileage is more distributed, except for the old females, who are all driving less than 5000 miles a year (refer back to Table 2-1).

Figure 2-4 illustrates the percentage of driving by type of roadway for each age group. For all age group most of the driving is performed on highway. Younger drivers tend to drive more in urban settings while middle age and elderly drive more in suburban environment. However, there is a strong variability within groups, as can be seen in Figure 2-5.

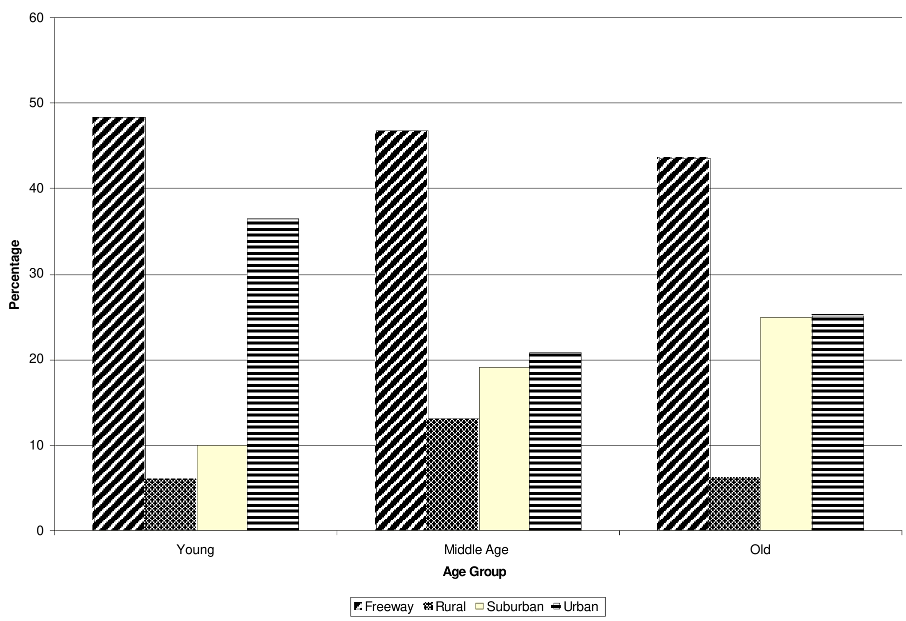


Figure 2-4. Percentage of driving by type of roadway for each age group.

[2] Mean (Standard Deviation)
[3] Number of Cases

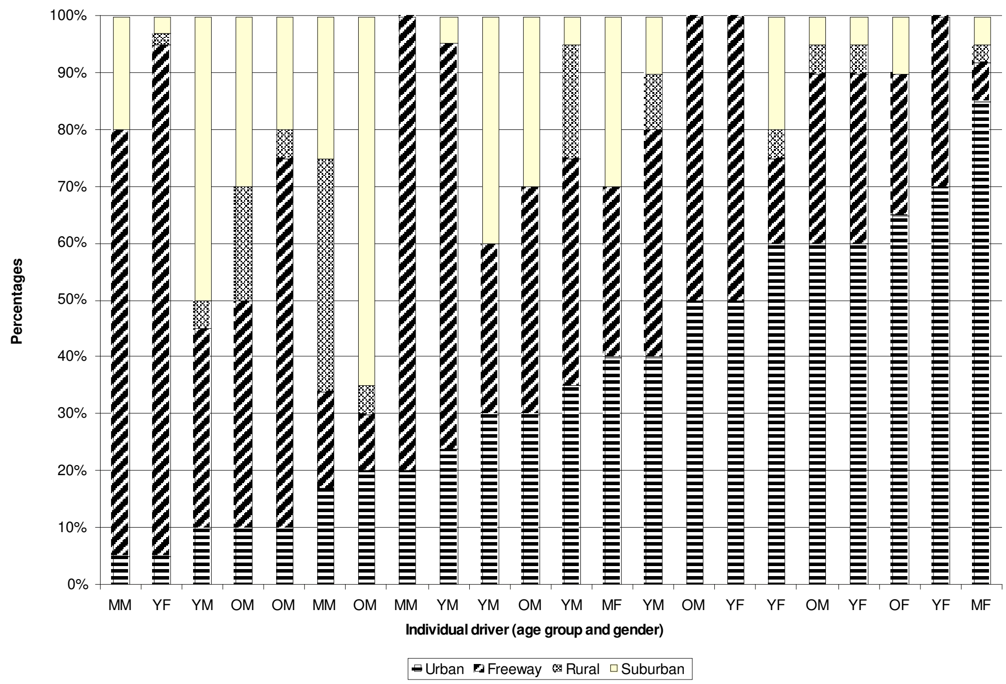


Figure 2-5. Percentage of driving by type of roadway per driver.

Note: In Figure 2-5,

- YM stands for young male
- YF stands for young female
- MM stands for middle aged man
- MF stands for middle aged female
- OM stands for old male
- OF stands for old female

In Figure 2-5, the data are sorted by urban driving in ascending order. Ten out of the twenty two[4] drivers who participated to the study are performing 40% or more of their driving in urban environment. Out of these 10 drivers, 7 are females. We propose to organize the data in terms of age group, gender and percentage of driving in urban area for the analyses.

As show in Figure 2-6, the majority of the driving was performed during the day time for all age groups, although the proportion of night driving slightly declines with age.

[4] One of the middle age drivers did not fill out the questionnaire properly for this question.

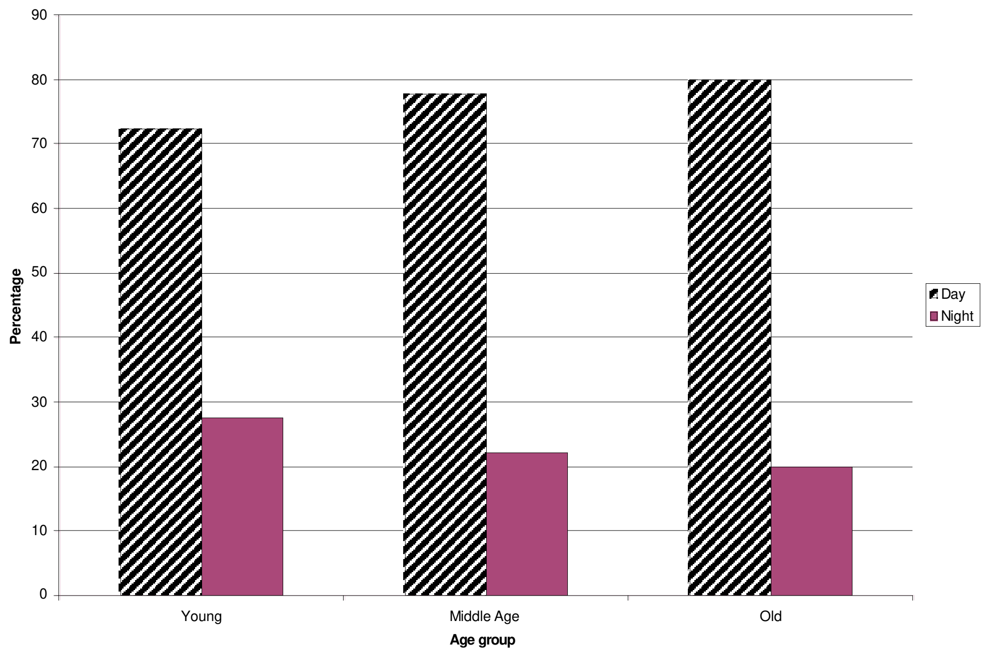


Figure 2-6. Percentage of driving day vs. night per age group.

As shown in Figure 2-7, the majority of driving is performed in familiar environment; although the proportion of driving in unfamiliar setting declines slightly with age.

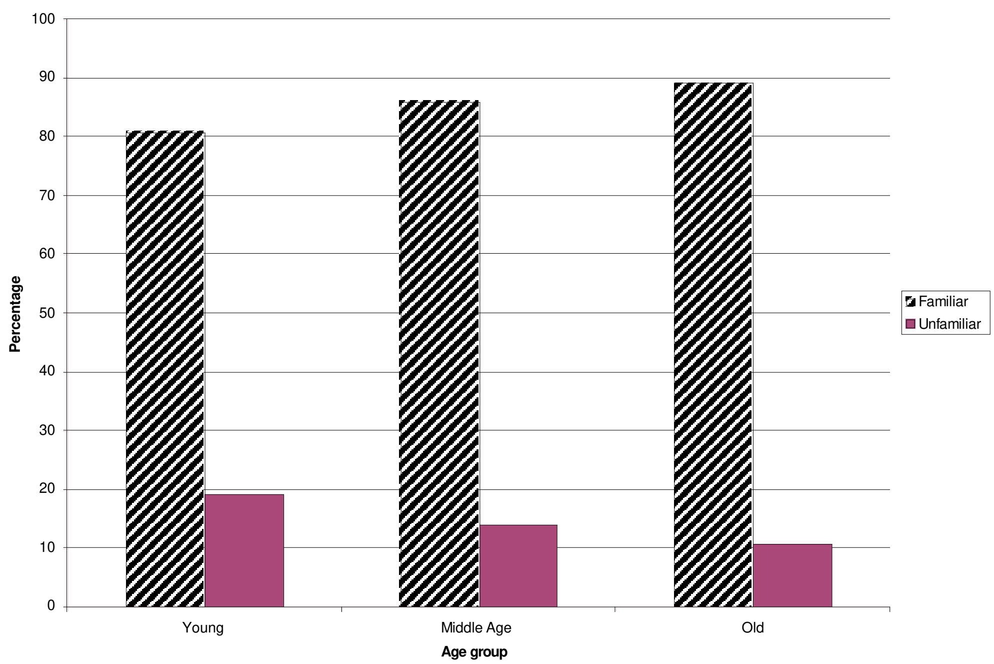


Figure 2-7. Percentage of driving in familiar vs. unfamiliar destination by age group.

2.3 Data Reduction

This section describes the data reduction method for the data analysis. It is composed of two sections. The first one describes the filtering and post processing conducted on the engineering data. The second part describes the generation of variables from the data in order to support the description of driver behavior when reaching the intersection for making a left turn.

2.3.1 Engineering Data Filtering and Reduction

Filtering and Post Processing Summary

This section describes how the engineering data were filtered, how the GPS data dropout were addressed, how the GPS data were converted to metric coordinates, and how the radar data were reduced. The engineering data were filtered and post-processed using Matlab for the following purpose:

- set speed to 0 when not moving (recorded speed saturates under 1.6 m/s at a constant value which is different every time the vehicle is stopped), in order to identify when the vehicle is truly stopped, we combined the wheel speed and the GPS speed into one speed and filter the speed signal
- calibrate throttle offset
- convert the GPS point into an XY coordinate in meters according to a single 0 point
- estimate the GPS coordinates when there is a dropout, i.e. no update in the longitude and latitude, using the vehicle steering angle and the course over ground true north (this is especially necessary for intersection 4 because of tree coverage)
- filter the GPS coordinates
- filter steering angle and throttle.

Noise filtering for vehicle sensor data

The data for the steering angle and throttle angle were noisy and required smoothing. We removed the high frequency noise with minimum time delay to preserve the driver inputs. We apply both forward and backward filtering so that there are no resulting time delays from the filters. Below is a set of graph illustrating the raw and filtered data.

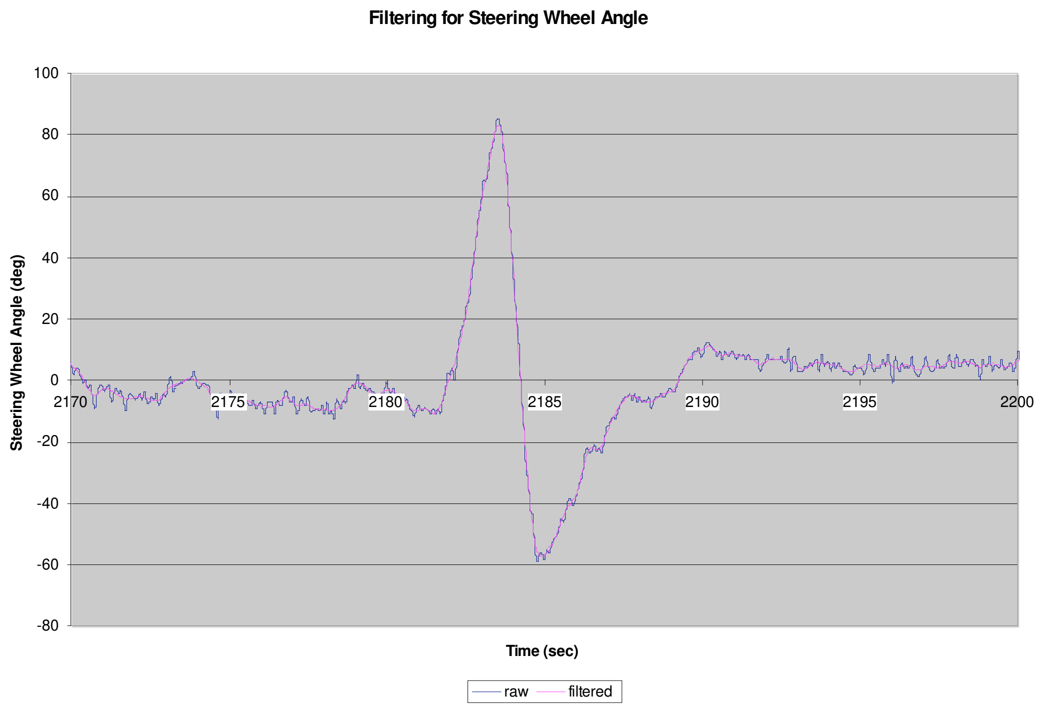


Figure 2-8. Raw and filtered steering wheel angle data.

The filter for steering angle is a third order 1.2 Hz low pass Elliptic filter with .05 db passband ripple and 20 db stopband drop.

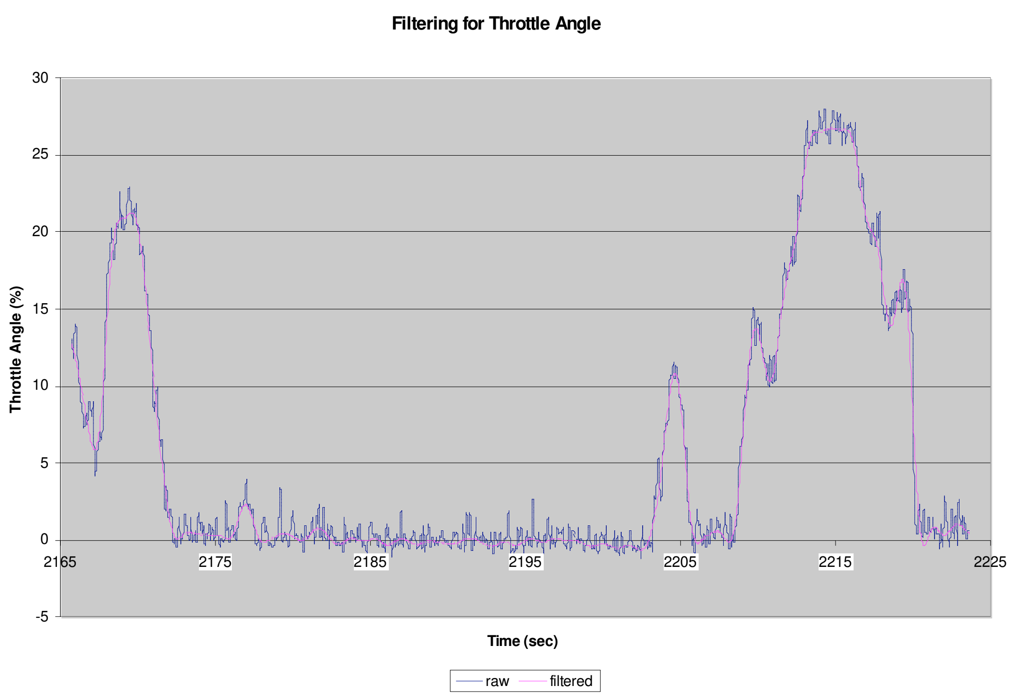


Figure 2-9. Raw and filtered throttle angle.

The filter for throttle angle is a third order 0.5 Hz low pass Elliptic filter with .05 db passband ripple and 20 db stopband drop.

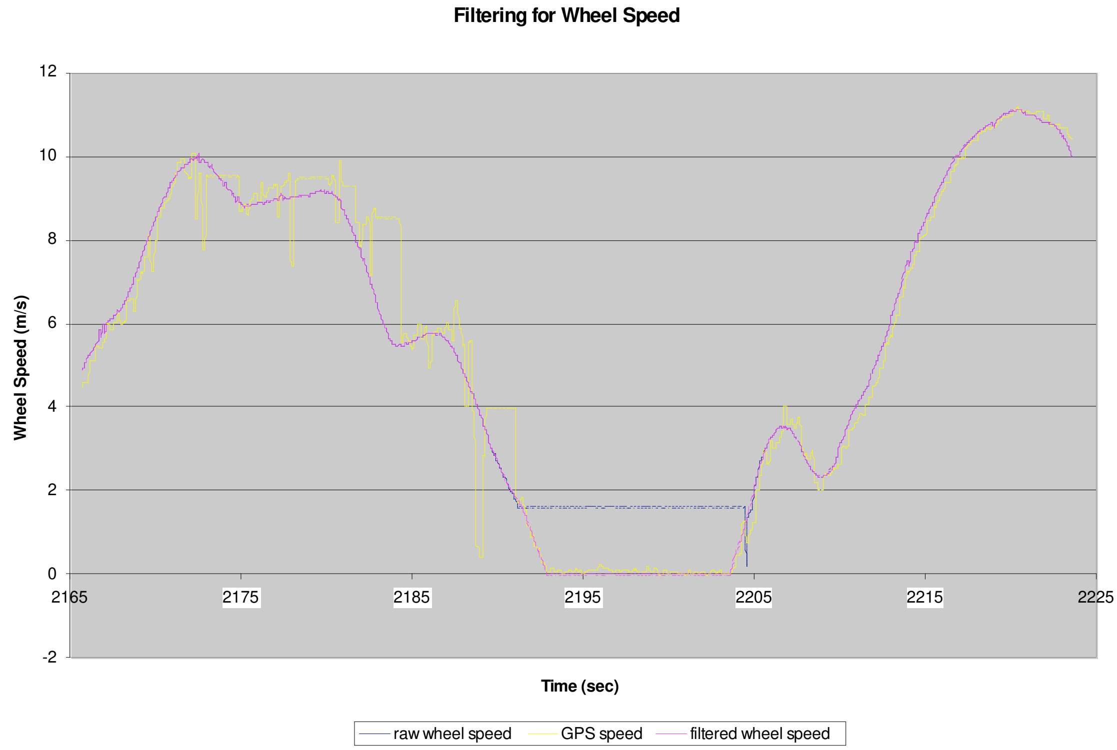


Figure 2-10. Raw and filtered speed.

The speed sensor does not allow measurement less than 2 m/s. In order to know when the vehicle was stopped, we combined the GPS speed with the wheel speed.

GPS dropout and coordinate conversion

Below is a description of the procedure applied in order to address the GPS dropout and how the GPS data were used in order to create local maps. The local maps are used for describing the driver behavior relative to the intersection geometry. Creating these maps supports comparison of driver performance, both within and in-between drivers.

In order to correct the GPS dropouts, we used the steering angle and vehicle speed. The procedure is as follows:

1. identify the areas of GPS dropouts
2. calibrate steering angle gains and offsets
3. identify initial conditions for the dropout sections
4. estimate GPS dropout using calibrated steering angle and vehicle speed
5. iterate the process from 2 if necessary

Figure 2-11 on the next page illustrates a dropout in the raw data and Figure 2-12 the results of the procedure described above.

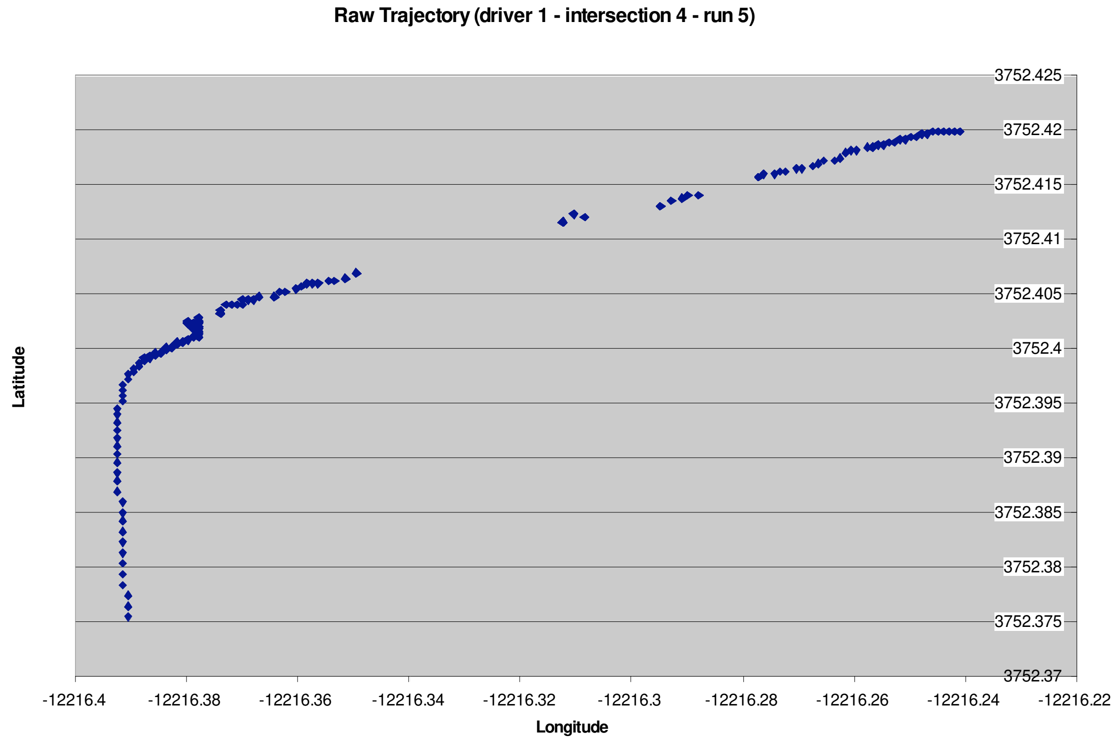


Figure 2-11. Raw GPS data with dropout.

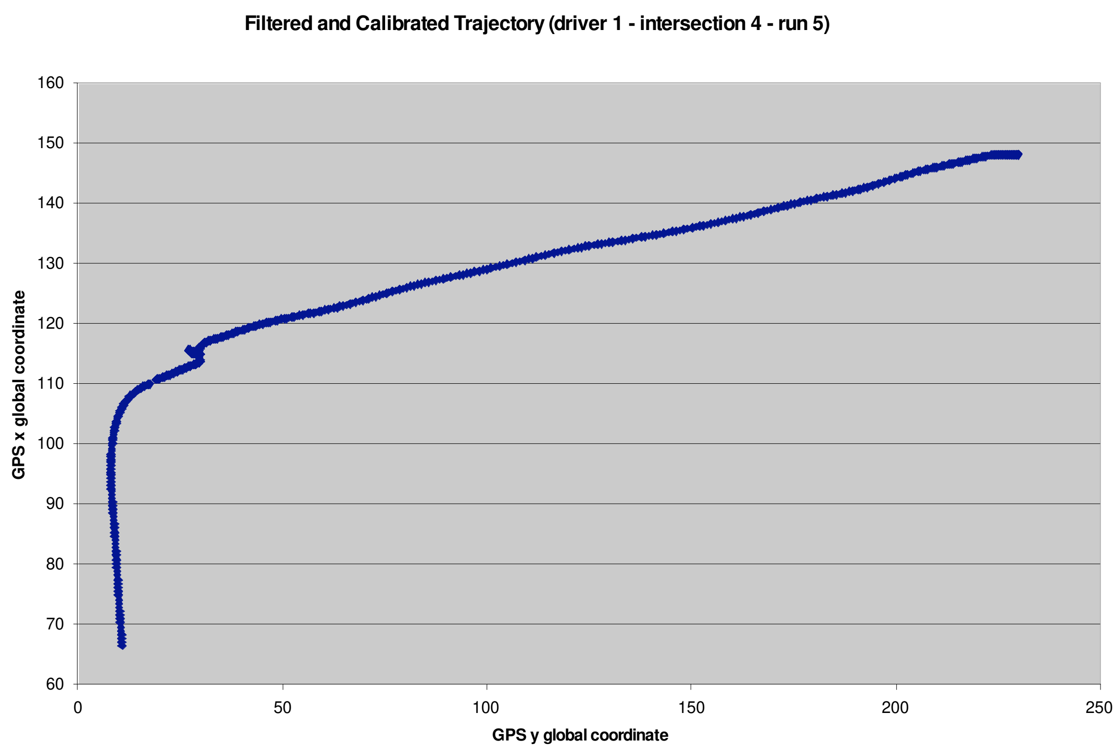


Figure 2-12. Filtered and calibrated (meters) trajectory.

GPS Reference points

Four points were gathered with the Taurus GPS sitting still for 15 minutes in order to create a reference point. This reference point was then used in order to create a local map of the area and to allow for automatic identification of the beginning of section observed for each intersection.

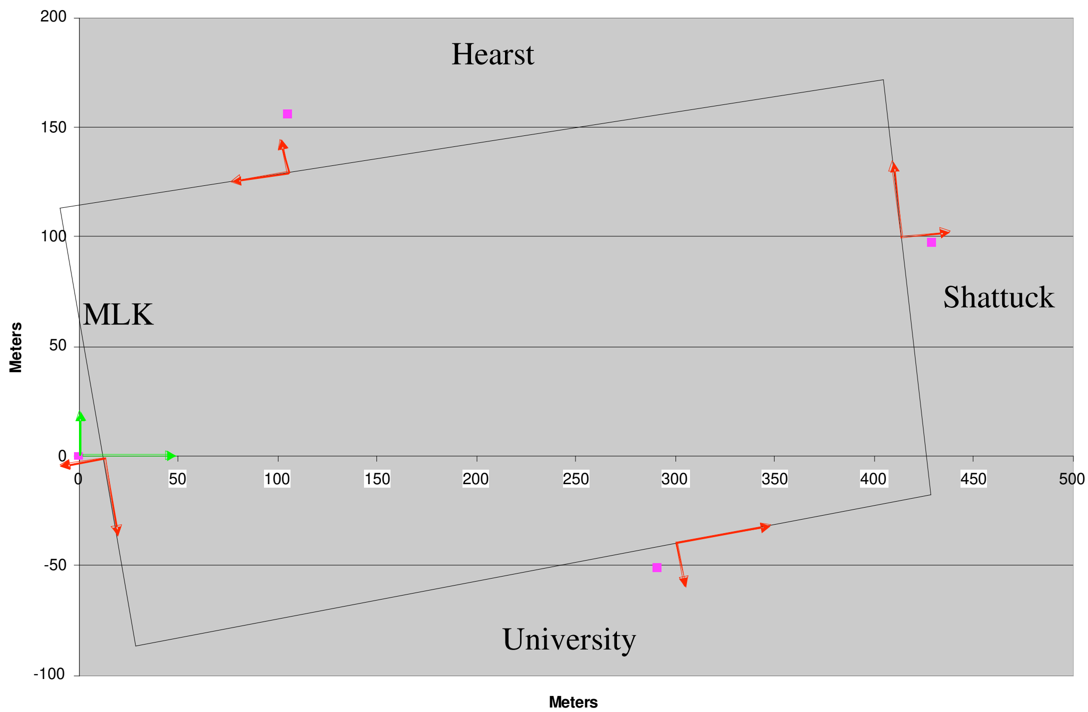
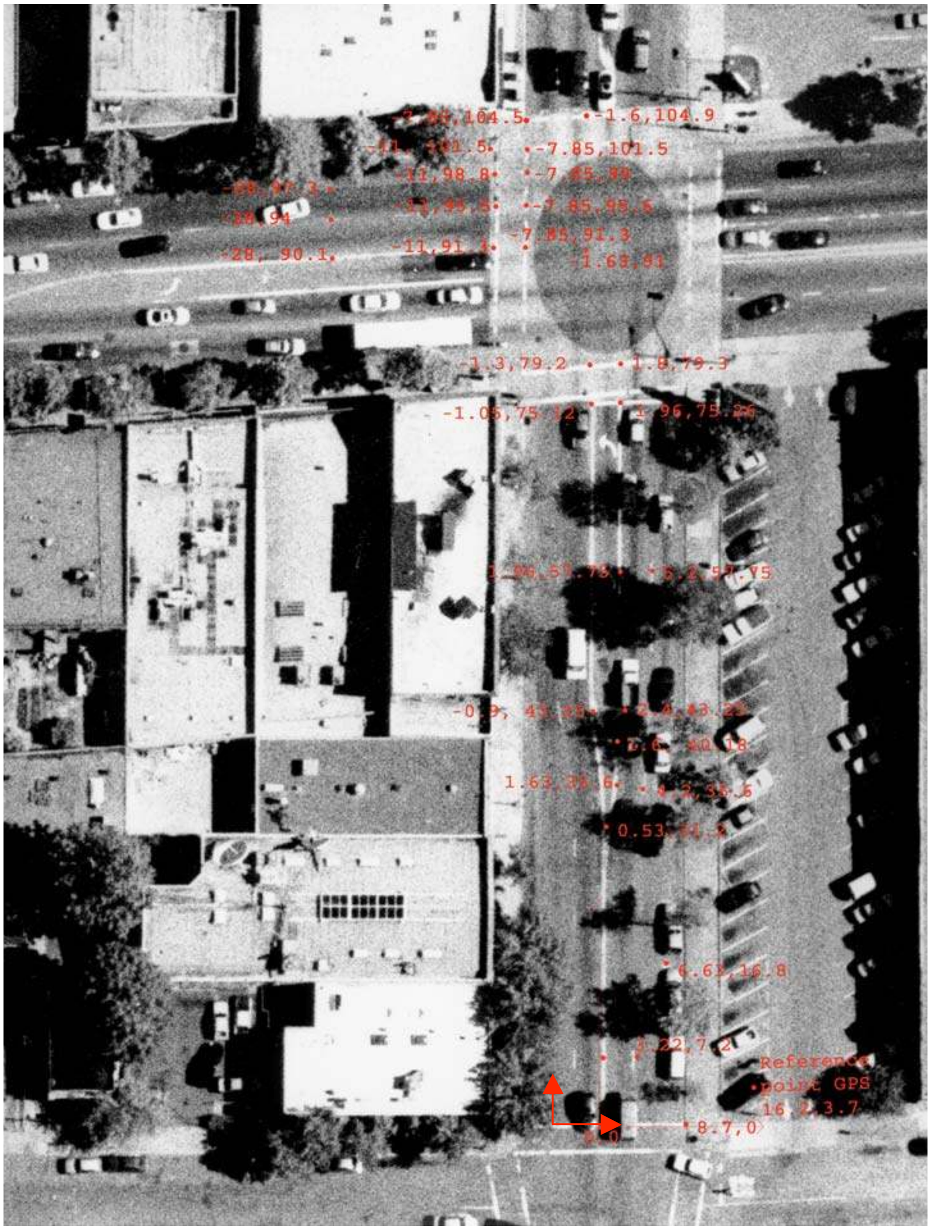


Figure 2-13. GPS Reference point for each intersection.

In Figure 2-13 above, the four reference points (pink squares) are displayed (the vehicle was parked on the parking lane or in parking lots). They were later adjusted to fall precisely on the vehicle route, i.e. the above rectangle. The reference point for MLK/University is used as the reference point for the bloc. For each intersection, a local set of point was measured on aerial picture in order to create a “local map” of each intersection. The origin of each local map (red arrows) is also displayed on the figure above. We used the GPS coordinates to create two set of (x,y) coordinate: global coordinates with reference to MLK/University intersection and local coordinates within the local intersection.

Local Map

Based on the XY, the closest starting point to the reference point was identified and used to compute a 0 for each intersection. From this, the data was organized into folders containing the synchronized data files corresponding to each intersection run number (each intersection crossing). For each intersection, a beginning point for the approach was determined. This point typically coincided with the last pedestrian crosswalk line before this intersection. A local map was created for each intersection as shown in Figure 2-14.



Scale on original picture: 1 cm=4.8 meters

Figure 2-14. Sample of aerial picture used for point gathering for intersection 1.

The approach for each intersection was defined as the distance between this last pedestrian crosswalk before the intersection and the stop bar at the intersection. The approach for Intersection 1 is 75 m long; for Intersection 2, 83 m; for Intersection 3, 70 m; and for Intersection 4, 82 m long. Based on the GPS coordinate, an x y in meters is computed and used to obtain a traveled path in meters that can be used for 2-D representations of data such as speed or brake or steering angle against the traveled path on the approach lengths. The benefit of this method is to allow the integration of specific elements of the intersection geometry, such as position of the beginning of the left turn pocket or the stop bar to a graph as detailed below by the specific points we defined (see Figure 2-15):

- P1: beginning of observed intersection
- P2: beginning of left turn lane pocket
- P3: first line of the pedestrian crossing, also stop line for SV driver for all intersections
- P4: second line of the pedestrian crossing
- P5: distance in the intersection corresponding to the number of lane of on-coming traffic in the destination leg
- P6: first line of the pedestrian crossing on the destination leg
- P7: 10 meters after the second line of the pedestrian crossing in the destination lane corresponding to the end of the observation.
- P8: first line of the pedestrian crossing for on-coming traffic.

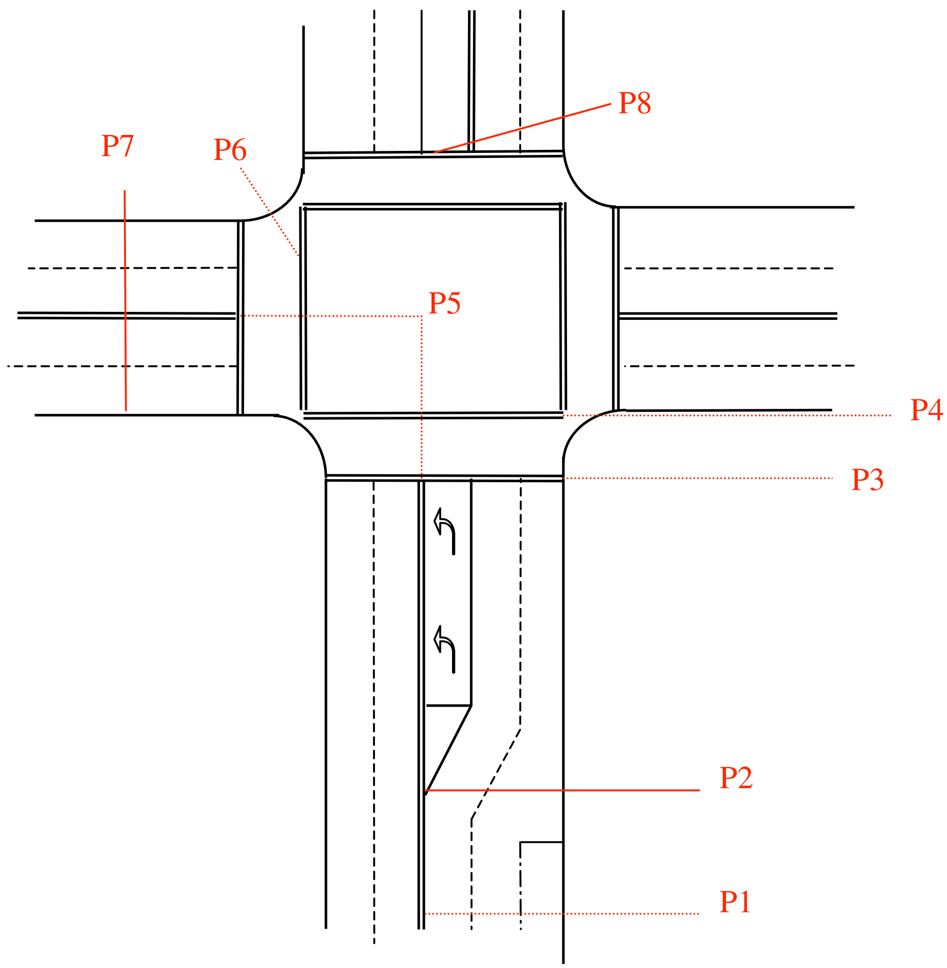


Figure 2-15. Intersection key points.

Radar Data Filtering

The radar data were collected from the SV and are the data from the front left radar. We filtered the data in order to exclude the vehicles going in the same direction than the SV. The EVT-300 provides the following data at a 13 Hz rate for each target and up to 7 targets at a time:

- range (0.1ft)
- range rate (0.1ft/sec)
- azimuth (0.002 rad)
- acceleration (0.001 ft/sec/sec)

We used mainly the range and range rate data. As the radar antenna is mounted on the vehicle, it is difficult to use the azimuth in order to assess the lane position of the on-coming target because we do not know the Taurus orientation within the intersection with enough accuracy. Other issues we met when collecting the radar data include the non detection of non moving target, a built in feature of the EVT-300. This issue aroused especially for red light cases for which the first vehicles of the on-coming platoon were not detected. Another limitation of the use of this radar for this specific application is the narrowness of the field of view, which lead to target drop-off at close range (see appendix for illustration of radar coverage when SV is at the stop bar).

The data reduction consisted of:

- changing the data units, from feet to meters
- range rate was treated as relative velocity and used in order to compute target speed
- Based on the target velocity, we sorted the targets going in the same direction than the SV and the on-coming one. We then kept only the target that corresponded to on-coming vehicles.

2.3.2 Post Driving Session Data Collection and Data Merging

Two topics are treated in this subsection. The first one describes the information that was gathered from the video. The second describes the variables that were generated based on the collected data.

<u>*Video Events File*</u>

The events files are constituted of information that can be obtained only by watching the video. The events that were marked include the following:

- Light status: green, amber, red
- Number of vehicles in front, requires a manual entry of a number
- Number of vehicle behind, requires a manual entry of a number
- Presence of pedestrian: on the leg before the turn and on the leg after the turn

We also categorized the intersection approaches based on the following four types of SV trajectories:

1. SV driver turns without stopping prior the intersection or when in the intersection.
2. SV driver stops prior to the stop line/crosswalk boundary, then crosses the intersection without stopping.
3. SV driver stops prior to the stop line and again in the intersection.
4. SV driver does not stop prior to the intersection but stops once in the intersection.

These trajectories occur because of differences on the traffic light status and the presence of POV and/or pedestrian. Trajectory 1 and 4 occur when the traffic light is green while the driver is approaching and trajectory 2 and 3 when the light is amber or red while the driver is approaching. Trajectory 3 and 4 happen when SV has to wait for POV or pedestrian once in the intersection before to complete the turn.

Variables Created Based on Travel Path

The GPS data are used to compute a traveled path. Figure 2-16 below is an example of a within-subject display of speed profiles.

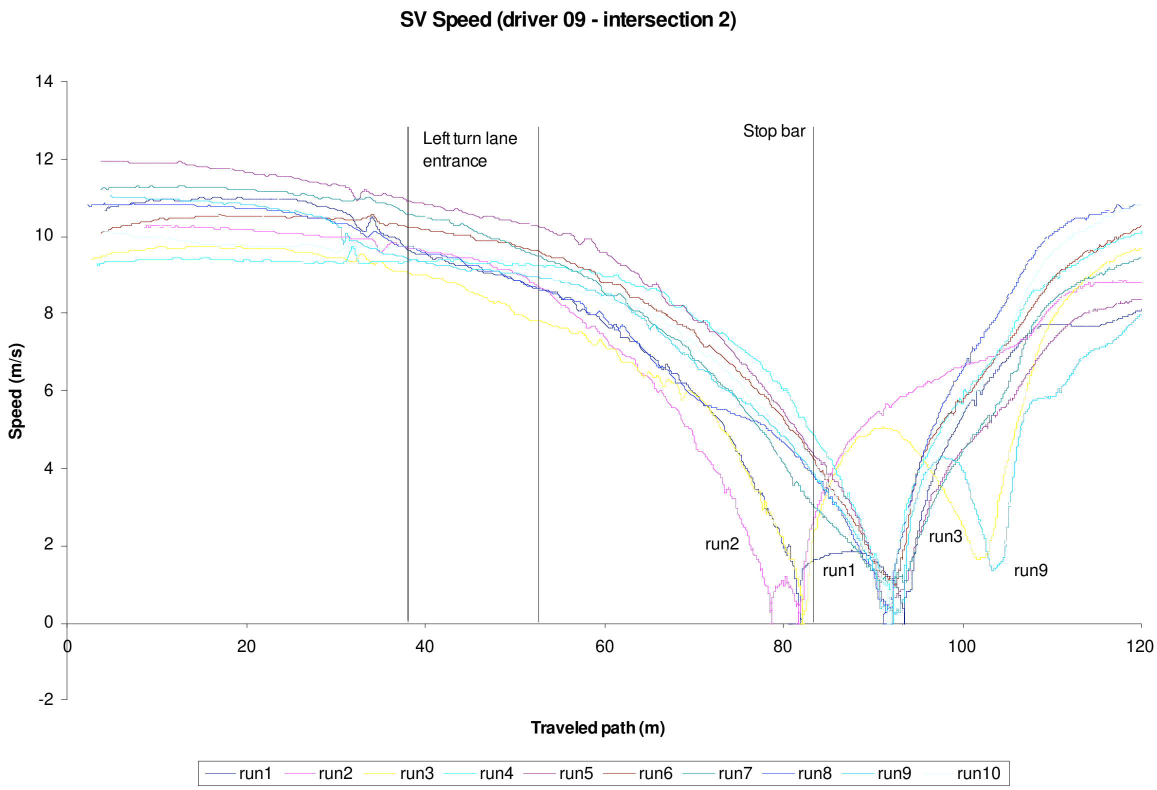


Figure 2-16. Multiple runs at intersection 2 for subject 9.

In Figure 2-16, the SV speed is plotted for the 10 runs. For runs 4 through 10, the driver reached the intersection at the green signal, there was no lead vehicle and he stopped for POVs before turning left. These stops occurred between 91 and 93 m. of traveled path. For the ninth run, the driver had to slow down while almost out of the intersection to leave room for an oncoming bus which was turning right, down the same intersection leg than the driver. The bus was turning onto the right lane of two lanes, while the SV driver was turning toward the left lane. For the first two runs, the traffic signal was red before the driver entered the left turn lane, and for the third run, the signal turned red while the driver was on the left turn lane. For the second run, a pedestrian began to cross as the driver entered the left lane. This pedestrian was out of the crosswalk boundaries, outside the intersection box. This caused the driver to stop prior to the stop bar to yield to the pedestrian. The driver then continued to the stop bar.

For this example, the origin is the beginning of the observed section. However, for the rest of the analysis, we found it more convenient to have the 0 at either the stop bar or the zone of conflict. Below is the description of how we computed these parameters.

SV Distance to Intersection 1

Based on XY coordinates and the speed and steering angle for correction, computation of a "local distance" for each intersection, starting at 0 and finishing at the end of the observed intersection.

SV distance to intersection 2

Here the local coordinate origin is changed to P3 (stop bar)

SV_{dti2} = SV Distance1 – P3

(negative before the intersection for the SV, so SV_{dti} increases with time)

SV time to intersection

$SV_{tti} = SV_{dti}$ / SV speed (m/s) (set to previous value if SV speed is 0)

SV distance to Point of conflict

$SV_{d2ZOC} = (SV_{dti1} – P5)$

SV time to Point of Conflict

$SV_{t2ZOC} = (SV_{dti1} – P5)$ / SV speed (m/s)

POV distance to intersection

POV_{dti} = POV Range – (SV_{dti} + (P8-P3))

POV time to intersection

The radar provides us with the POV distance to the SV and we compute the POV velocity.

$POV_{tti} = POV_{dti}$ / POV speed (m/s)

POV distance to Point of Conflict

POV_{dpoc} = POV Range + (SV_{dti2} - (P5-P3))

(positive before the intersection for the POV, so POV_{dpoc} decreases with time)

POV time to Point of Conflict

$POV_{tpoc} = POV_{dpoc}$ / POV speed (m/s)

Crossing time

We define the intersection crossing time as the duration between when the front of the vehicle crosses the outside line of the crosswalk while entering the intersection and when the rear of the vehicle passes the outside line of the crosswalk where the vehicle exits the intersection.

Turning time

Turning time begins at the moment the driver releases the brake when in the intersection and accelerates and ends when s/he exit the intersection.

Waiting time

We define the waiting time as the amount of time a driver waits for obstructions (pedestrian/POV) to clear his/her pathway. We measure this time from when the intersection is entered to when the brake is released once in the intersection. This value is valid for Trajectory 3 and 4 only, as drivers do not stop within the limits of the intersection bloc for the two other trajectories.

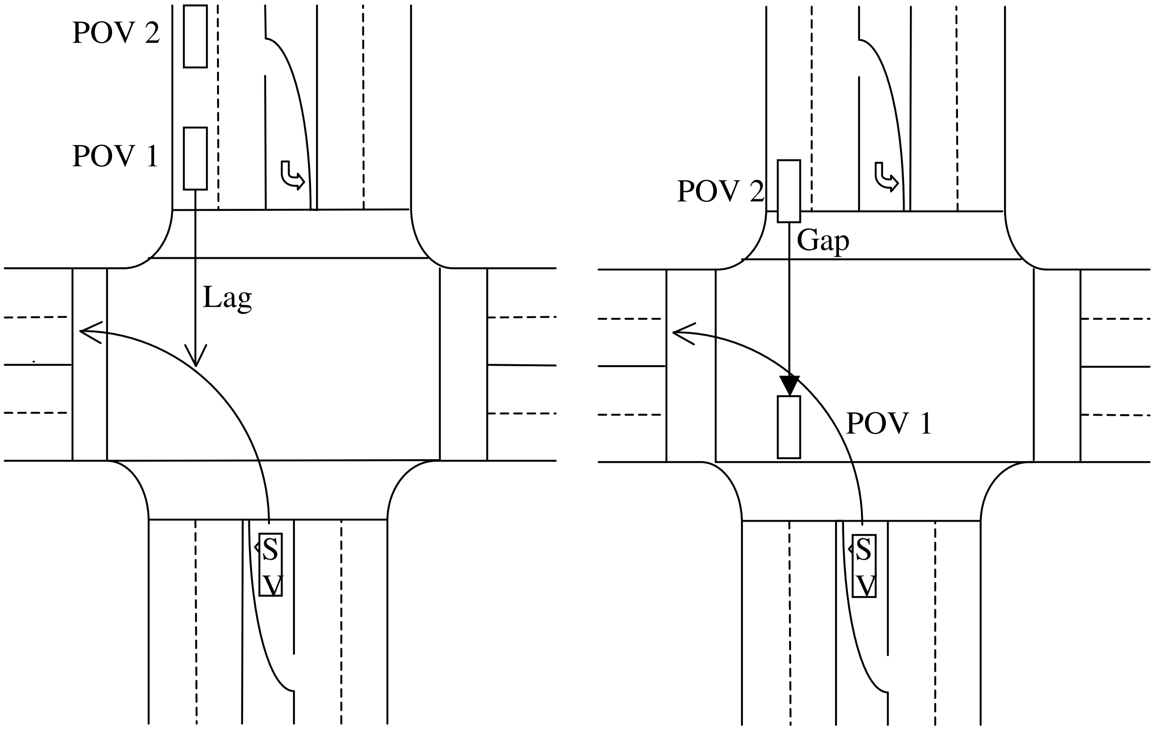
Decision Zone

We define the decision zone as the zone where the driver starts decelerating before to reach the intersection in order to make a left turn. This zone is determined by comparing trajectories where the driver does not stop for turning with trajectories where the driver stops within the intersection box.

Gap and Lag Measurement

In order to determine the relationship between the POV and SV, we must first consider and define two situational possibilities as shown in Figure 2-17. First, a lag (a) is defined as a measurement corresponding to the difference between the SV and POV reaching a similar point in the intersection. Second, a gap (b) is traditionally defined as distance between two successive POV's through which and SV can turn.

Based on the specific points defined in the previous section, and the traveled path computed with the GPS data, we computed parameters that facilitate the analysis of the relationship of the SV and POV relative to the intersection and the zone of conflict (ZOC), i.e., the portion of the intersection where the SV and POV trajectories would meet. This information can be presented in either time to ZOC (T2ZOC), as illustrated on Figure 2-18 or distance to the zone of conflict (Figure 2-19).



a) depiction of lag   b) depiction of gap

Figure 2-17. Illustration of the difference between a lag and a gap.

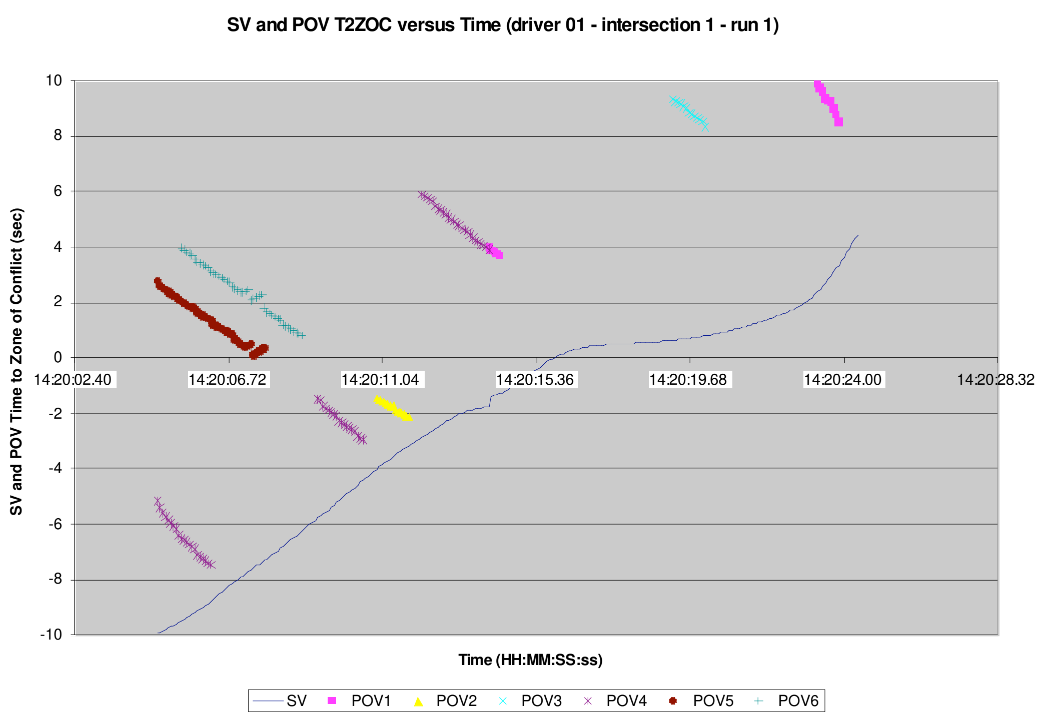


Figure 2-18. Example of SV and POV time to Zone of Conflict for trajectory 1.

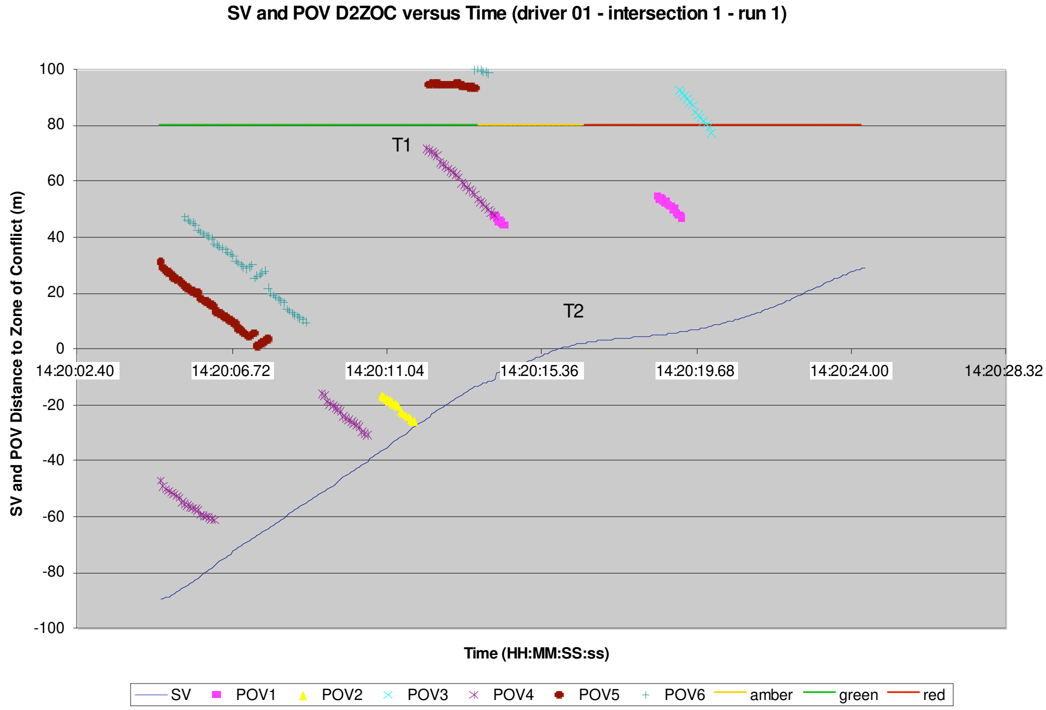


Figure 2-19. Example of SV and POV distance to zone of conflict with traffic light status for trajectory 1.

For the case described in Figures 2-18 and 2-19, at T1, the estimated lag between the path of the SV and POV is of 3.14 sec or 47 m, and at T2, the estimated lag (we extended the target trajectory assuming a constant approach, in this case, the light changed to amber when the SV driver was already well into the turn) is of 2 sec. or 27 meters. The data points that we will extract for the analysis of lags and gaps is the T1, or when the POV is first sensed by the radar. The rational for this choice is that drivers make their decision before we can measure the result of the decision, hence, because the speed profile tend to be fairly constant at a distance from the intersection, we can expect that the difference of T2ZOC will be similar to the one used by drivers when they are making their decision. The closer one at T2 already results from the driver's decision.

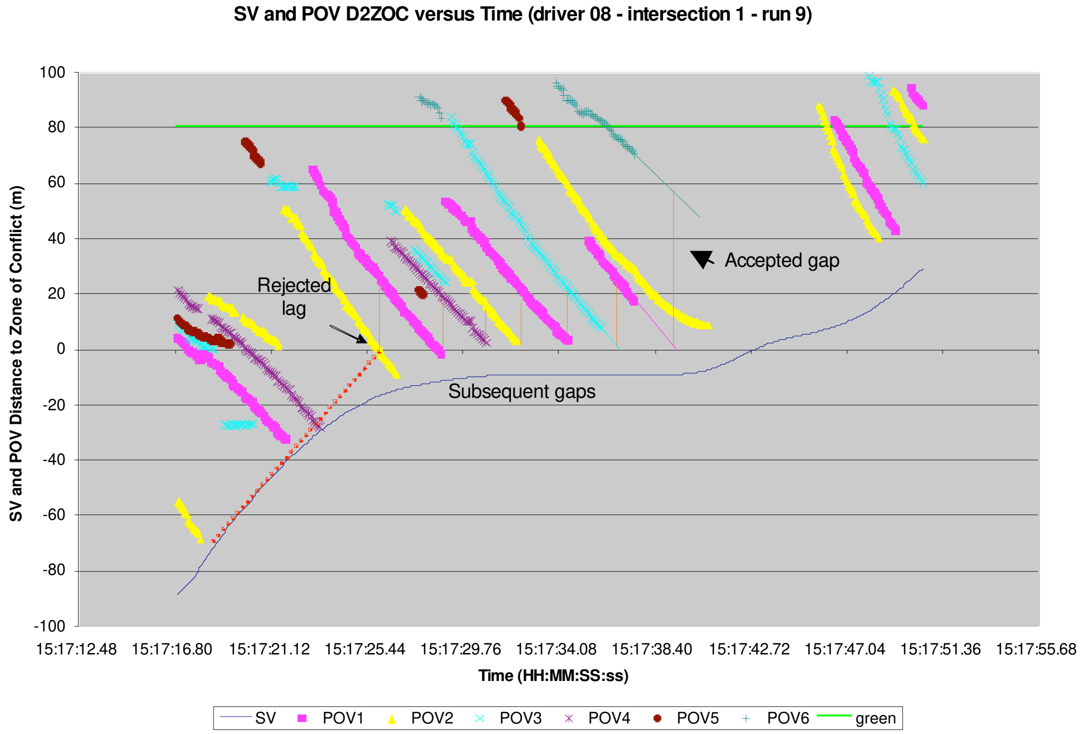


Figure 2-20. Representation of gaps and lags on radar data.

In Figure 2-20 above, we distinguish three types of data extracted from the radar data. The first one is a rejected lag, the red dotted line shows how the two trajectories would have conflicted. We consider this space as a lag because the targets before it had cleared the intersection well before the SV arrived at the intersection (SV is at approximately 40 m from the zone of conflict, which is about 25 m from the stop bar). After this rejected lag, we can identify six rejected gaps, a vehicle turning left (at the same moment than the last POV with a rejected gap) and finally an accepted gap of approximately 54 m from the zone of conflict (a gap of about 6.2 seconds with the last clearing POV).

Figures 2-21 to 2-23 below represent aggregation of POV in the 10 seconds before SV crosses the zone of conflict for trajectory 1, i.e., cases where the driver did not stop within the intersection. Each figure represents the data for one intersection. These figures were made in order to identify a “clear window” within which there would be not target and would then give an indication of the absence of POV to describe the size of the gap for which there would be no target prior to the turn. From these figures, it appears that no window could be clearly identified. Hence, we proceeded to manual collection of point for each run and noted whether the driver was first faced with a lag or a gap or any special circumstances.

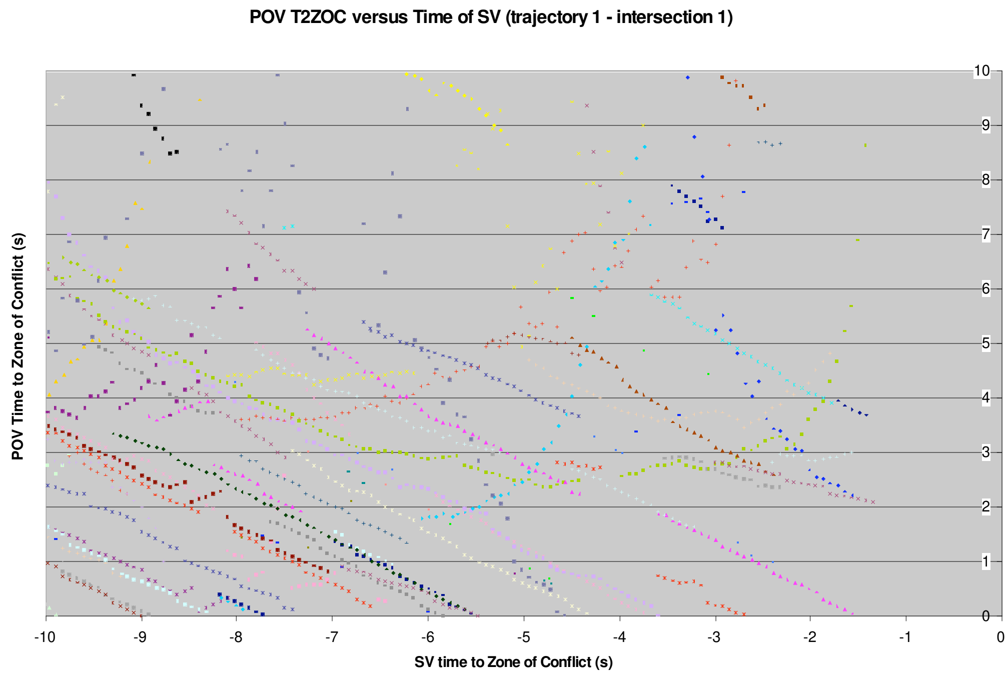


Figure 2-21. SV time to ZOC versus POV time to ZOC for intersection 1, trajectory 1.

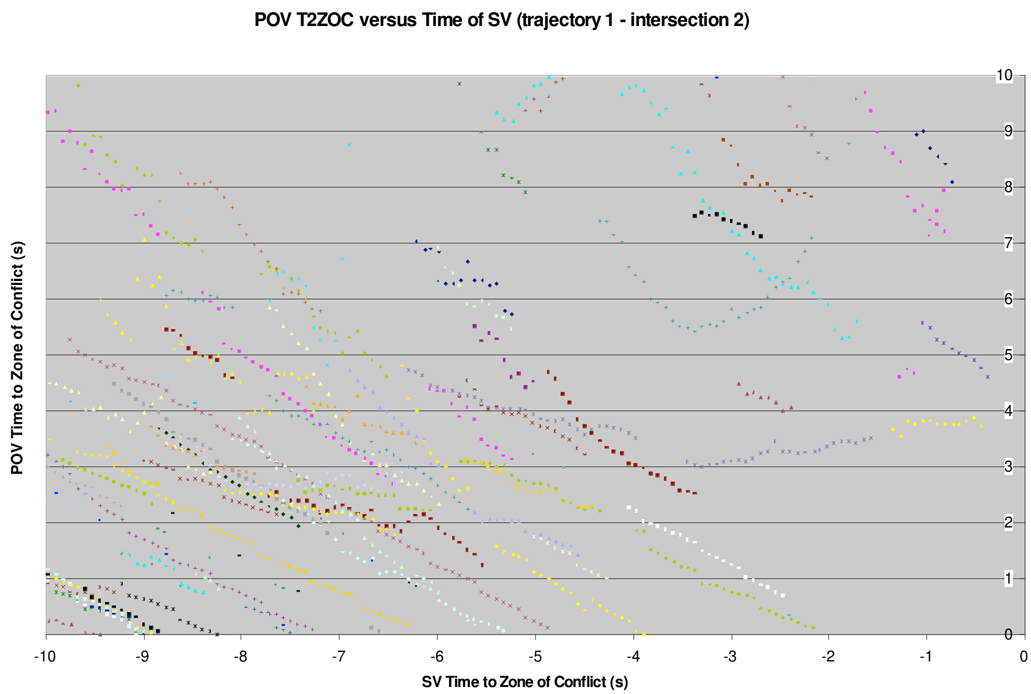


Figure 2-22. SV time to ZOC versus POV time to ZOC for intersection 2 trajectory 1.

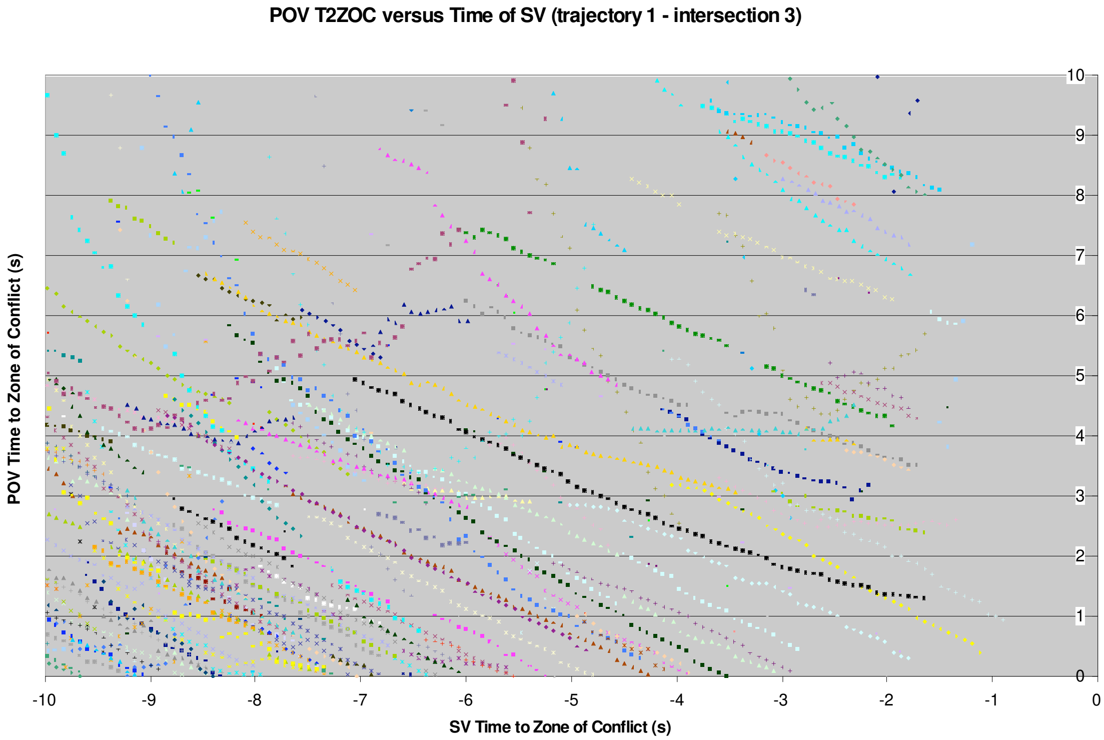


Figure 2-23. SV time to ZOC versus POV time to ZOC for intersection 3 trajectory 1.

2.4 Results

This section is composed of four parts. The first part provides a short general description of the collected data, in terms or representation of each trajectory in the sample of data. The second part describes the SV driver approach for left turn. The description entails the speed profile, the relevance of using the speed profile for determining the decision zone boundaries. The third part provides the description of the intersection crossing times, which will be decomposed in terms of turning time and waiting time for situations where the driver stopped before to turn. This part will open up a discussion on gap availability. The fourth part describes the lag and gap acceptance/rejection characteristics, with the emphasis on cases were the driver is approaching the intersection to make the left turn, vs. situation where the driver is waiting in the middle of the intersection to make the left turn. We will insist on the closed loop and dynamic aspects of the gap evaluation and acceptance/rejection process and propose a preliminary set of factors explaining this process, with a critic of the factors we already have access to with our data set and the one that we will need to gather via further data collection.

2.4.1 General description of collected data

For the 920 intersection crossing that we observed, trajectory 1, when SV driver does not stop prior to turn, represents 11.3% of the cases or 104 cases, trajectory 2 represents 28.4 % (261 cases), trajectory 3 represents 40.3% (370 cases) and trajectory 4 accounts for 19.3% (177 cases). Seven intersection crossing are missing, because the GPS data could not be used for the traveled path computation.

Table 2-2. Representation of trajectories per intersections.

Intersection	Trajectory	Number of cases	Percent
1	1	26	11.3
	2	96	41.7
	3	94	40.9
	4	14	6.1
2	1	27	11.8
	2	33	14.4
	3	73	31.9
	4	96	41.9
3	1	45	19.6
	2	19	8.3
	3	102	44.3
	4	64	27.8
4	1	6	2.6
	2	113	49.1
	3	101	43.9
	4	3	1.3

Table 2-2 illustrates that the proportion of each trajectories varies for each intersection. For intersections 1 and 4, the majority of cases are almost equally distributed between trajectory 2 and 3, while intersection 2 has a majority of trajectory 4 and intersection 3 has a majority of trajectory 3.

The trajectory categorization results of factors non controlled by the experimenter and not dependant only on the driver, but also on the level of traffic and light status, hence, we will not present a repartition of the percentages per driver groups, as it would be biased by these other factors.

2.4.2 Left Turn Approaches

The characteristics describing the approach to the intersection that will be presented are: the speed profile, and the factors affecting it, the application of speed profile for the assessment of the decision zone, and the identification of a stopping point within the intersection boundaries.

Speed profile when turning without stopping

Figure 2-24 on the next page illustrates the speed profile observed for drivers who did not stop for turning at the first intersection. These profiles were sorted in two categories:

1. There were **no interference** for making the turn, no pedestrian in destination lane, the light was green before the left turn lane and there were no POV near the intersection at the time of the turn.
2. There was an **interference** at the moment of the turn as described below:

    a. **Pedestrian** on the destination leg that the driver had to wait for before to be able to turn
    b. The **light** turned from **red to green** while the driver was already in the left turn lane
    c. There was a **POV** at the intersection at the moment of the turn

d. The driver made an **error**, e.g. in one case the subject went through a red light, which can be explained by the intersection set-up as the on-coming traffic has an earlier green, a more common case is of drivers going straight at the intersection and already along the left turn lane when the experimenter corrected the behavior.
e. There was one or more **lead** present at the intersection and waiting to make a turn when the SV driver reached the intersection.

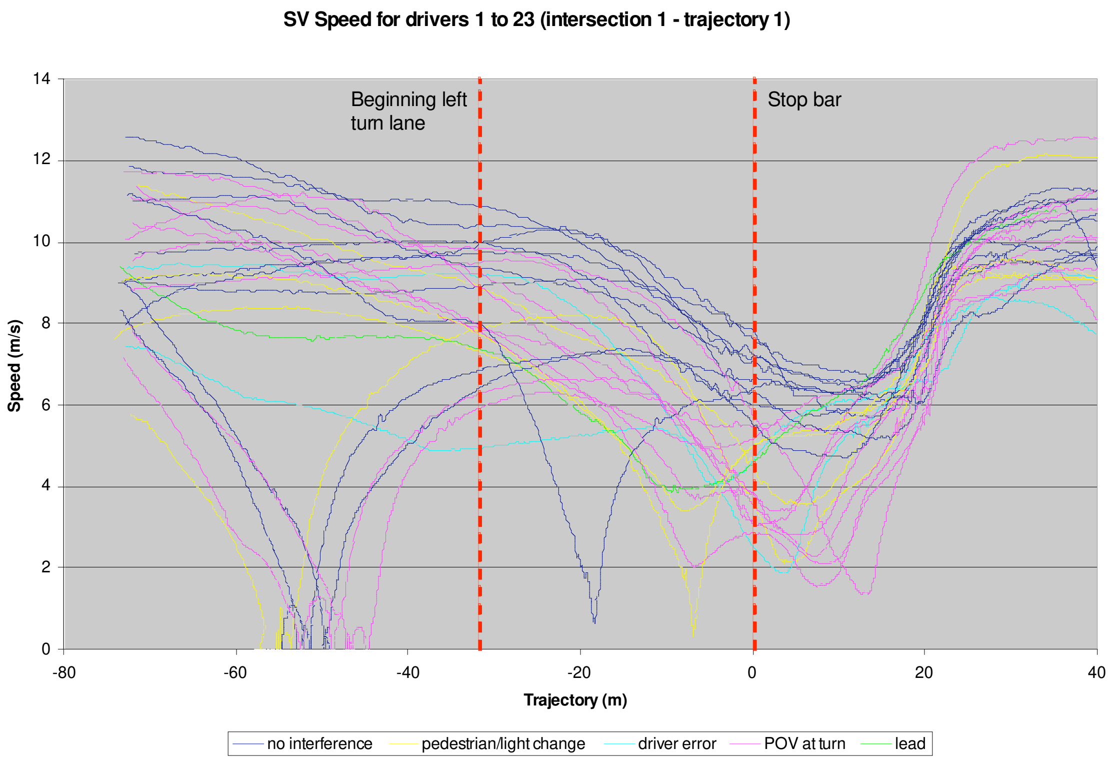


Figure 2-24. Behavior pattern for trajectory 1 at intersection 1.

This categorization allows explaining the variation for both the minimum speed variation, which ranges from 7 to 2 m/s and where this pick occurs. For the cases with no interferences, the minimum speed varies between 5 and 7 m/s, with a majority of the cases between 6 and 7 m/s. For these cases, the pick is after the stop bar and quite constantly at 13 meters past the stop bar. On the other hand, the lowest pick for the situation with interferences is much more variable and can be located before the stop bar, shortly after the stop bar or shortly before the one for cases without interferences. For these cases, the lowest speed once within the intersection tends to be between 2 and 4 m/s.

In order to pursue the analysis about gap acceptance, we kept only the cases where there were no interferences and an interference caused by a POV in the intersection vicinity as they are the clearest patterns that can be identified (see Figure 2-25).

The same procedure has been applied for intersection 2 and 3 (there is only 6 Trajectory 1 cases for intersection 4 and no trend can be illustrated with this little amount of cases) and the results are illustrated in the figures below.

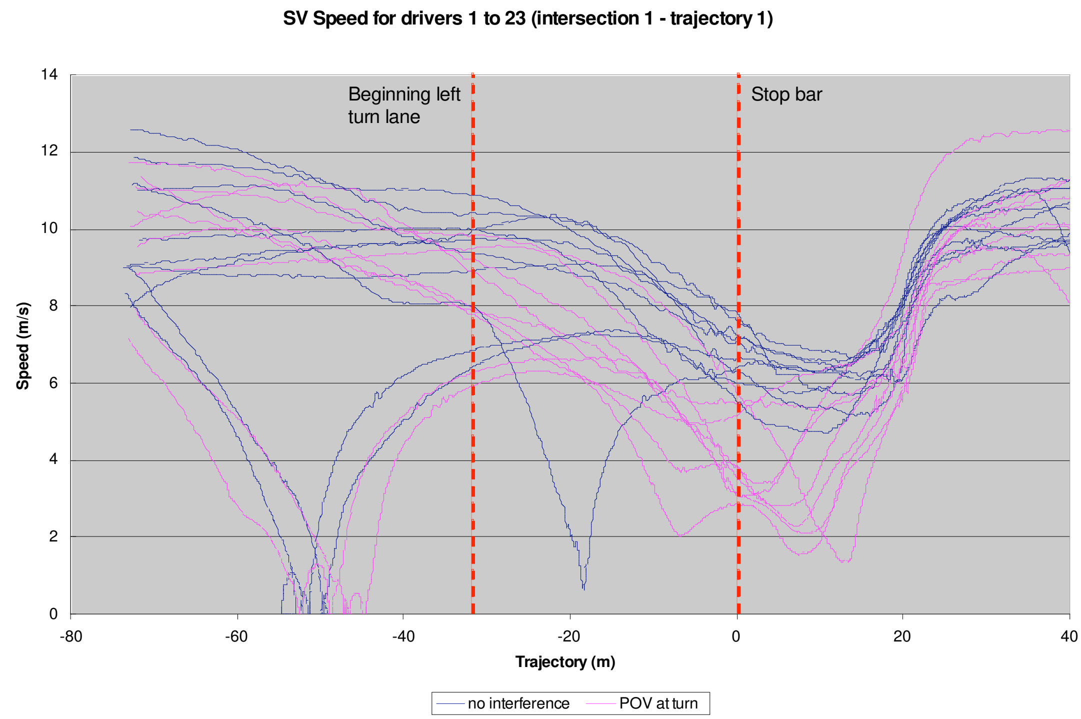


Figure 2-25. No interference and POV present within intersection 1.

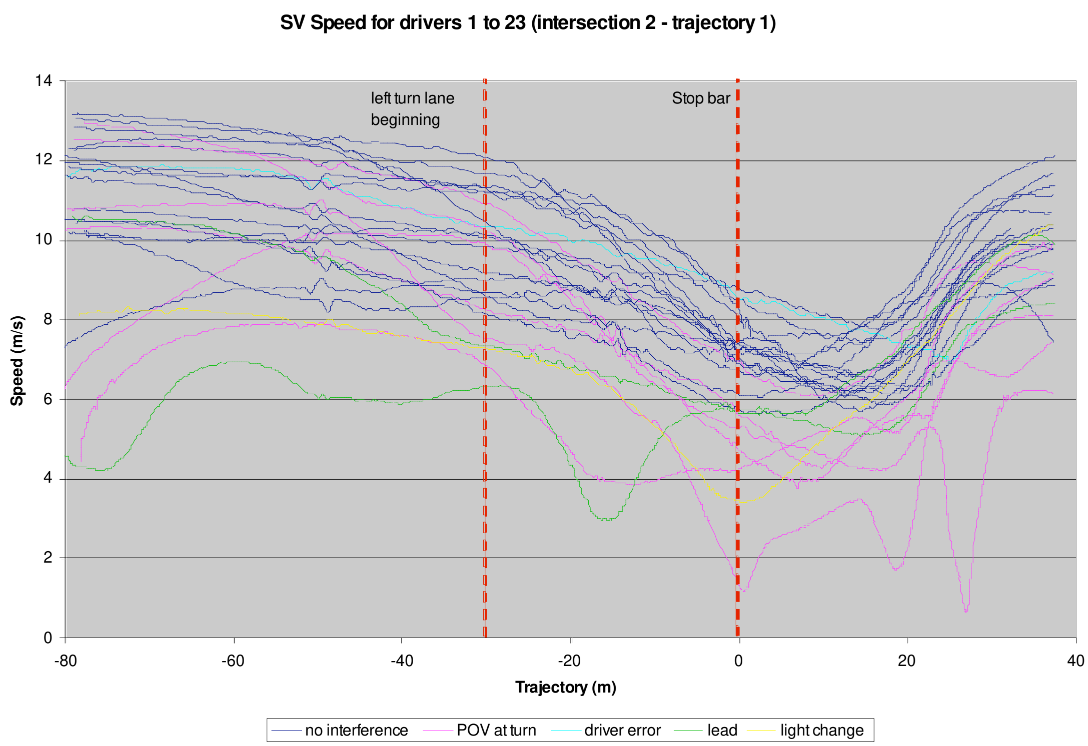


Figure 2-26. No interference and POV present within intersection 2.

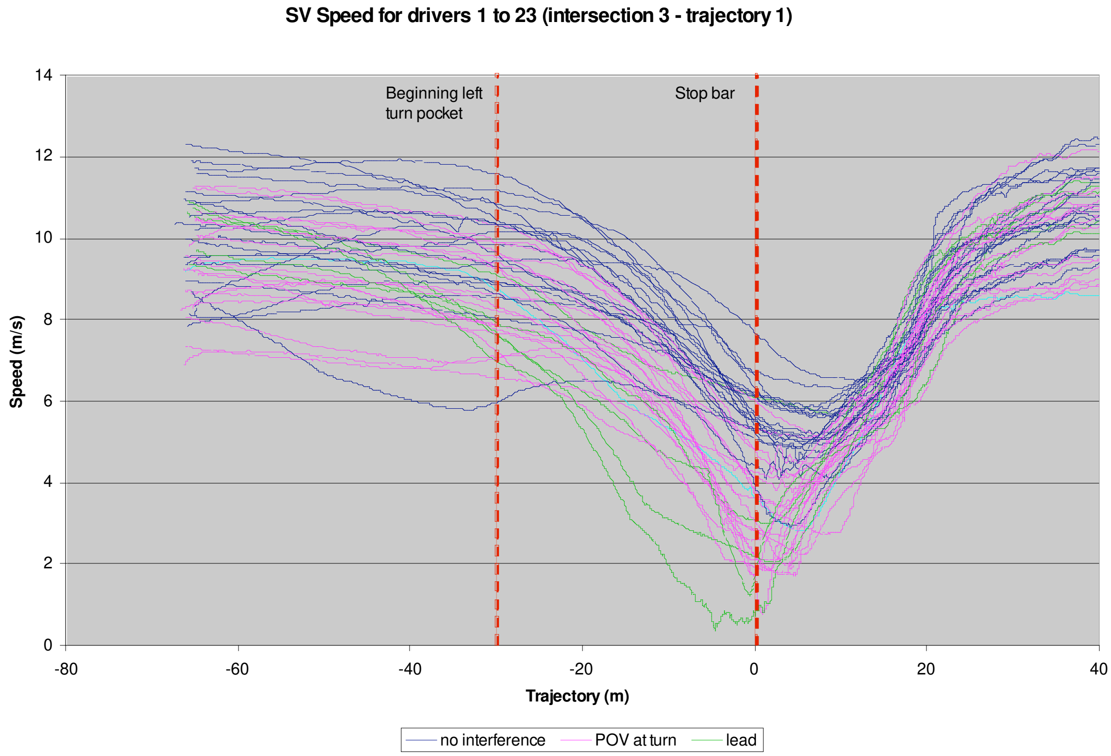


Figure 2-27. No interference and POV present within intersection 3.

Speed profile and determination of stopping/proceeding "decision zone"

The goal of determining this zone is to support the determination of when to present supporting information to the driver. In order to identify this zone decision zone, we compared the speed profile for trajectory 1 when there were no interferences and trajectory 4 as drivers approach the intersection (0 represents the stop bar). We assume that for trajectory 4 the interference is "detected" before the intersection and led to a decision to stop.

In the Figure 2-28, it is possible to starts to dissociate the trajectories 1 from trajectory 4 at approximately 17 meters of the stop bar, which is over 2 seconds of travel time (driver are still decelerating). This point corresponds to the one where the difference between the two trajectories can be observed via a speed decrease, hence, in order to determine the "earlier" the decision time can occur, we have to consider several steps. Assuming that this point is Time 0, the preceding sequence can be described as:

- Time -1: assuming that the deceleration profile is similar for Trajectory 1 and trajectory 4, a change in deceleration should be identifiable. Deceleration for Trajectory 4 should either be stronger or longer. This analysis will be conducted later as it will require a lot of manual analysis for each case.
- Time – 2 the decision is implemented by the driver, which could be measured by a changed in brake pressure (this variable was not measured for this data collection)
- Time – 3 the decision is taken.
- Time – 4 the situation is assessed.

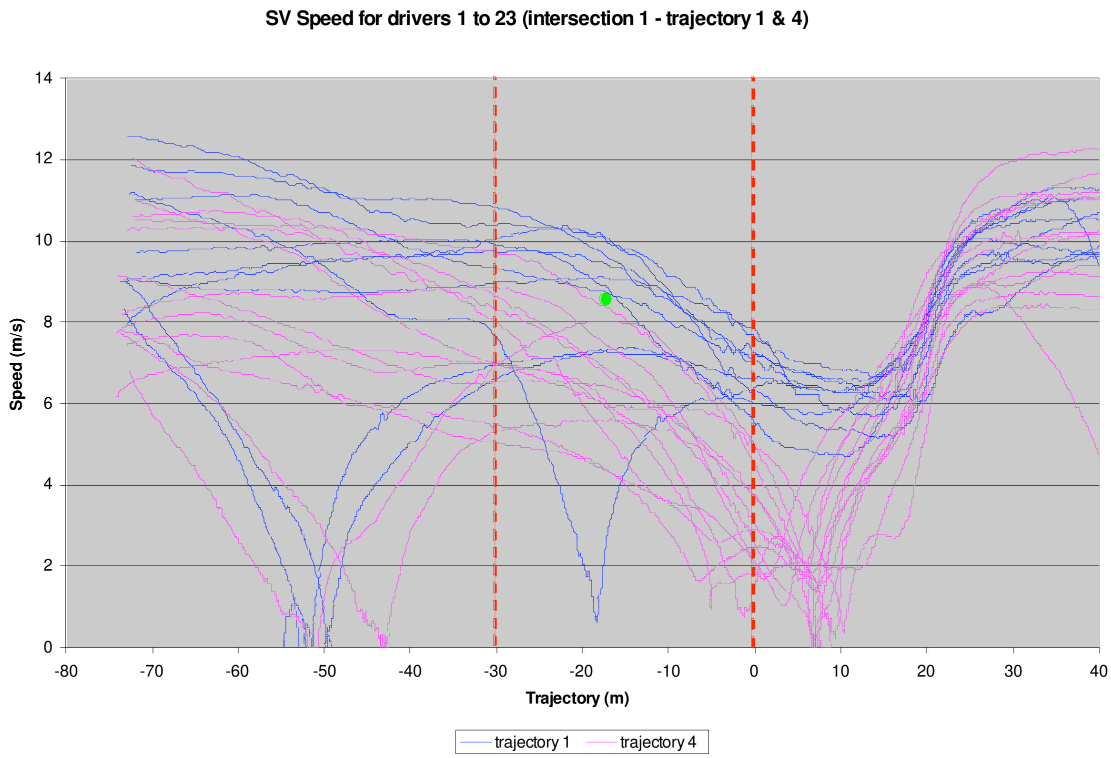


Figure 2-28. Trajectory 1 and 4 Intersection 1.

[4]Olson (2002) reports an effort from [5]McGee, et al. (1983) to deduce driver perception-response time based on summation of the assumed components and list three components:

1. perception, which can be decomposed in four steps:
   - latency
   - eye movement
   - fixation
   - recognition
2. decision
3. brake reaction

Perception corresponds to our time-4, decision to time-3 and brake reaction time-2. Olson provides a range to time from the 50 to the 99 percentile. The perception time for the 50 percentile is 0.93 seconds, the decision time is 0.5 sec and the brake reaction is 0.85 seconds, or a total of 2.3 sec. For the 99 percentile, the perception time is 1.39 sec, the decision time is 1 sec and the brake reaction is 2.16 sec, or a total of 4.6 sec. Based on the current data, it is difficult to measure the perception and decision time. If we applied the one provided by [5]McGee, et al. (1983) with our own measurement to time-1, we could reach an estimate of when the decision zone begins. This will be one of the goals of the next round of data analysis.

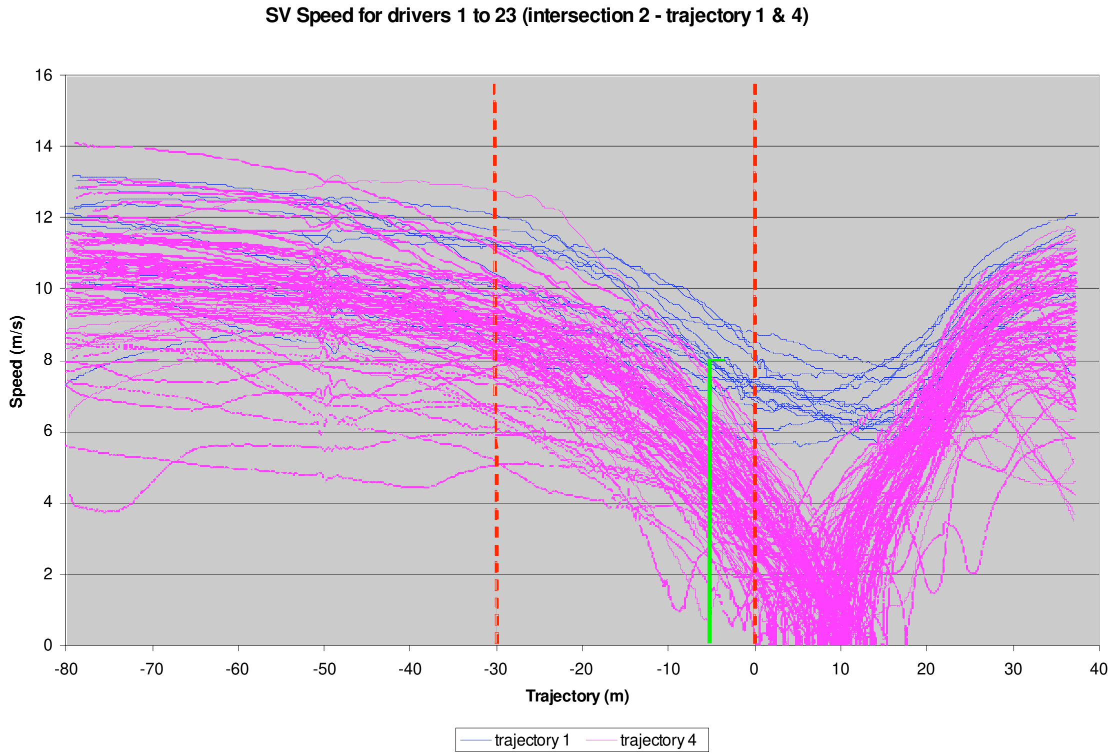


Figure 2-29. Trajectory 1 and 4 intersection 2.

For intersection 2, the observable difference between trajectory 1 and 4 is closer to the stop bar, at approximately 5 m from it. This can be explained by this intersection geometry. On the POV leg, 50 meters before the stop bar is a signal controlled T-intersection (see Figure 2-30 below). When the light at the observed intersection is red, a platoon builds up (Platoon A). When the light turns green, this platoon clears. When the light at the T-intersection turns green, Platoon B enters the intersection approach. This often creates a short period of time after Platoon A clears, where there is no on-coming POVs at the observed intersection because the vehicles from Platoon B cannot be seen by our driver. In numerous occasions, the SV driver was reaching the intersection after the first platoon cleared and had no POV in sight, when Platoon B started to turn the corner and enter the intersection. This led to several different behaviors, including drivers speeding up at the last minute trying to beat the second platoon, drivers slowing down early in expectation of the second platoon, or drivers attempting to adjust their approach strategy in order to arrive during the “hole” between the two on-coming traffic streams.

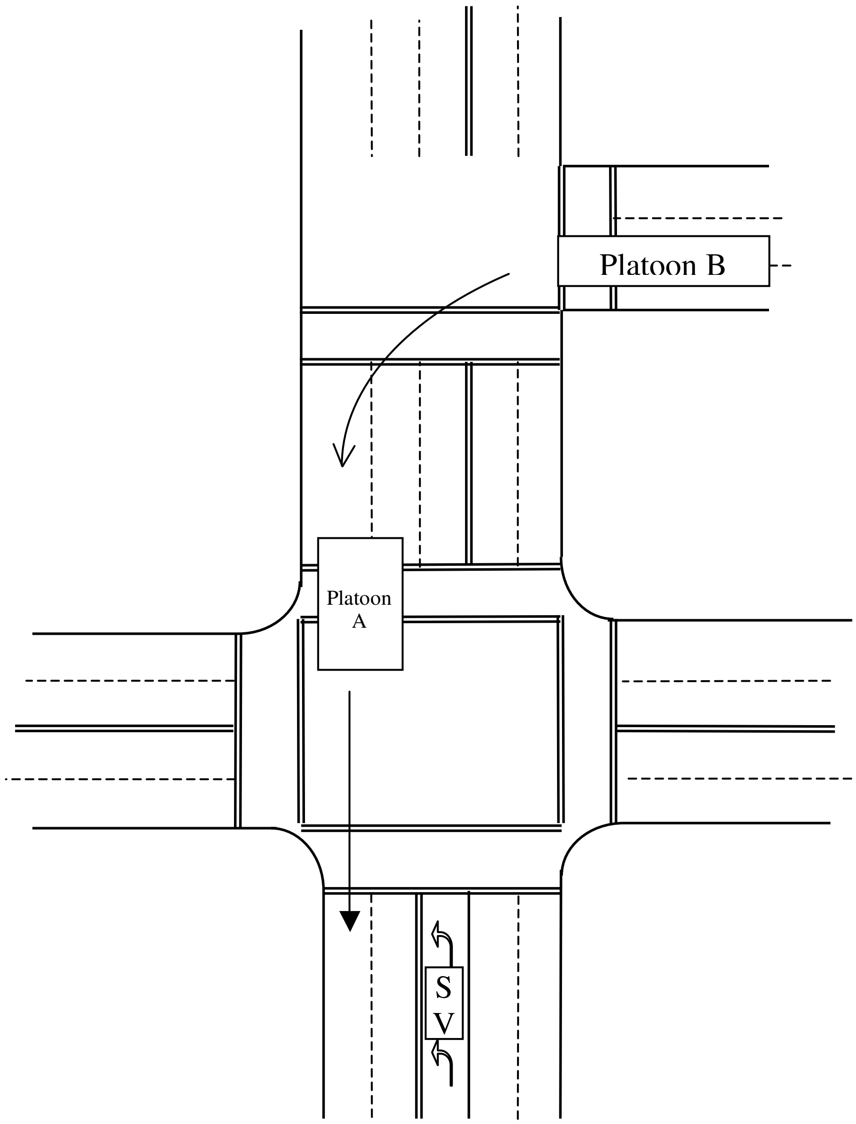


Figure 2-30. Geometry of intersection 2 (not to scale).

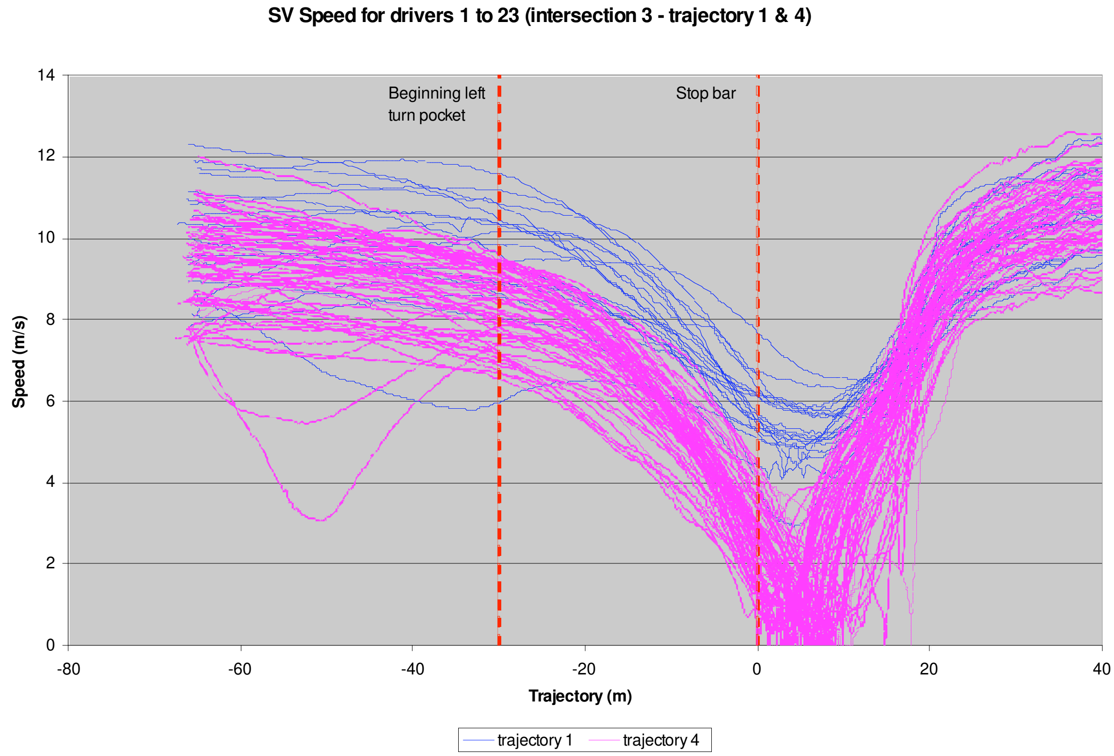


Figure 2-31. Trajectory 1 and 4 - intersection 3.

For intersection 3 (Figure 2-31), it is interesting to note that part of the speed profile for Trajectory 1 are higher than the one for trajectory 4. Also, the speed pattern for Trajectory one, after the stop bar, can be differentiated in two trends of lowest speed, with one trend centered around 6 m/s and the other one centered around 5 m/s. The initial approach speed does not seem linked to the difference in terms of lowest speed (see Figure 2-32 on next page). The fastest profiles of Trajectory 1 seem to be distinguishable from the one of Trajectory 4 right after the entrance on the left lane. However, the real distinction between the two trajectories can be done only very close to the stop bar.

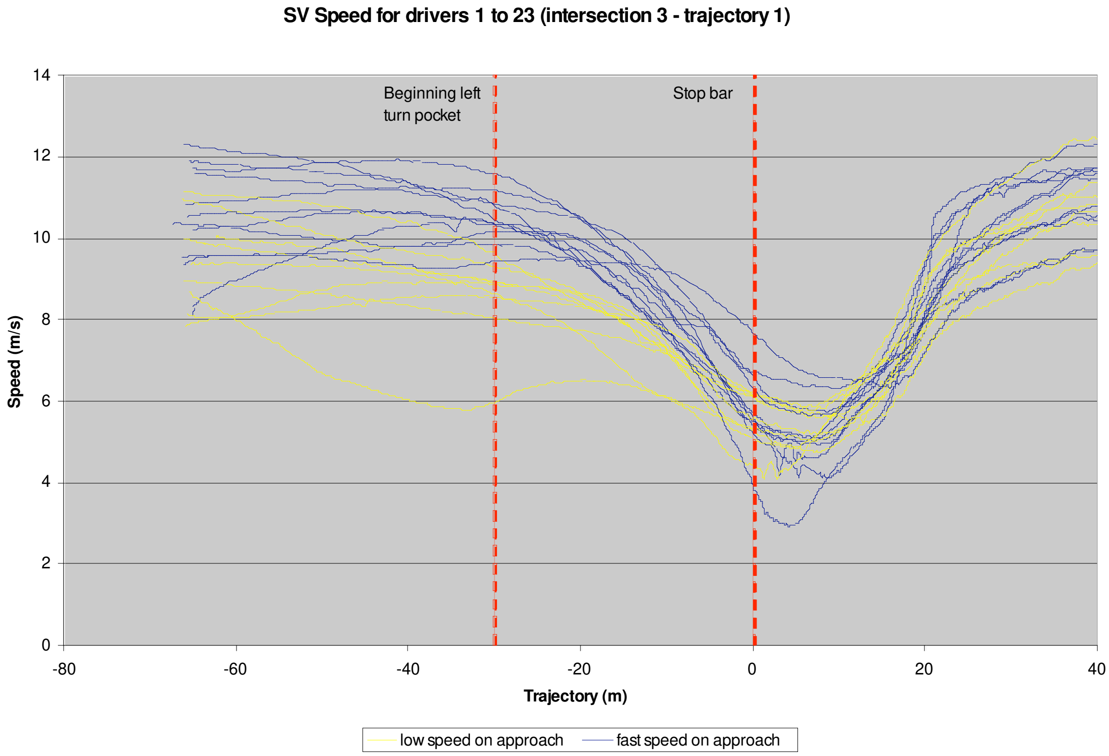


Figure 2-32. Intersection 3 speed patterns for the no interference cases.

In summary, in order to identify the beginning of a decision zone, the comparison of the speed profiles for cases where drivers turned without stopping and interferences and the one of drivers who had to stop in the intersection seems to be an efficient method that needs to be associated with an estimation of the perception-decision-action components leading to it. The cases for which drivers dealt with interferences provide support to the denomination of decision zone and illustrate drivers' adaptability and adoption of different course of action during the approach. The special case of intersection 2, it appears that drivers' decision can be made at different "points" while approaching the intersection and that the decision can be affected by factors such as the intersection geometry, the traffic pattern or the traffic light status. Therefore, for one specific intersection, the information to provide to the driver will be context dependent and the design of the intersection decision support system might have to include different "location" on the approach to provide information to the driver.

Analysis of stopping point within intersection box

The two trajectories for which drivers stop inside the intersection box are 3 and 4. As a reminder, for trajectory 3, drivers will stop before the stop bar (usually for a red light) and for trajectory 4 they will stop only after passing the stop bar. This analysis is conducted in order to determine the point within the intersection where the warning algorithm would aim at stopping the SV driver. In order to do so, we intend to answer the following questions:

1. Is the stopping point trajectory dependant?
2. Does the stopping point vary based on drivers' age?
3. Does the stopping point vary based on drivers' gender?
4. Does the stopping point vary based on urban driving "experience"?

We expect that the stopping point will be dependant on the intersection geometry; hence all of the data are analyzed by intersections. Also, the cases including one or more lead vehicles were excluded from the analysis, as the driver had to stop behind these vehicles.

Table 2-3. Stopping point characteristics.

Intersection	N	Trajectory 3					Trajectory 4				
		n	Mean	Std Dev	Min	Max	n	Mean	Std Dev	Min	Max
1	84	70	9.68	3.01	5	17.34	14	9.74	3.02	5.05	14.29
2	132	55	12.43	2.95	5.02	18.18	77	12.43	3.12	5.04	18.84
3	142	83	8.57	2.3	5	14.78	59	9.46	2.62	5.02	16.56
4	94	92	6.97	2.08	4.95	12.82	2	-	-	7.65	11.19

In Table 2-3 above, N is the total number of stop inside the intersection box. n is the number of cases per trajectory. Only 2 cases were observed for intersection 4 trajectory 4, hence we did not compute the characteristics for these cases.

Although the sample size is different for each of the trajectories at each intersection, the difference between the mean for trajectory 3 and 4 is fairly small and well within the standard deviation of each other. Hence, we consider that there is no significant effect of the motion of the SV driver to the location where he will stop inside the intersection and that the results for trajectories 3 and 4 can be treated together for the rest of the analyses.

Gender Differences

Table 2-4 below presents the mean stopping point for each intersection for Male and Female drivers.

Table 2-4. Mean stopping point by gender.

Gender	Intersection 1			Intersection 2			Intersection 3			Intersection 4		
	n	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev
Female	47	9.59	2.88	58	12.38	3.36	73	9.06	2.57	54	7.05	2.07
Male	37	9.82	3.17	74	12.47	2.77	69	8.80	2.36	40	6.97	2.17

The difference between the mean stopping point for male and female does not seem to vary significantly and are well within the standard deviation of each set of data.

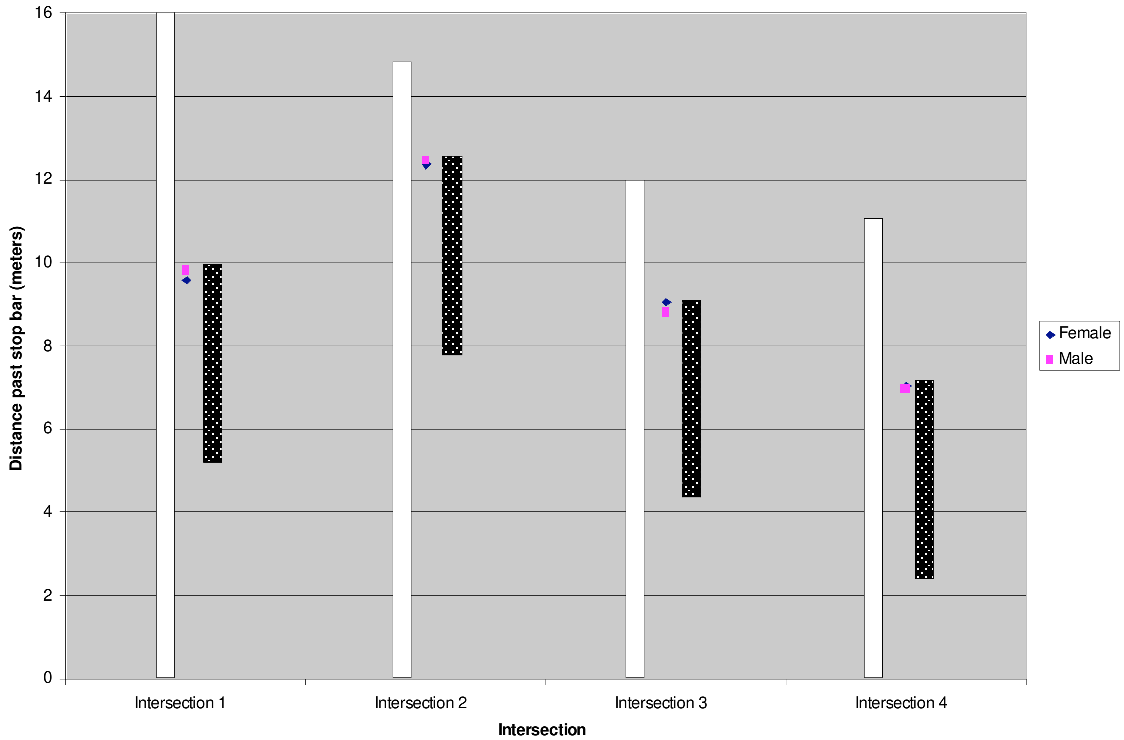


Figure 2-33. Mean stopping bar by gender.

The white rectangle in the figure above illustrates the distance between P3 and P5, or the distance between the stop bar and the middle of the intersection. The smaller rectangle represents the approximate length (5 meters) of the vehicle the SV driver was. It illustrates that the difference between male and gender are pretty small.

Age differences

Table 2-5 below presents the mean stopping point for each intersection for the young, middle age and older drivers.

Table 2-5. Mean stop characteristics per age group.

	Intersection 1			Intersection 2			Intersection 3			Intersection 4		
	n	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev	n	Mean	Std. Dev
Young	39	9.97	2.90	59	12.12	3.17	68	8.69	1.99	44	6.46	1.88
Mid. A	26	9.39	3.10	37	12.26	2.68	38	8.54	2.39	22	6.66	1.88
Older	19	9.52	3.15	36	13.11	3.13	36	9.82	3.12	28	8.17	2.20

For intersection 1 age does not seem to affect the mean stopping point. For intersection 2, 3 and 4, elderly drivers seem to stop slightly further in the intersection than the two other age groups. This difference can be seen in the figure below. We consider this difference not to be practically significant for two reasons. On the one hand, the difference between the mean is within the standard deviation of the distributions. On the other hand, a difference of over a meter considering the size of the vehicle, intersection, and error produced by measurement systems does not seem very big.

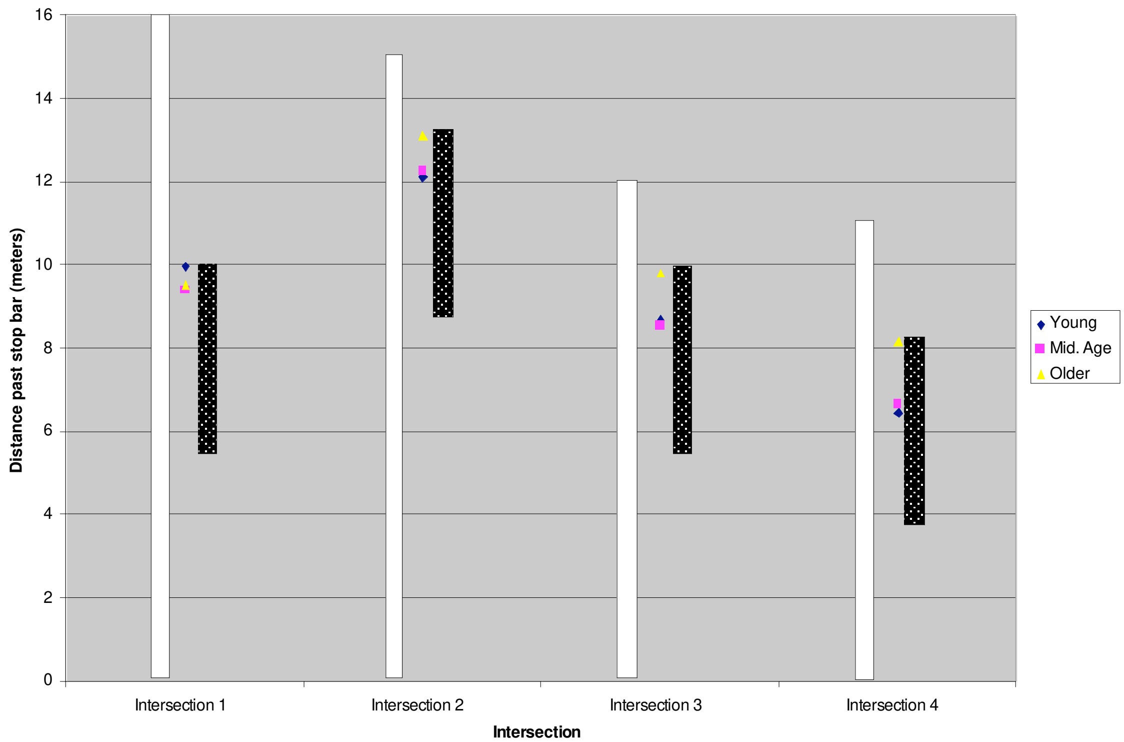


Figure 2-34. Mean stopping point per age group.

Urban driving experience

Table 2-6 below presents the mean stopping point for each intersection based on the level of experience with urban driving.

Table 2-6. Mean stopping point per urban driving experience.

	Intersection 1			Intersection 2			Intersection 3			Intersection 4		
	N	Mean	Std. Dev	N	Mean	Std. Dev	N	Mean	Std. Dev	N	Mean	Std. Dev
Low	37	9.93	3.02	75	12.58	2.92	80	8.84	2.56	46	7.35	2.42
High	43	9.54	3.12	53	12.17	3.27	58	9.06	2.39	43	6.75	1.76

The level of experience with urban driving does not seem to significantly affect the stopping point.

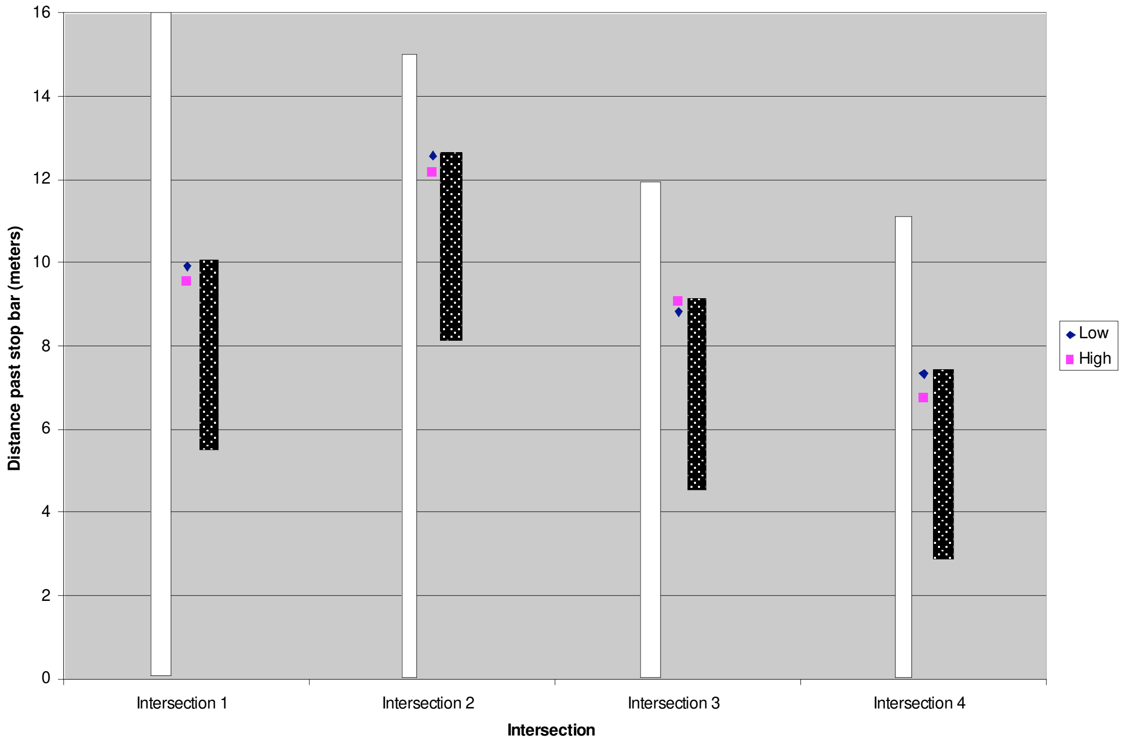


Figure 2-35. Mean stopping point by urban driving experience.

In summary, the stopping point within the intersection does not seem to be affected by either the driver gender or amount of driving performed in urban environment. For intersection 2, 3 and 4, it seems that elderly driver might tend to stop a little further within the intersection than the subjects from the two other age groups. Also, the variation of stopping point was not analyzed within subjects due to a lack of data. The same driver rarely stopped more than three times at the same intersection, running analysis on such small amount of data is not very revealing of any trend.

2.4.3 Description of intersection crossings

This subsection focuses on the description of the timing for crossing the intersections and, for cases where the driver stopped prior to complete the turn, either at the stop bar (trajectory 2) or in the intersection (trajectories 3 and 4), the turning time, and finally, for trajectory 3 and 4 we document the waiting time. All of these timing are provided per intersection, as the geometry and traffic patterns vary between the intersections. We will also discuss the time between the crossings of the zone of conflict by the last POV for trajectory 4. This discussion will be for all intersections.

Table 2-7 on the next page describes the characteristics of crossing time (defined as time between the crossings of the inner pedestrian crossing bar on the arrival leg to the one of the inner pedestrian crossing bar on the destination leg) in seconds.

Table 2-7. Crossing time (seconds) per intersection and trajectories when SV is first vehicle.

Intersection	n	Trajectory 1			Trajectory 2			Trajectory 3			Trajectory 4		
		n	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev
1	173	25	5.86	1.77	64	6.55	1.31	70	14.65	5.23	14	11.66	4.2
2	177	24	5.54	1.71	21	7.87	2.3	55	21.43	6.1	77	17.48	5.83
3	190	40	5.78	1.07	8	10.44	4.08	83	20.29	6.85	59	15.017	5.82
4	169	5	5.68	.78	72	7.5	2.6	90	16.67	4.19	2	10.50	.53

The crossing time for trajectory 1 is very consistent within each intersection as the small standard deviation shows. The crossing time for trajectory 2 (SV driver stopped prior the stop bar and then crossed the intersection without stopping) is slightly longer and more variable than for Trajectory 1, at the exception of Intersection 3, but the small number of cases explains the bigger variance, where one odd case can pull the mean. The difference between the crossing time for trajectory 1 and 2 can be explained by the difference of initial speed (in trajectory 2 drivers start from 0) and also by a slower speed to let a small platoon of POV clear the intersection. The crossing time for trajectory 3 and 4 is really composed of the waiting time and turning time and are more illustrative of the difference of waiting time.

Table 2-8 below describes the turning time, defined as the difference of time between when the driver let go of the brake once in the intersection and the time when the driver crosses the inner line of the crosswalk in the destination leg – P6 in Figure 2-15). Trajectory 1 was excluded from this table because the drivers did not stop and this measure is not relevant for that trajectory.

Table 2-8. Turning time (seconds) per intersection and trajectories when SV is first vehicle.

Intersection	n	Trajectory 2			Trajectory 3			Trajectory 4		
		n	Mean	Std Dev	n	Mean	Std Dev	n	Mean	Std Dev
1	148	64	6.61	1.52	70	5.36	.96	14	5.21	1.12
2	153	21	7.59	2.3	55	6.14	1.61	77	6.59	2.17
3	150	8	7.84	2.24	83	5.98	1.4	59	6.11	1.7
4	164	72	6.29	1.69	90	5.56	1.91	2	5.05	.36

The difference of turning time between Trajectory 3 and 4 is negligible while there is a bigger difference between trajectory 2 and the two others. Here also, this can be explained by the fact that in trajectory 2 drivers could have let short platoon of POV clear the intersection and go slightly slower and that they had a slightly longer distance to cover. Table 2-9 below presents the waiting time characteristics for Trajectory 3 and 4.

Table 2-9. Waiting time (seconds) per intersection and trajectories when SV is first vehicle.

Intersection	N	Trajectory 3			Trajectory 4		
		n	Mean	Std Dev	n	Mean	Std Dev
1	84	70	9.28	5.1146	14	6.45	4.43
2	132	55	15.28	6.2829	77	10.89	5.50
3	142	83	14.30	7	59	8.90	6.15
4	92	90	7.11	4.43	2	5.44	.16

For all intersections, the mean waiting time is longer for trajectory 3 than 4. This can be explained by the fact that in the case of trajectory 3, longer platoon of vehicles form during the red cycle and they are slower to clear the intersections than moving POV for trajectory 4.

Out of the three measurement presented above, we consider that the one the most driver dependant is the turning time. Below are the turning time characteristics per gender (Table 2-10) and age groups (Table 2-11).

Table 2-10. Turning time per gender for each intersection and trajectory.

Intersection	Trajectory	Gender	N	Mean	Std. Deviation
1	2	female	30	6.68	1.56
		male	34	6.55	1.51
	3	female	40	5.27	.95
		male	30	5.49	.98
	4	female	7	5.26	.55
		male	7	5.17	1.55
2	2	female	11	8.19	1.83
		male	10	6.93	2.67
	3	female	30	6.21	1.53
		male	25	6.06	1.74
	4	female	28	6.14	1.81
		male	49	6.84	2.33
3	2	female	1	8.77	.
		male	7	7.71	2.39
	3	female	37	5.76	1.18
		male	46	6.16	1.55
	4	female	36	5.87	1.28
		male	23	6.48	2.18
4	2	female	31	6.11	1.55
		male	41	6.43	1.79
	3	female	50	5.76	2.22
		male	40	5.30	1.42
	4	female	1	4.79	.
		male	1	5.31	.

Figure 2-36 on the next page displays Table 2-10 data and illustrates that the results are intersections dependant. For Intersection 1, there is no gender difference for either trajectory. For Intersection 2, it is interesting to note that there is a small gender difference for trajectory 2, where male seems to have faster turning time than female, none for trajectory 3, and that for trajectory 4 females tend to have a slightly faster turning time. For intersection 3, as there is only once case for female and 7 for male in trajectory 2, it is difficult to isolate a trend. Females seems to be slightly faster than males for trajectory 3 and 4, however, these difference being under 1 second and the standard deviation of each of the distribution being well over a second, it is hardly significant. Similar conclusions can be reached for Intersection 4, trajectory 2 and 3, and no trend can be identified for trajectory 4 as there is just one case for each gender. In short, there is no trend of one gender being faster then the other when it comes to turning time.

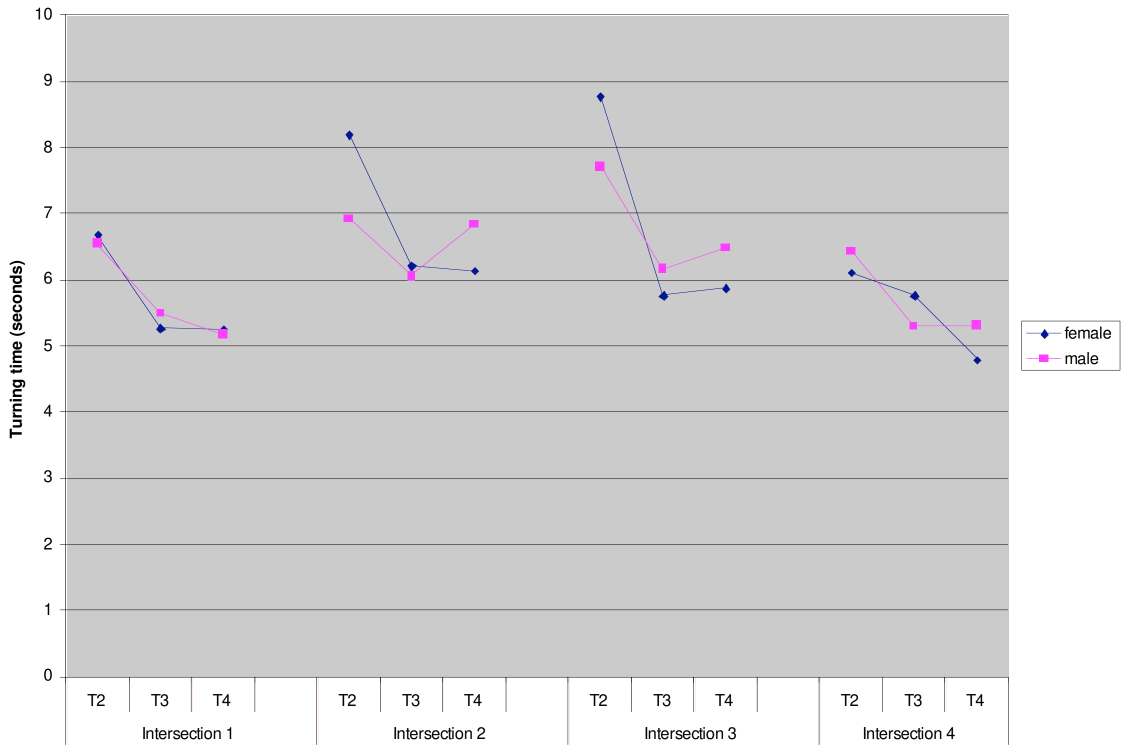


Figure 2-36. Turning time per gender for each intersection and trajectory.

Table 2-11 below presents the characteristic of turning time per age group for each intersection and trajectory, at the exception of trajectory 1.

Table 2-11. Turning time per age group for each intersection and trajectory.

Intersection	Trajectory	AGE	N	Mean	Std. Deviation
1	2	Young	25	6.45	1.11
		middle age	14	6.72	1.48
		Older	25	6.72	1.91
	3	Young	32	5.21	.77
		middle age	23	5.84	.96
		Older	15	4.95	1.09
	4	Young	7	4.76	1.12
		middle age	3	5.22	1.02
		Older	4	6	.95
2	2	Young	9	7.50	2.37
		middle age	5	7.62	.69
		Older	7	7.68	3.14
	3	Young	25	5.93	1.22
		middle age	11	6.31	1.43
		Older	19	6.32	2.14
	4	Young	34	6.27	1.32
		middle age	26	6.81	.92
		Older	17	6.88	4.13
3	2	Young	5	8.06	2.72
		middle age	1	7.94	
		Older	2	7.23	2.17
	3	Young	35	5.90	1.45
		middle age	32	6.18	1.53
		Older	16	5.75	.99
	4	Young	33	5.95	1.38
		middle age	6	6.08	.96
		Older	20	6.38	2.28
4	2	Young	30	6.01	1.61
		middle age	23	6.38	1.72
		Older	19	6.63	1.78
	3	Young	41	5.46	1.61
		middle age	23	5.34	.76
		Older	26	5.90	2.87
	4	Older	2	5.05	.36

Figure 2-37 below displays the Table 2-11 data. Across all of the intersection, there is no clear trend that can be attributed to age.

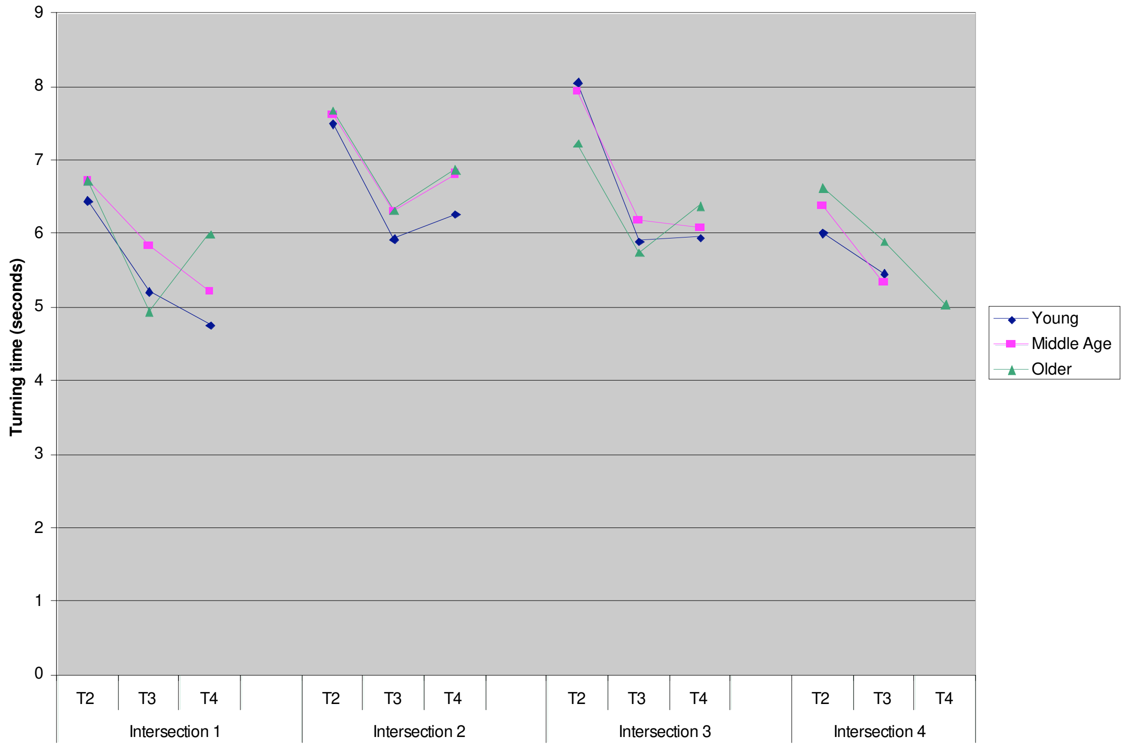


Figure 2-37. Turning time per age group for each intersection and trajectory.

2.4.4 Gap Acceptance

Evaluating a gap for turning relies on vision and precognitive process. One of the characteristic of this process is that it is a closed-loop[5] process (as described in [6]Czaja, 1997). In other words, as a driver is approaching an intersection and looking at the on-coming traffic, he/she can control his/her speed to a certain extent in order to adapt the gap. The results of this evaluation/adjustment lead to three major observable behaviors:

- the SV driver turns in front of an on-coming vehicle(s) without stopping or slowing down "more than necessary to complete the turn"
- the SV driver turns after an on-coming vehicle(s) clears the intersection, slowing down more than required for the turn but without stopping. A variant of this situation is when the SV driver slows down and is ready to wait and the POV turns right or left, the SV driver can then perform the turn.
- the SV driver stops in the intersection and turns after on-coming clears the intersection

We examined the data relative to these three behaviors and aimed at comparing the lag or gaps that were accepted, sorting lags or gaps that:

[5] We used the following definition from Czaja in Salvendy (1997): Closed loop system perform some process which requires continuous control and feedback information for error correction. Feedback mechanisms exist which provide continuous information regarding the difference between the actual and desired state of the system.

- generated a slow down (close POV)
- did not generate a slow down (Distant POV)
- generated a stop

We focused this analysis on the case of the SV driver approaching the intersection. The two first cases correspond to trajectory 1 situations. We focused the analysis on intersection 1 and 3. Although intersection 2 presents many cases, because of its geometry and the "sudden presence" of POV, we will analyze the result for this intersection as part of the data mining in CICAS.

Accepted lags and gaps when approaching an intersection

Intersections 1 and 3 combined present 70 cases of trajectory 1 (Intersection 1 = 26 cases and Intersection 3 = 44 cases). Out of these 70 cases:

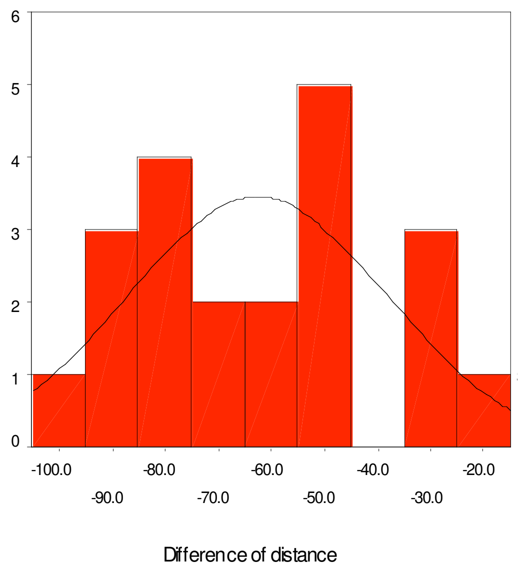
- 25 did not involve any distant POV but 4 of which involved one or more POV within the left turn pocket
- 22 were special cases and did not involve accepting a lag/gap with a distant POV. These cases were singled out because they presented one of the following characteristics:
  - In 15 cases, SV drivers slowed down to let POVs clear the intersection
  - The presence of a lead
  - The SV turned on red after a POV
  - The distant POV actually turns left or right, so a lag/gap that was initially rejected is accepted. (A variant of this case results when assessing whether or not a POV will stop for a red light.) For all of these cases, the driver was initially going to reject the gap, but then adapted their behavior to accept the gap (see example below with driver 21).
  - No POV present, but a pedestrian present on destination leg
- 21 cases of accepted lag with a distant POV
  - 12 did not involve any special conditions
  - 9 involved an initial clearance of the intersection by a close POV
- 2 cases where there is a POV in sight but for which the data is corrupted (no detection by the radar and poor data quality)

The table below presents the characteristics of the 21 cases of accepted lag. An initial separate treatment of the 12 and 9 cases showed that the characteristics were pretty similar for both sample of cases, so all cases are presented together.

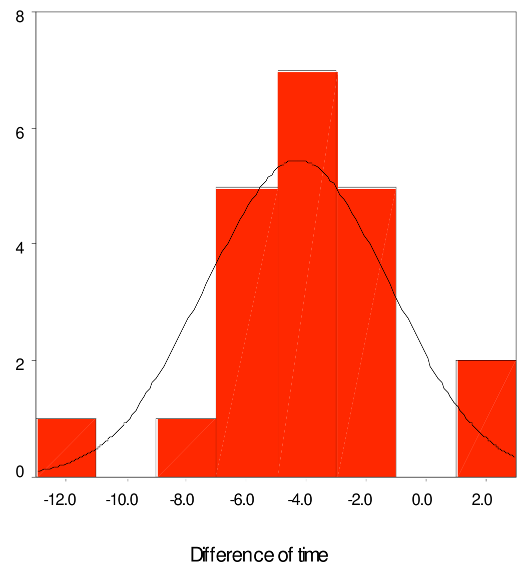
Table 2-12. Characteristics of accepted lag not generating a slow down.

Parameter	Minimum	Maximum	Mean	Std. Deviation
POV Distance to ZOC (meters)	49.00	113.00	85.61	18.09
POV time to ZOC (seconds)	4.30	16.00	8.04	2.74
SV Distance to ZOC	10.00	50.00	23.09	11.62
SV Time to ZOC	2.10	6.30	3.76	1.08
Lag in time	-12.30	1.40	-4.27	3.06
Lag in distance	-98.00	-20.00	-62.52	24.21

In Table 2-12 above, we provide the distance and time to ZOC for SV and POV when the lag was computed (as a reminder, when POV is sensed by the radar). A negative difference means that the SV would clear the zone of conflict before the POV; a positive difference means that the POV would clear the zone of conflict before the SV. The two last lines describe the lag in terms of time and distance. It is to be noted that although all of the lags in terms of distance are negative, 2 lags in time are positive. This is due to cases where the POV was very close to the intersection and in the process of accelerating. These cases illustrates that the lag, for situations where the SV is moving toward the intersection, is a very dynamic process. The two graphs below in Figure 2-38 illustrate that the distributions do not follow a normal distribution (note: the y axis represents the number of cases).



a)



b)

Figure 2-38. Distribution of difference of distance and time to ZOC between SV and POV for accepted lags.

In terms of lag in time, if using the mean and the standard deviation, it seems that the SV driver would complete the turn with a little over 1 second of spare time.

Rejected gaps when approaching an intersection resulting in a slow down

A total of 17 cases for which the SV driver slowed down more than required for the turn but did stop have been identified. Out of these 17 cases, 15 could be processed. Their characteristics are presented in Table 2-13.

Table 2-13. Characteristics of lag generating a slow down but not a stop.

Parameter	Minimum	Maximum	Mean	Std. Deviation
POV Distance to ZOC (meters)	18.00	82.00	54.93	20.83
POV time to ZOC (seconds)	2.80	8.50	5.20	1.55
SV Distance to ZOC	27.00	62.00	39.667	11.44
SV Time to ZOC	3.20	6.70	4.93	.96
Lag in time	-2.70	2.60	-.27	1.33
Lag in distance	-42.00	19.00	-15.26	18.75

Table 2-13 is very similar to Table 2-12. It is interesting to compare the mean time lag between this scenario and the preceding one. In this scenario, the mean lag time is very close to 0 and corresponds to situation where there was virtually no spare time. The distributions in time and distances are presented below.

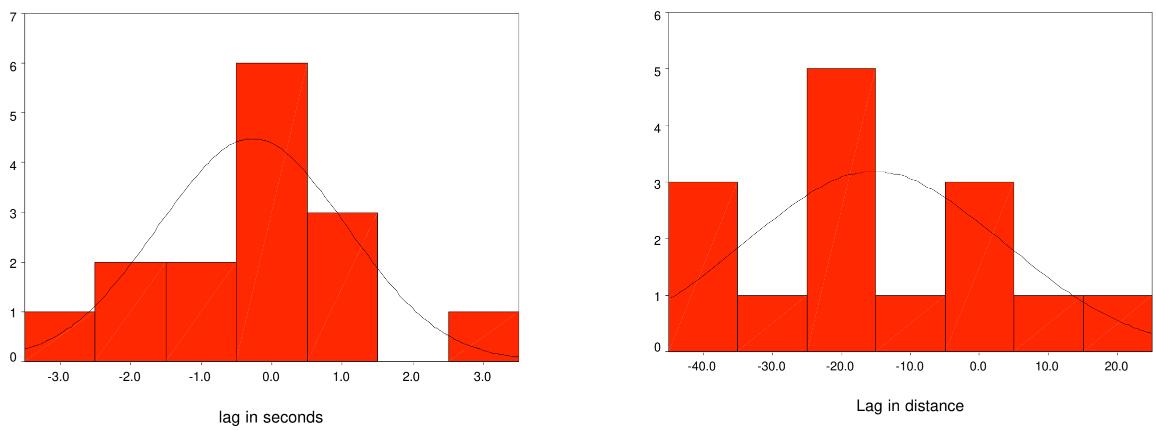


Figure 2-39. Distribution of difference of distance and time to ZOC between SV and POV for rejected lags.

Rejected gaps when approaching an intersection resulting in a stop

For Intersection 1 and 3 (Intersection 2 was excluded from the preliminary analysis because of its peculiar geometry and timing), we identified 74 cases (out of 460) where the SV driver stopped within the intersection box, out of these cases:

- 9 are considered gaps, i.e., a space between two POVs. Among these 9 cases, data are missing for 2 of them because the targets were in the right lane outside of the radar's field of view.
- 32 are lags, i.e., a space is between the SV and POV. Out of these cases, 10 were considered special cases, for reasons such as a traffic light change or the POV turning at the intersection.
- 2 were due to the presence of a lead
- 6 were caused by pedestrians crossing on the destination leg
- 25 were caused by platoons of waiting POVs, a situation that happens when the light turns green just as the SV driver reaches the intersection.

Table 2-14 below and 2-15 on the next page describe the characteristics of the rejected gap and lags in distance and time.

Table 2-14. Rejected gap characteristics.

Parameter	n	Minimum	Maximum	Mean	Std. Deviation
Gap between POVs (m)	7	18.00	72.00	40.28	22.64
Gap between POVs (sec)	7	2.40	5.00	3.80	1.03

In Table 2-14, the rejected mean gap time is 3.8 sec. In Table 2-15, the rejected mean lag is -.45 seconds (the SV would have cleared the ZOC a half second prior to the POV).

Table 2-15. Rejected lags characteristics.

Parameter	n	Minimum	Maximum	Mean	Std. Deviation
Lag (m)	32	-70.00	56.00	-24.81	23.65
Lag (sec)	32	-7.90	7.00	-.45	2.49

The difference lag and gap mean time can be explained by the added time for crossing after a POV. In the case of a lag, the driver can accelerate to cross in front of the on-coming POV, while in the case of a gap; the driver has to wait for the first POV to clear the ZOC before to enter the ZOC. A distribution of this time is presented in Figure 2-40 below, where the y axis is the number of cases.

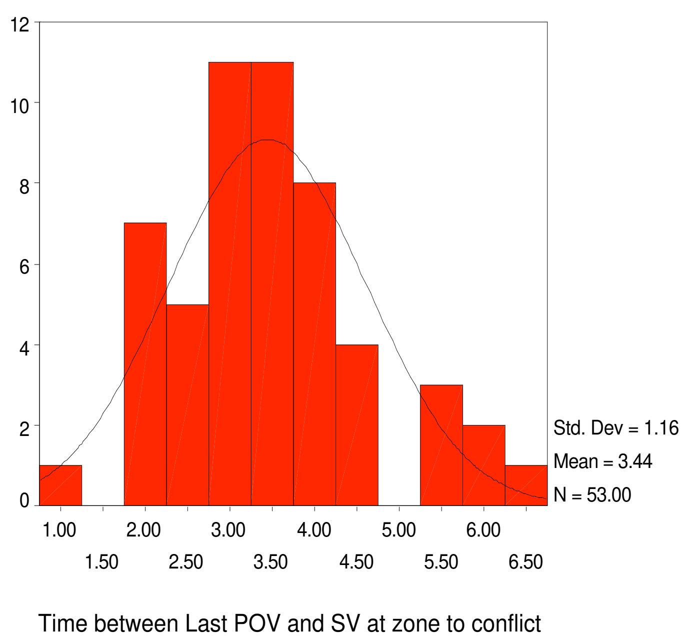


Figure 2-40. Distribution of time between last POV and SV at ZOC.

The mean time between last POV and SV at ZOC is 3.44 sec, which is very close to the mean of rejected gap of 3.8 sec. In short, for our analysis, we compare lag in terms of clearance of the on-coming POV path and gap with the time of clearance after the last POV.

Turning Decisions are based on more factors than the gap or lag size

The main point of this section is that gap and lags cannot be considered individually. In order to substantiate this point, we offer two related arguments. First, a comparison of the three different lags that we presented in the previous section, i.e:

- lag that led drivers to slow down more than necessary for turning
- lag that led drivers to stop at the intersection
- lag that did not affect the drivers course

Figure 2-41 illustrates the three different types of lags. A similar pattern can be identified for lags that led drivers to slow down more than necessary for turning or to stop at the intersection, while a different pattern can be seen for the accepted lag. The main difference between the two first types of lag is the context at the intersection. In some cases, a gap with a second POV was too short, other cases involved pedestrian or change of light.

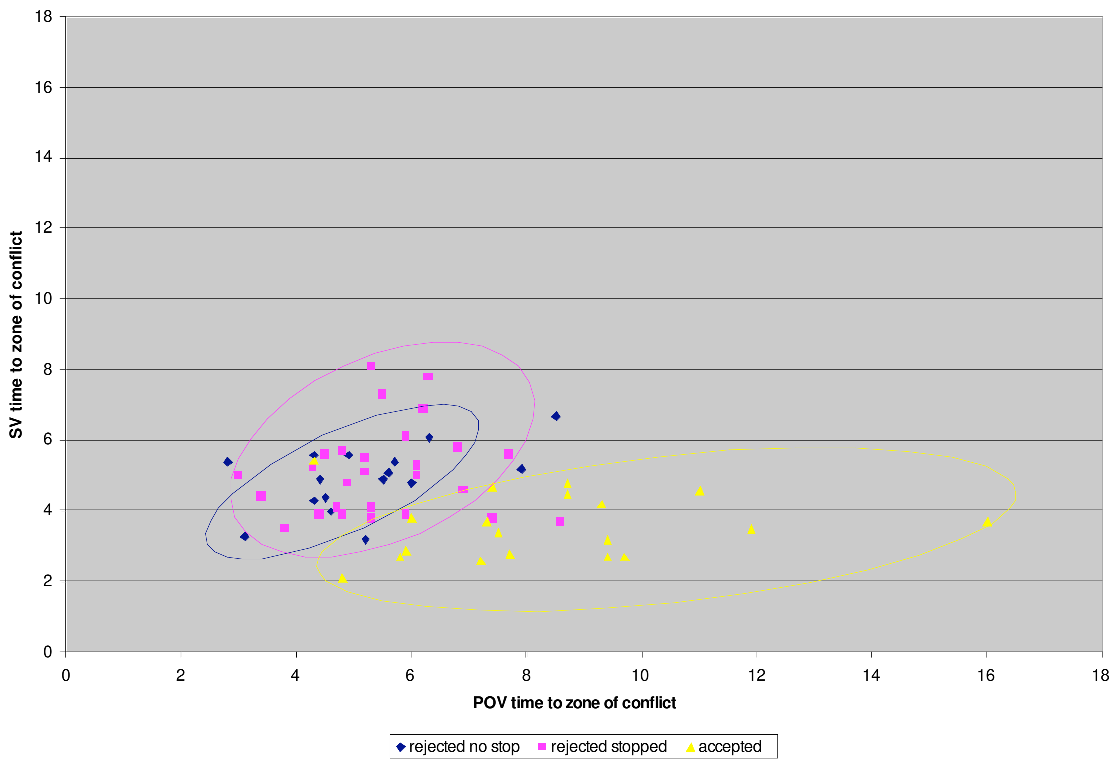


Figure 2-41. Lags leading driver to stop vs. lags leading drivers to slow down and vs. lags for which drivers turned.

Second, the effect of platoon clearing when the driver has been waiting at a red light. For these cases, drivers probably use a heuristic and do not look at each gap until the formed platoon is cleared. Figure 2-42 below illustrates this case. In this example, the light turned green when the SV driver was at 9.3 seconds from the intersection. A platoon of 15 POVs had formed during the red phase, and by the time the SV driver reaches the intersection, 5 POVs had cleared the intersection. The top left picture illustrates the gap between the POV in the intersection and the next POV. In the second picture, it is possible to see the line of vehicles and the gap sizes. Finally, the last picture illustrates that there is not technically a gap between the two last POVs because each of the vehicles is in a different lane.

Figure 2-42. Example of a platoon clearing the intersection.

The corresponding radar data is displayed in Figure 2-43 below for the distance to ZOC and Figure 2-44 for the time to ZOC.

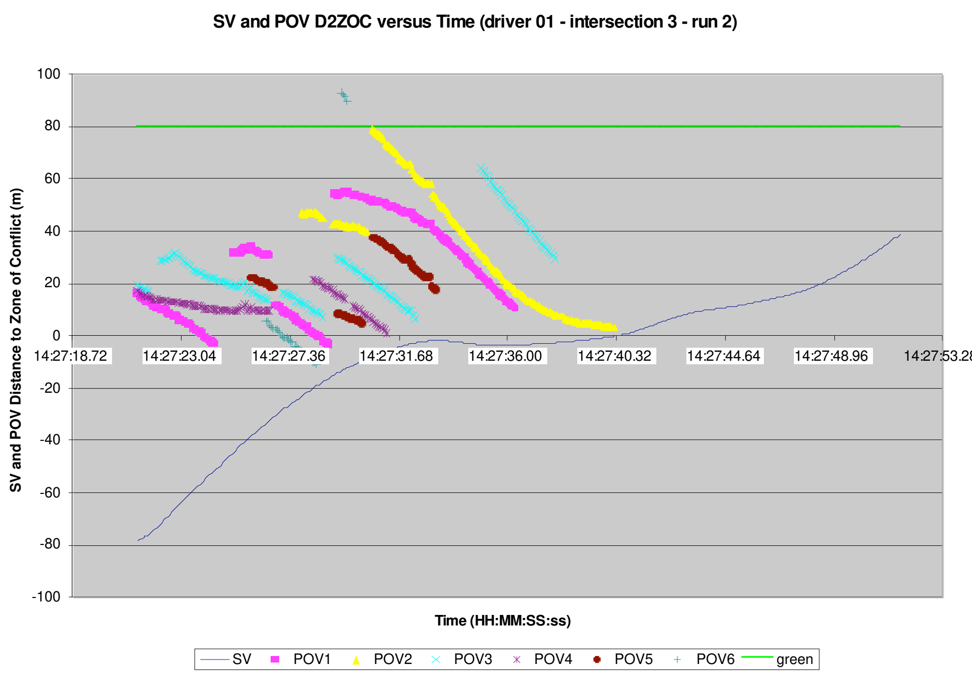


Figure 2-43. Example of a clearing platoon – SV and POV Distance to ZOC vs. time.

The graph above illustrates the POV distance to ZOC. All of the targets were not detected because all of the vehicles were so close to the others. However, it shows that the zone of conflict was busy with POV as SV approached the intersection and how short the gaps between the POV were. The graph below shows that most of the gaps are of approximately 2 seconds.

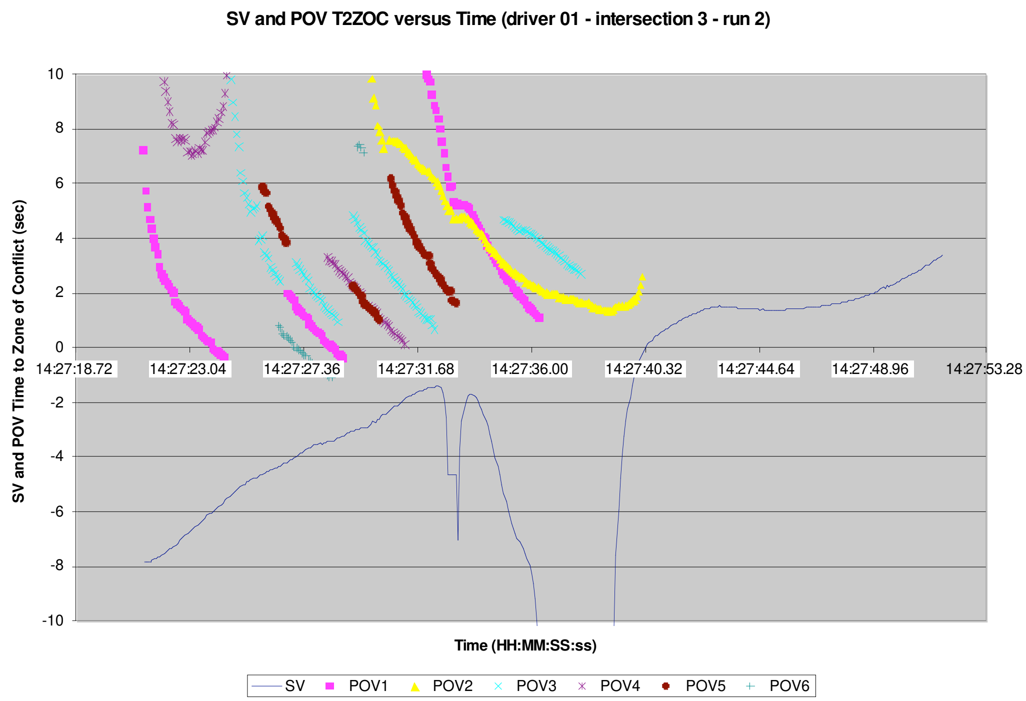


Figure 2-44. Example of a clearing platoon – SV and POV Time to ZOC vs. time.

Below is the list of characteristics/factors other than zone of conflict availability that we will investigate during the next round of data analysis and subsequent data collection:

- type of traffic light cycle. In our data collection, Intersection 1 had an earlier green, which affected the size of platoon that drivers were dealing with,
- time within the green phase that the drivers reaches the intersection – especially true for intersection 2, where there is a gap in traffic between University and Shattuck during the green, that driver 1 had identified after several run and led to finally a chance to reach the intersection between these two traffic flows.
- density of on-coming traffic (number of platoon and platoon size)
- investigate a new parameter, zone of conflict availability, as a potentially more generic measure than gap or lag acceptance rejection, where we would like into the time the ZOC is free prior to SV estimated arrival and the time it is free after SV estimated arrival.

2.5 Concluding Remarks

The concluding remarks address three topics: the conclusions that can be drawn from the field operation test, how to improve the data collection paradigm and finally what are the next steps in terms of analysis of this current set of data and other data collection to be carried on. The main points of this preliminary data analysis are as follows:

- Description of the approach for left turn:
    - The analysis of speed profile benefited from a categorization based on the presence of interference at the moment of the turn vs. no interference. This categorization allowed to reduce the range of speed observed. The cases when there is no interference can be used in order to compute a baseline speed for clearing the intersection without stopping.
    - The speed profile also supported the understanding of when the driver makes a decision about whether to stop at the intersection or not. A first comparison of speed profiles for cases where drivers did not stop and drivers stopped within the intersection shows that this decision can be taken as early as the entrance in the left turn lane. In order to reach this conclusion, we considered the time when we could observe the difference of pattern between the two types of behaviors. However, the speed profiles for situation with interferences show that the drivers is very adaptive to a change of situation and that based on the context, driver can change a course of action fairly fast.
- Age or gender did not seem to significantly affect the turning time or the location where the drivers choose to stop within the intersection. However, because the sample were not equilibrated (different number of drivers and different number of cases), this result is to be taken within this context.
- Gap and lag acceptance rejection should not be considered individually but in the context of the number of POV and the gap in-between the POVs. The data collected did not allow for gender or age investigation. Part of the values that were measured relies on projection of speed and on small cases, hence, this data collection allowed to understand the relation between variables, such as POV and SV time to zone of conflict, rather than find the "universal value" describing when gaps are accepted or rejected.

This data collection paradigm could benefit:

- From a different sensing method in order to identify the vehicles in the vicinity of the intersection. The radars' field of view was too narrow. Another issue with the radar is the loss of information as soon as the SV vehicle initiate the turn, which does not allow for i) comparison of estimated and actual lags and gaps, ii) the description of cases where the SV driver block the intersection because of pedestrians in the destination leg. Observations carried on at an instrumented intersection will yield more accurate measurement of lags and gaps.
- From a different protocol for obtaining more cases allowing a better investigation of the effect of age and or gender. The solution could be either to focus all of the observation a single intersection or move toward a less natural setting.

The next data collection steps that we suggest are:

- Relative to this data set:
    - Analysis of reason why driver turned. A list of reason includes:
        - no on-coming
        - gap with on-coming
        - light turn amber and no more on-coming
        - light turn amber and on-coming stops
        - light turn red and no more on-coming
        - light turn red and on-coming stopped

        - We will describe for the 920 cases the reason to turn in order to have a better representation of how often drivers where in the situation to accept or reject a gap in the data that were gathered.
    - The analysis of gap acceptance rejection for the situation where the SV driver stopped in the intersection or just prior the intersection
- In term of new data set, we suggest to run data collections in more controlled settings in order to investigate further drivers factors such as age and gender.

APPENDIX A

A.1 Radar Coverage At Each Intersection When the SV Was At The Stop Bar

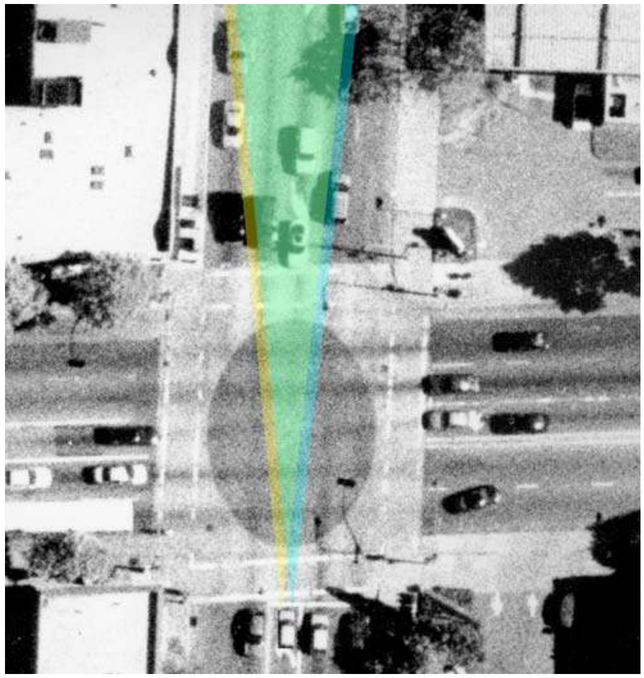


Figure A-1. SV radar coverage at intersection 1.

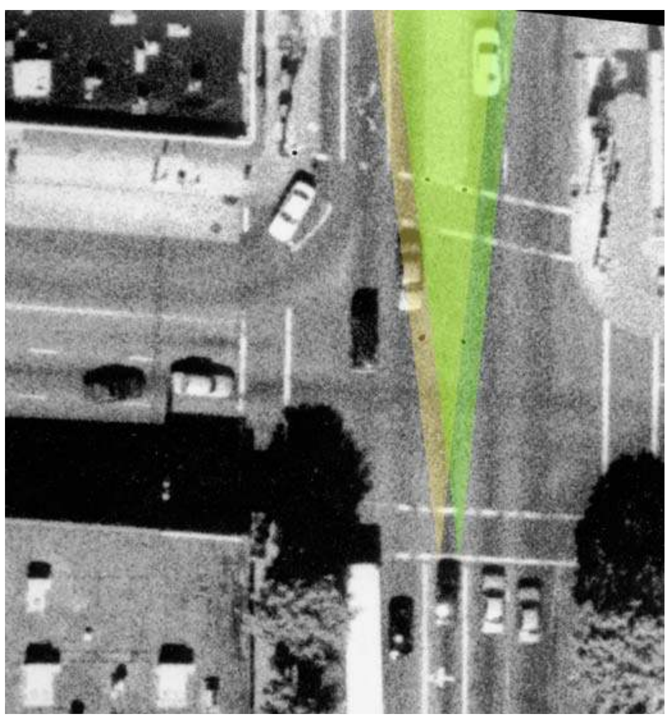


Figure A-2. SV radar coverage at intersection 2.

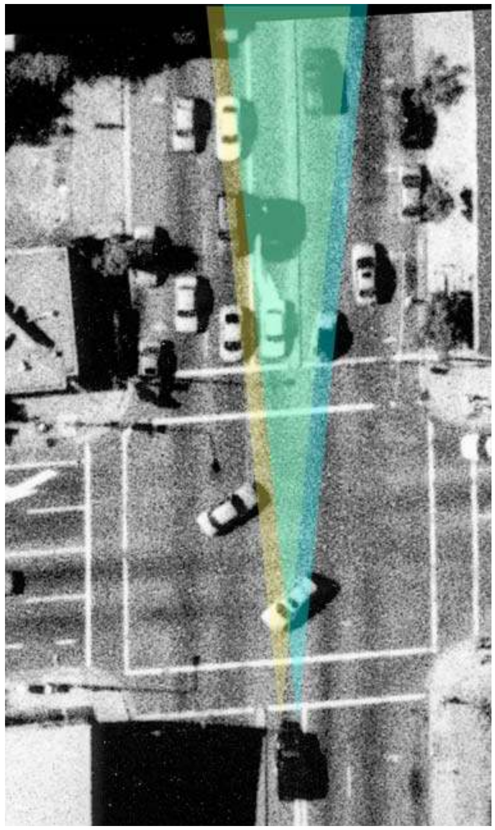


Figure A-3. SV radar coverage at intersection 3.

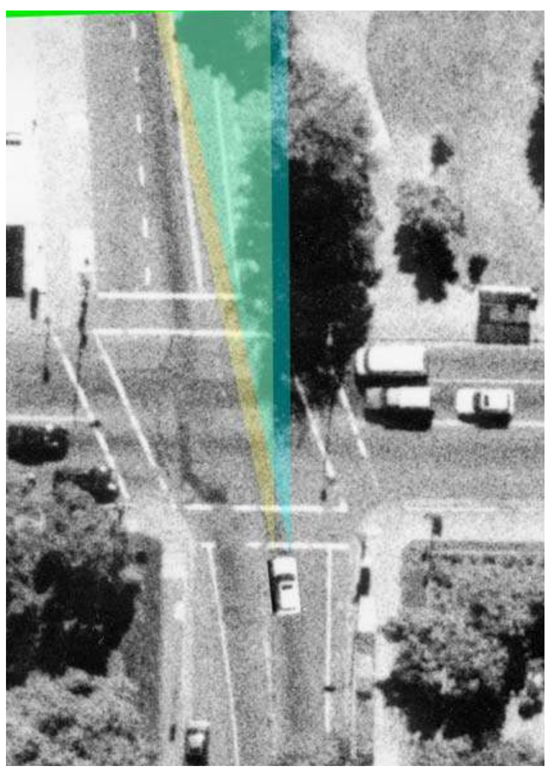


Figure A-4. SV radar coverage at intersection 4.

A.2 Driving Behavior Questionnaire

Driving Opinions

Do you think that urban/city driving can be difficult or problematic?

❑ Often Difficult ❑ Sometimes Difficult ❑ Not a Problem

What factors cause the most difficulty? *(Please check any that apply)*

❑ Intersections Complexity

❑ Other Drivers

❑ Pedestrians

❑ Other: ....

Estimate the speed of other vehicles is…

❑ Often Difficult ❑ Sometimes Difficult ❑ Not a Problem

What situations cause the most difficulty in speed estimation?

❑ Left Turn with Oncoming Traffic

❑ Left Turn with Lateral Traffic

❑ Right Turn

❑ Merging

❑ Overtaking

❑ Other: ....

Would you like to be contacted about participation in future driving-related studies organized at California PATH? *(Answering "Yes" in no way obligates you to participate in future studies.)*

❑ Yes ❑ No

Driver Vision and Health

Do you wear corrective lenses when you drive?

❑ Glasses ❑ Contacts ❑ None

If so, How long have you worn glasses/contacts? ....

Are you: *(Please check all that apply)*

❑ Myopic (Near sighted)
❑ Hyperopic (Far sighted)
❑ Astigmatic
❑ Presbyopic (Far sighed due to aging)
❑ Other: ....

Have you had corrective eye surgery (e.g., LASIK)?

If so, what procedure? ....

When? ....

Are you currently taking any medications? ❑ No ❑ Yes

If yes, please describe?

....

If yes, for how long? ....

Do any of the medications you are currently taking contain warnings against driving while on that medication?

❑ No ❑ Yes

3.0 DII ONSET EXPERIMENT

Written by Christopher Nowakowski

3.1 Research Questions

As part of the IDS project, several data collections were conducted for the purpose of better understanding left-turn maneuvers with on-coming vehicles. This report section describes the results of a study conducted at the Richmond Field Station instrumented intersection. In this study volunteer drivers were recruited to drive California PATH's instrumented vehicle on a closed test track with confederate on-coming vehicles. The purpose of the study was to explore the concept and design of an LTAP/OD DII, and furthermore, this study intended to address the following three research questions:

1. How do we measure or predict the available gap as vehicles approach the intersection?
2. What is considered an unsafe gap?
3. When should you give the warning to be effective in influencing the drivers' decisions?
4. How effective might the system be in reducing the number of unsafe turns?

In order to define what an unsafe gap is, we must first establish a method for describing and measuring gap. The term *gap* (either measured in distance or time) has most often been used in the literature to describe to the space between the rear bumper of one vehicle and the front bumper of the next. Thus, there could only be a gap in traffic between two oncoming vehicles. While this can be the case sometimes, it cannot be used to describe all possible cases experienced while driving. Occasionally, the term *lag* (again either in terms of time or distance) has been used in the literature to describe the space between the front bumper of the turning vehicle and the front bumper of an approaching vehicle. Finally, from an intersection-centric point of view, all vehicle movements might be described in terms of *t2i* (time to intersection) or *d2i* (distance to intersection).

Unfortunately, none of these terms adequately describe the situation where the SV is still approaching the intersection and making the initial decision about whether or not there will be time to turn in front of the POV. For example, if we were to describe the vehicle movements in terms of lag, the values and interpretation changes as the vehicles approach the intersection. A lag of 3 seconds where the SV is already at the intersection is entirely different than a lag of 3 seconds where both vehicles are still 1.5 seconds away from the intersection. To eliminate this problem, researchers at California PATH have introduced the concept of *trailing buffer*. The trailing buffer roughly equates to a measure of spare time, assuming that the SV would attempt to complete its turn in front of the POV. Given the very preliminary and conceptual nature of this study, trailing buffer was intended to be studied from the range of nobody would turn in front of the approaching traffic to everybody would turn.

The third research topic relates to the question of decision point. At some point during the SV's approach, the driver must decide whether there is time to turn or whether s/he must stop at the intersection and wait for the approaching traffic to clear. Any advice or alert given by a system should coincide with this decision making process. Warnings that come too late carry the risk of being ignored if the driver has already committed to the turn and does not have time to integrate the warning or change his or her behavior. Warnings that come too soon might be seen as a nuisance, especially if the driver initially disagrees with the system's assessment of the situation.

The preliminary results from the IDS field test (described in Section 2 of this report) examined the decision point issue by observing drivers making left turns in an urban environment setting. As shown in Figure 3-1 (data collected during the field test), the SV enters the left turn lane typically traveling between 20 and 30 mph (for a nominal speed limit of 25 mph). Based on the initial speed, it is impossible to tell whether that vehicle will turn without stopping or stop and then turn. However, around 20-25 meters from the stop bar, two clusters of speed trajectories become noticeable: those that intend to stop, and those that intend turn without stopping. This evidence suggested that the decision point lies in the range of 20-30 m from the stop bar. Further analysis of the field test data confirmed this finding, further suggesting that the decision point becomes distinguishable based on the vehicle trajectories around 17 meters from the stop bar. These results were used as the basis for the design of the DII onset experiment, which as detailed later, tested several warning onset points in the range described above.

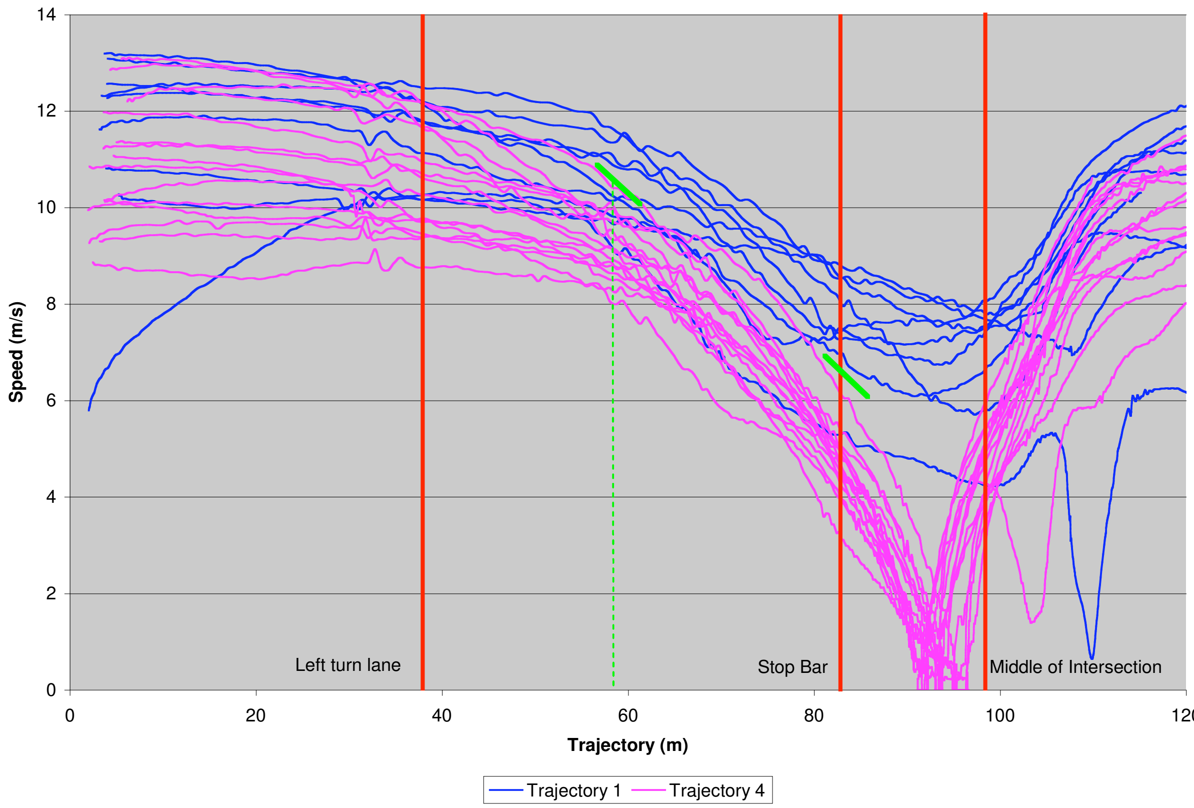


Figure 3-1. Intersection Approaches: Turned Without Stopping vs. Stopped Before Turn

3.2 Test Plan

3.2.1 Test Plan Overview

The goal of this experiment was to observe driver LTAP/OD behavior with the introduction of a conceptual infrastructure-based warning system. The warning system measured the speeds and distances of the vehicles approaching the intersection and provided an alert to the driver if it was deemed unsafe to make a left turn in front of the oncoming vehicle. During the experiment, the SV approached the intersection at approximately 20 mph with instructions to make an unprotected left turn at the intersection (i.e., the SV has a green light but legally must yield the right of way to oncoming traffic). The POV approached the intersection from the opposite direction at approximately 25 mph. The arrival of the vehicles (the available gap to turn in front of the POV), the warning criteria, and the timing of the warnings were varied in the experiment.

3.2.2 Test Participants

Twenty licensed drivers in two age groups, ten younger (20 to 38 years old, mean of 28.3) and ten older (65 to 84 years old, mean of 75.2), participated in this experiment. Within each age group, there were five men and five women drivers. Participants were recruited through email advertisements placed on various UC Berkeley student mailing lists and a "Resource Center on Aging" (see < http://ist-socrates.berkeley.edu/~aging/>) monthly newsletter. All subjects were paid a nominal $30 for their participation regardless of their performance in the experiment.

Based on the responses to a background questionnaire, the majority of the test participants regularly drove small to midsized sedans or wagons, such as the Toyota Corolla or Honda Accord. Ten percent of the participants drove small SUV's, such as the Honda Element or Suburu Forester, and twenty percent drove larger cars such as the Buick Century or VW Passat. As shown in Table 3-1, younger drivers reported driving less than 5000 miles per year more often than older driver, which most likely reflects the younger driver sample population being weighted towards urban university graduate students.

Table 3-1. Test participants' annual driving mileage.

ANNUAL MILEAGE	YOUNGER	OLDER
< 5000	40%	20%
5000 - 10,000	40%	40%
> 10,000	20%	40%

As shown in Table 3-2, most of the driving time for younger drivers was spent on freeways, with the rest of the time split between urban and suburban settings. Older drivers were more varied, spending most of their time in urban driving. Neither age group spent much time on rural roads. Overall, these results are not inconsistent with the mix of roads in the San Francisco Bay Area.

Table 3-2. Driving habits by driving environment.

	YOUNGER			OLDER		
	Female	Male	Mean	Female	Male	Mean
Freeways	52%	42%	47%	41%	21%	31%
Urban	20%	34%	27%	45%	45%	45%
Suburban	20%	18%	19%	9%	31%	21%
Rural	8%	8%	8%	4%	3%	3%

Tables 3-3 and 3-4 show the mix of day vs. night driving and familiar vs. unfamiliar destinations. Younger drivers reported slightly more night driving with a mean of 40 percent of their time spent behind the wheel at night, while the older drivers only averaged 30 percent. Similarly, younger drivers were also more apt to visit unfamiliar destinations, than were older drivers.

Table 3-3. Driving habits by time of day.

	YOUNGER			OLDER		
	Female	Male	Mean	Female	Male	Mean
Day	57%	63%	60%	61%	78%	69%
Night	43%	37%	40%	39%	22%	31%

Table 3-4. Driving habits by destination.

	YOUNGER			OLDER		
	Female	Male	Mean	Female	Male	Mean
Familiar	79%	59%	69%	81%	77%	79%
Unfamiliar	21%	41%	31%	19%	23%	21%

About 40 percent of older drivers and 70 percent of younger drivers reported that urban/city driving was “sometimes difficult.” Regarding the factors that cause the most difficulty in driving, 65 percent reported “other drivers,” 45 percent reported “intersection complexity,” and 35 percent reported “pedestrians.” Left turn across path with opposite direction traffic and freeway merging were most often reported as the most difficult driving maneuvers when it came to estimating vehicle speed.

3.2.3 Experiment Design

Overview

Three factors were manipulated in this experiment. The first factor manipulated was the arrival of the SV and POV to the intersection, which translates to time available for the SV to turn in front of the POV. Related to this, the second factor manipulated was the warning criteria, which translates to a trailing buffer used to trigger the warning. The third factor manipulated was the warning timing, the point during the SV’s approach to the intersection, at which, the warning was given. The mean SV approach speed was 20.7 mph ranging from 15 to 31 mph. The mean POV approach speed was 24.5 mph ranging from 21 to 29 mph.

Trailing Buffer (Spare Time)

The arrival of both the SV and POV were described using the concept of trailing buffer which was measured in seconds. This calculation roughly equates to a theoretical projection of how much spare time would remain if the SV made a typical turn in front of the POV. Thus for any given SV position, the predicted trailing buffer could be calculated by subtracting the predicted SV time to clear the intersection from the current POV *t2i*. In this calculation it is assumed that the POV will maintain its current speed. Likewise, the SV will maintain its current speed until it decelerates to a turning speed, then continue through the intersection at its turning speed. A regression of trials at the RFS intersection (see Appendix B.1) showed that the typical SV turning speed was 13.18 mph (5.89 m/s), and the typical deceleration rate was 0.16 g (1.61 m/s/s). Using this model, the predicted turning time for the RFS intersection (the time from SV d2i equals zero to the time the SV rear bumper clears the intersection) was 2.85 s.

In interpreting the trailing buffer, a positive value would indicate that the SV's rear bumper cleared the intersection before the arrival of the POV. For a nominal POV speed of 25 mph and a 10-meter wide intersection, a trailing buffer between -2 and 0 seconds would indicate a very close call or a potential collision. Trailing buffers less than about -3.5 seconds would indicate that the POV cleared the intersection before the SV even arrived at the intersection. For this experiment, three nominal target trailing buffers, -1.5, -0.5, and 0.5 seconds, were planned based on the results of pilot testing. However, trailing buffer could not be precisely controlled. Variations occurred due to the SV and POV driver reactions to the trial start signal, variations in their acceleration profile, etc. The actual predicted trailing buffers recorded during the experiment ranged from -4 to 4 seconds.

Warning Timing

There were four conditions relating to the warning timing used in the experiment. First, there was the possibility that no warning would be given on a particular trial. Otherwise, warnings were given at one of three SV distances to intersection stop bar (the outer crosswalk line): 16, 24, or 32 m. At an SV speed of 20 mph, these values roughly translated to 2, 3, and 4 seconds to the intersection stop bar. The decision of whether to warn the SV driver or not was made at the warning point and held for the remainder of the trial. Thus, if the SV driver passed the warning point and no warning was issued, the DII remained off, even if the SV slowed to let the POV pass. Likewise, if a warning was triggered at the warning point, the DII remained on, even if the SV accelerated and turned in front of the POV.

Summary

A total of 4 practice trials and 30 test conditions or intersection approaches were completed for each driver. Table 3-5 shows the number of trials for each combination of warning point and target trailing buffer. A warning was never shown when the trailing buffer value exceeded 1.0 seconds as this was almost universally considered a safe turning condition in pilot testing. Similarly, a warning was always shown when the predicted trailing buffer was less than -1.5 seconds.

Table 3-5. Number of trials for each test condition.

TRAILING BUFFER	WARNING POINT			
	16 m	24 m	32 m	No Warning
-1.5 s	3	3	3	0
-0.5 s	3	3	3	6
0.5 s	0	0	0	6

3.2.4 Test Materials and Equipment

<u>*Test Vehicles*</u>

The test participants drove the California PATH instrumented Ford Taurus sedan, model year 2000 (refer back to Figure 2.2), which was designated at the SV, or the vehicle making the left turn at the intersection. The POV was a white 1996 Buick LeSabre, driven by a confederate driver. As discussed in section 2.2, the Taurus was outfitted with a video recording system, a vehicle data recording system, and an off-head, video-based FaceLab eye tracking system (running software version 3). Additionally, for this experiment a laptop dedicated to intersection communication and experiment control was added. However, the only instrumentation visible to the driver were the two cameras mounted on the dashboard for the eye tracking system, and an in-vehicle display used only to alert the driver to the start of a trial.

The in-vehicle display used a 7" LCD display (Xenarc Model 700YV), mounted in the high center position as shown in Figure 3-2 in an attempt to approximate the position of a typical navigation system display. Although the display mimicked a working navigation display, it was merely provided as context. The real purpose of the display was simply to provide the driver with a trial start signal. All of the information displayed on the Taurus DVI was received via an 802.11b wireless link from the infrastructure.

Figure 3-2. In-vehicle display for experiment control and the driver's perspective.

Test Intersection

The experiment was run at the UC Berkeley, RFS Intelligent Intersection. This intersection is a typical four-leg intersection with one lane in each direction (no left or right turn lanes). The approach from the POV direction was approximately 1000 meters, while the approach from the SV direction was approximately 100 meters. Using a suite of in-pavement magnetic loops, 3M microloops, and EVT-300 radars, and 802.11b wireless links to the vehicles, a roadside PC-104 monitored the SV and POV speed, distance, and acceleration continuously during each trial. The roadside PC-104 then rebroadcast the information to the SV over the 802.11b wireless link. The traffic signal was kept in the green phase for the SV and POV throughout each trial.

DII

The DII used during the experiment was the “looming no-left turn sign” developed at California PATH. Figure 3-3 illustrates the three stages of the sign. When activated, the sign alternated between the low and high states at a rate of about 2 Hz. Within each half-second cycle, the low state was on for 200 ms and the high state was on for 300 ms. This produced a “looming” effect along the edges of the red circle to attract the attention of the SV driver and distinguish the dynamic nature of the sign from static versions. The DII was mounted on the left corner of the intersection just underneath the left side traffic signal, in the same location that a typical static, no-left-turn sign would be found.

Off Low High

Figure 3-3. The three stages of the DII.

3.2.5 Experimental Protocol

Test Activities and Sequencing

Upon the arrival of the test participant, s/he was greeted and asked to read and sign a consent form and fill out a background questionnaire (see Appendices B.2 through B.5). They were then seated in the instrumented Taurus and allowed to adjust the seat position, mirrors, and steering wheel to a comfortable position. The eye tracking system was calibrated for each driver, and the sequence of the experiment was explained step-by-step before beginning the practice trials (see Table 3-6). The experimenter sat in the rear passenger seat of the Taurus throughout the experiment.

The arrival of the vehicles at the intersection (and subsequent trailing buffer) was manipulated by adjusting the start time of the SV relative to the start time of the POV, both of which were controlled by the roadside PC/104 computer. The POV driver started each trial by sending a signal to the roadside computer, which in turn, started a countdown, sending a start signal to each driver at the appropriate time. To the SV driver, the start signal seemed to come at a random time between 10 and 15 seconds after the experimenter radioed that the SV was in position and ready. The trial was considered completed after the test participant completed the left turn.

Table 3-6. Typical trial sequence.

<table>
<tr><th>ACTIVITY SEQUENCE</th><th>DRIVER INSTRUCTION</th><th>IN-VEHICLE DISPLAY</th></tr>
<tr><td>1. Line up vehicles</td><td>The test participant parks the SV approximately 80 m from the intersection and waits for the start signal. (The POV parks 260 m from the intersection.)</td><td rowspan="4">
</td></tr>
<tr><td>2. Safety check</td><td>The experimenter radios that SV is in position and ready to start when the track is clear.</td></tr>
<tr><td>3. POV driver starts the trial</td><td>The POV driver initiates the start of the trial by sending a signal over the wireless to the roadside PC-104.</td></tr>
<tr><td>4. POV receives the start signal</td><td>The POV driver accelerates up to 25 mph towards the intersection.</td></tr>
<tr><td>5. SV receives the start signal</td><td>Upon hearing the phrase “Left Turn Ahead” given by the in-vehicle display, the test participant was instructed to accelerate to 20 mph, drive up to the intersection, and make a left turn.</td><td>

Audio: “Left Turn Ahead.”</td></tr>
<tr><td>5. SV receives the unsafe gap alert</td><td>At the designated warning point for the trial, the DII displayed a warning based on the trailing buffer.</td><td>(Same as Activity 5)</td></tr>
<tr><td>6. Trial completed</td><td>After the SV has made its left turn, the trial was completed, and the experiment asked probing questions about the trial.</td><td>(Same as Activities 1-4)</td></tr>
</table>

Practice Trials and Instructions to Drivers

The test participants were instructed to approach the intersection at 20 mph and make a left turn as they would normally. They were instructed to turn in front of the oncoming vehicle if they felt it was safe and appropriate, whether or not a warning was present. Warnings were to be treated as advice. The test participants were also discouraged from speeding up faster than 20 mph in order to beat the oncoming vehicle.

Four practice trials were given before the start of the test. The first two practice trials were given without the DII unsafe gap alert, simply to familiarize the drivers with the trial protocol, the intersection layout, and the handling of the Taurus. The second two practice trials added the concept of DII warnings. Both the warning and its meaning were described to the driver *a priori*, and thus, the drivers were not required to blindly interpret the meaning of the device.

Post-Trial Probing Questions

After each trial, the test participant was asked two probing questions by the experimenter.

1. Did you think there was enough time to turn in front of that car?

Responses were coded as follows:

   a. *Driver answered yes, and turned in front of the POV.*
   b. *Driver answered yes, but stopped to let the POV pass.*
   c. *Driver answered maybe, if s/he was in a hurry, but stopped to let the POV pass.*
   d. *Driver answered no, and stopped to let the POV pass.*

2. When the warning came, did you feel it was early, late…?

Responses were coded on a scale of 1-5 with 1 being too early, 5 too late, and 3 just right.

3.3 Results

3.3.1 Predicted Trailing Buffer

For each trial or intersection approach, there were two possible outcomes, the driver could turn in front of the oncoming vehicle or stop and wait for it to pass. If the driver chose to stop, an opinion was solicited as to whether the driver thought there was enough time to turn (after the fact). Figure 3-4 depicts these results broken down by half-second increments of predicted trailing buffer. Note, the trailing buffer in this graph represents a prediction made when the SV was 24 m or 3 seconds from the intersection stop bar. Thus, when the predicted trailing buffer was greater than 1.0 seconds, almost all drivers turned in front of the oncoming car. Conversely, when the predicted trailing buffer was less than -1.5 seconds, all drivers stopped to let the oncoming car pass. The 2.5-second range in between (from -1.5 to 1.0 second) shows that the percentage of turns increases proportionally with the predicted trailing buffer.

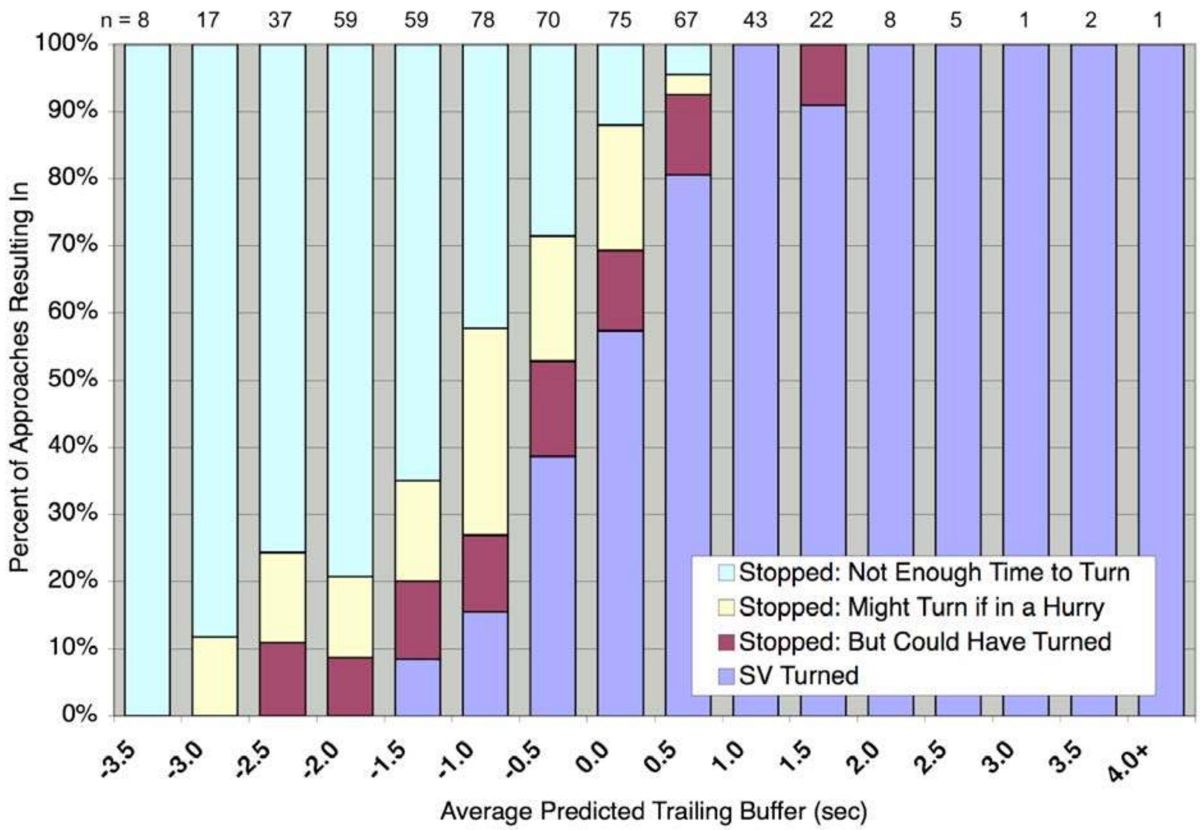


Figure 3-4. Decision to turn as a function of predicted trailing buffer.

It's also interesting to note that in the -1.5 to 1.0 second range, when the driver stopped to let the POV pass, about 10 percent of the time (regardless of the predicted trailing buffer), drivers felt they would have had time to safely turn. Similarly, an opinion of "might turn if in a hurry," although more variable, averaged near 20 percent and did not appear to consistently increase or decrease with the trailing buffer prediction.

As shown in Figures 3-5, the effect of age on the decision to turn was difficult to quantify. In the -1.5 to -1.0 second predicted trailing buffer range, the actual turning rate was similar for both age groups, between 5 and 7 percent, but 80 percent of the younger drivers commented that there was not enough time to turn versus only 35 percent of the older drivers, making older drivers appear to be potentially more aggressive. However, this trend reverses for the -1.0 to -0.5 second predicted trailing buffer range. In this condition, younger drivers appeared more aggressive, making the turn almost 30 percent of the time, compared to less than 5 percent for older drivers. As the predicted trailing buffer approached 0 seconds, the differences between younger and older drivers became negligible.

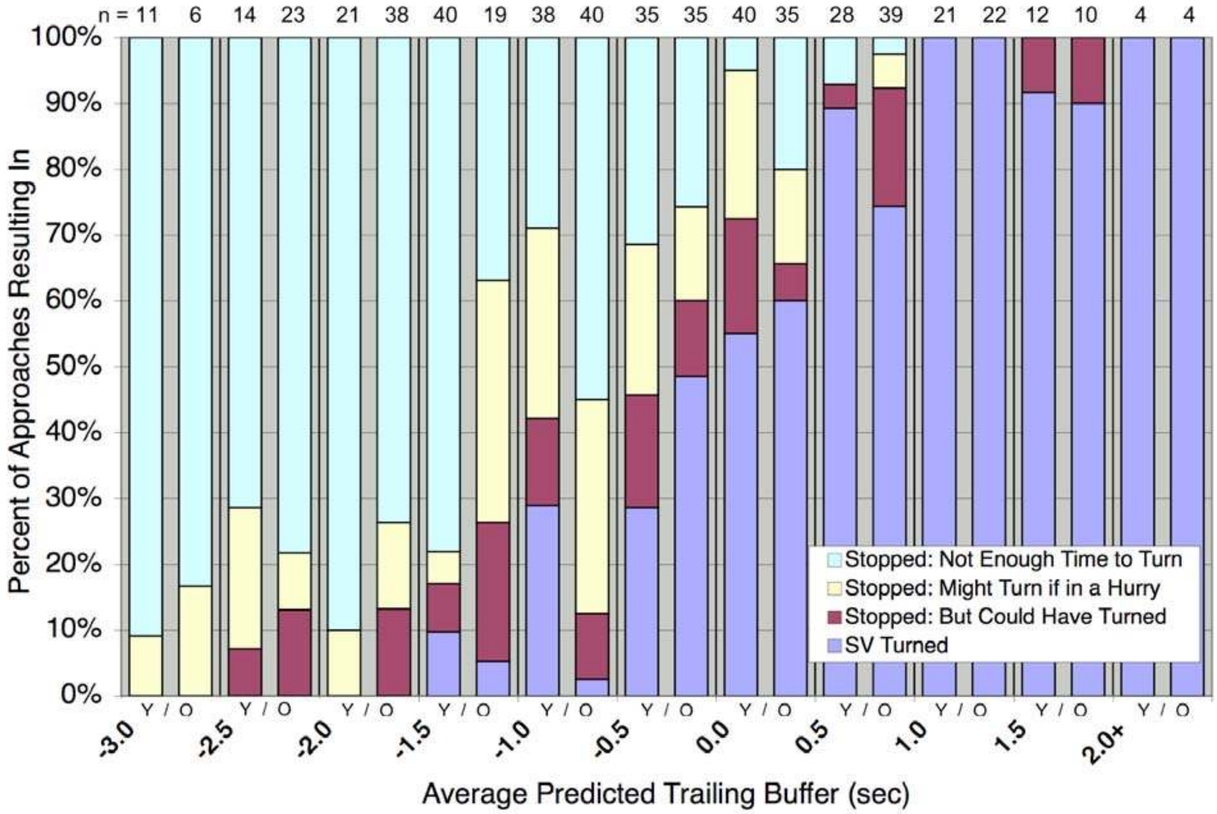


Figure 3-5. Comparing younger and older drivers' turning decisions.

The most troubling aspect of these results, comparing the turning rate to the predicted trailing buffer, is the fact that turns are made when the predicted trailing buffer was as low as -1.5 seconds. As a reminder, a predicted trailing buffer of 0 seconds would indicate that the SV would clear the intersection box just as the POV was entering the intersection box. Although this definition allows some slack, technically, a predicted trailing buffer greater than -0.5 seconds is a predicted collision between the SV and the POV, suggesting that our prediction should be shifted by about 1.5 seconds since there were no collisions during the experiment.

There are two possible behavioral explanations for this discrepancy. First, the SV drivers might deviate from our prediction model by attempting to beat the POV to the intersection. Since the model already accounts for the SV's initial speed, the only ways to "beat" the prediction algorithm would be to delay the braking point and/or enter the intersection at a faster speed. Although the analysis failed to show any differences in braking point, Figure 3-6 does show that the mean SV speed as it entered the intersection was slightly faster when the predicted trailing buffer was less than 1.0 seconds. The predicted trailing buffer algorithm used a value of 5.89 m/s for the SV turning speed, but the mean SV turning speed was as high as 6.48 m/s. As discussed in Appendix A, these variations in driver behavior might lead the model to overestimate the SV *t2i* by up to 0.7 seconds and to overestimate the required turning time by up to 0.25 seconds.

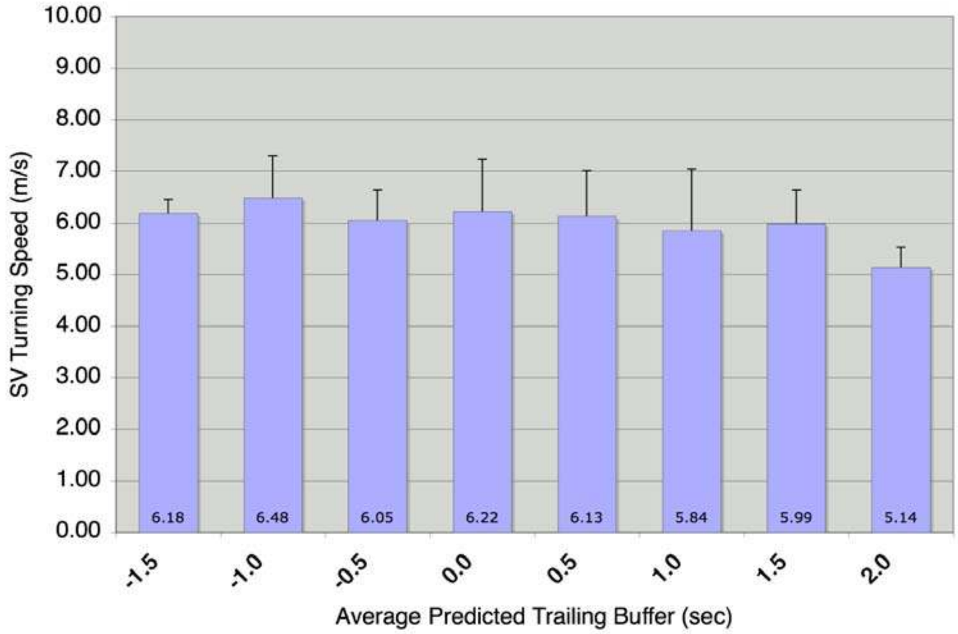


Figure 3-6. SV turning speed as a function of predicted trailing buffer.

A second behavioral possibility to explain the -1.5 second trailing buffer discrepancy might lie in the interaction between the SV and POV. If the SV driver was really making turns that might result in a very close call or collision as the model predicted, then the POV driver might naturally decelerate. The POV drivers were informally asked whether or not there were any close calls that required braking during the experiment, but none were reported. As shown in Figure X.3-7, the mean POV deceleration rate was higher when the predicted trailing buffer was less than -0.5 seconds. However, the largest mean POV deceleration rate was only 0.05 g, which might correspond to letting off the accelerator, but probably would not correspond to a braking event. Even over a 3 second SV turning time, a 0.05 g deceleration from an initial POV speed of 25 mph could account for a 0.3 second increase in the trailing buffer.

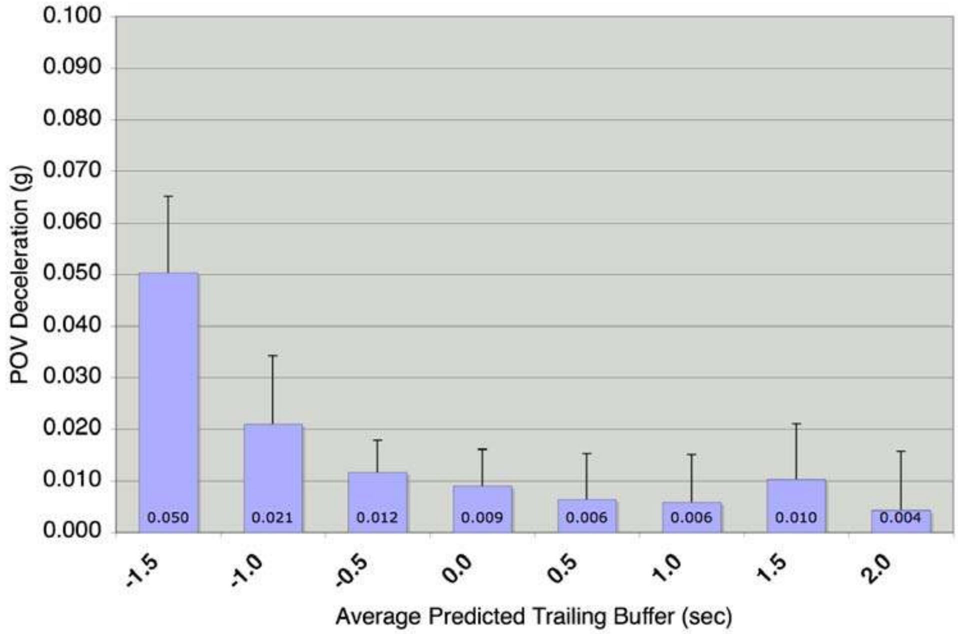


Figure 3-7. POV deceleration rate during the SV turning maneuver.

3.3.2 Warning Timing

It was theorized that the decision of whether to turn or to stop and wait for the approaching vehicle to pass occurred somewhere between 20 and 30 m from the stop bar for a typical 25 mph intersection approach. The values tested for the DII warning point were 16, 24, and 32 m from the stop bar. After each trial where a warning was shown, the drivers were asked to rate the timing on a scale of 1 to 5 with 1 being too early and 5 being too late. The mean ratings (and standard deviations) are summarized for each warning point in Table 3-7; however, the differences in mean ratings were not very large when compared to their standard deviations.

Table 3-7. Drivers' mean rating for each warning point.

WARNING POINT	MEAN RATING	YOUNG	OLDER
16 m	3.57 (0.81)	3.26	3.91
24 m	2.98 (0.78)	2.78	3.19
32 m	2.71 (0.76)	2.65	2.80

Figure 3-8 (on the next page) depicts the percentage of time each warning point was rated in each category, suggesting that, overall, drivers were fairly insensitive to the variations in warning point. All of the warning points tested were rated as "just right" between 45 and 60 percent of the time. However, the 16 m warning point was rated as late almost 50 percent of the time, while being rated early only than 5 percent of the time. Conversely, the 32 m warning point was rated as early at least 25 percent of the time, while being rated late less than 8 percent of the time. The middle warning point, 24 m, was equally rated as either too early or too late about 20 percent of the time.

Additionally, there was a pronounced age effect on the timing of the warning point. Overall, older drivers preferred the warning to be given earlier than younger drivers. The older drivers rated the latest warning point (16 m) as being late almost 65 percent of the time, as compared to younger drivers who rated this condition as being late only 38 percent of the time. Similarly for the earliest warning point (32 m), older drivers rated this condition as late 15 percent of the time while younger drivers never rated this condition as late. The comments from older drivers supported these findings as many of the older drivers suggested that earlier was always better. Even when rating a warning point as early, the older drivers often qualified their answer by saying that the warning was early, but still good, or early, but certainly not annoying.

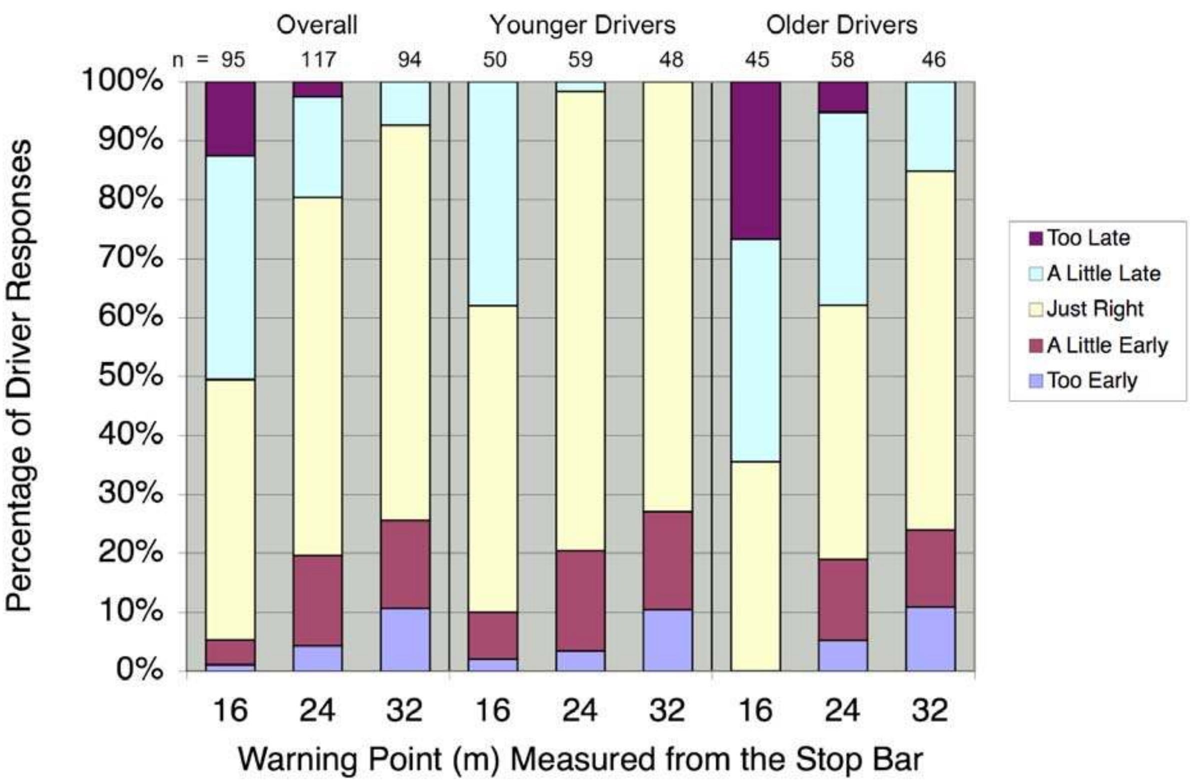


Figure 3-8. Percentage of driver responses by warning point.

The analysis of the driver ratings of various warning points provides a subjective evaluation of the warning timing. One possible objective measure would be a comparison of the warning point to the braking point. As shown in Table 3-8, a typical driver began braking 16.7 m from the stop bar when intending to turn in front of the oncoming vehicle with no warning was present. When the drivers intended to stop and let the oncoming vehicle pass, the mean braking point was slightly earlier, 19.4 m from the stop bar. Older drivers typically began braking earlier, 20.5 m from the stop bar, while younger drivers began braking later, 18.2 m from the stop bar.

The warning, and subsequently, the warning point, had little influence on the initial braking point. However, given that braking typically started before the 16 m warning point, this analysis would suggest that the 16 m warning came after the driver had already made a decision, and thus, came too late. The 24 m warning came about a half-second before the point of initial braking, suggesting that there was at least a chance for drivers to see and integrate this warning into their initial decision.

Table 3-8. Drivers' mean initial braking point.

Condition	Mean Braking Point in Meters from the Stop Bar (std. dev.)					
	Overall		Younger Drivers		Older Drivers	
No Warning / SV Turned	16.7	(5.4)	15.9	(6.1)	17.5	(4.5)
No Warning / SV Stopped	19.4	(5.0)	18.2	(5.5)	20.5	(4.3)
16 m Warning / SV Stopped	18.5	(5.0)	18.3	(4.0)	18.7	(5.8)
24 m Warning / SV Stopped	18.9	(4.7)	18.2	(4.3)	18.6	(4.9)
32 m Warning / SV Stopped	19.7	(5.0)	19.2	(4.0)	20.1	(5.8)

3.3.3 Driver Comments on the DII

General Comments

Overall, the driver reactions to the DII were positive. Only one driver, an older female, commented that the DII was initially a little distracting, but she also later commented that the she could probably get used to it. Other drivers positively commented that the sign was attention grabbing, well located, and not too invasive. Several drivers specifically commented on the appropriateness of the DII location, suggesting that even though the bulk of their attention was focused on the oncoming car throughout the encounter, the DII was still clearly within their field of view and easily noticed. One older male driver brought up a good counterpoint, noting that the DII became obscured by the vehicle's A-pillar once the intersection had been entered. However, he also noted that this was also a problem for many traffic control devices, including overhead traffic signals.

As part of the experiment, drivers were asked to treat the sign as advice and to feel free to violate the sign if they thought that there was enough time to safely or comfortably turn in front of the POV. Interesting, several drivers commented towards the beginning of the experiment that it seemed unnatural to violate the sign, comparing it to a traffic signal. There were also several noticeable cases where the driver appeared to change his or her decision to turn, shortly after the DII illuminated.

Perfect Warnings and Comfortable Gaps

Throughout the experiment, four trials were commented on as being the "perfect" scenario for a warning. Two of the trials used a warning point of 24 m (3 seconds) and two of the trials used a warning point of 32 m (4 seconds) from the intersection. The average predicted trailing buffer ranged between -1.2 to -0.4 seconds. The POV *d2i*, when the SV *d2i* was 32 m (at the earliest warning point), ranged between 66 and 74 m.

Conversely, two trials where the SV actually turned in front of the POV were commented on as being a scenario with a "comfortable gap." The average predicted trailing buffers for these two trials were 0.66 and 0.89 seconds. The POV *d2i's*, when the SV *d2i* was 32 m (at the earliest warning point), were 81.7 and 83.7 m for the two trials.

Aggressive Turns

Three trials where the SV driver turned in front of the POV were reported by the SV driver as being somewhat of an aggressive turn on their part. The average predicted trailing buffers for these trials ranged from -0.05 and -0.51 seconds, and the DII was not active for any of the trials. The POV *d2i*, when the SV *d2i* was 32 m (at the earliest warning point), ranged from 69.1 and 77.3 m. Interestingly, the predicted trailing buffer range for an aggressive turn overlaps slightly with the range for a perfect warning.

Decision Changes

Two trials were flagged by the experimenter as having a noticeable decision change. In these cases, it appeared as if the SV driver was going to attempt to turn in front of the POV, but then changed his or her mind. In one case the warning point was at 24 m (3 seconds), and in the other case the warning point was at 32 m (4 seconds) from the stop bar. In both cases, the DII was active. The average predicted trailing buffers for the two trials were -1.00 and -0.75 seconds, respectively. In both cases, the SV began braking much later than typically found throughout the study with the point of initial braking being observed at 12.0 and 8.3 m from the stop bar.

These types of decision change events might suggest some basis for creating a natural "last-possible-second" DII warning point. These two data points would seem to suggest that the 16 m (2 second *t2i*) could be effectively used as a warning point., even though it was generally considered late by drivers. Although the information would not be provided in enough time to integrate it into the driver's initial decision, the 16 m (2-second) warning point might be able to provide the driver with enough time to alter his or her initial decision and stop.

3.3.4 Warning Effectiveness

Although this experiment put drivers into a highly contrived situation where they were making the same left turn over and over again for about an hour, one measure of the system effectiveness was to compare the percentage of turns made for a given trailing buffer when no warning was present versus the percentage of turns made when a warning was present (see Figure 3-9). Comparing these conditions, there was a consistent reduction (averaging about 20 percent) in the percent of turns made in front of the oncoming POV when the DII was illuminated.

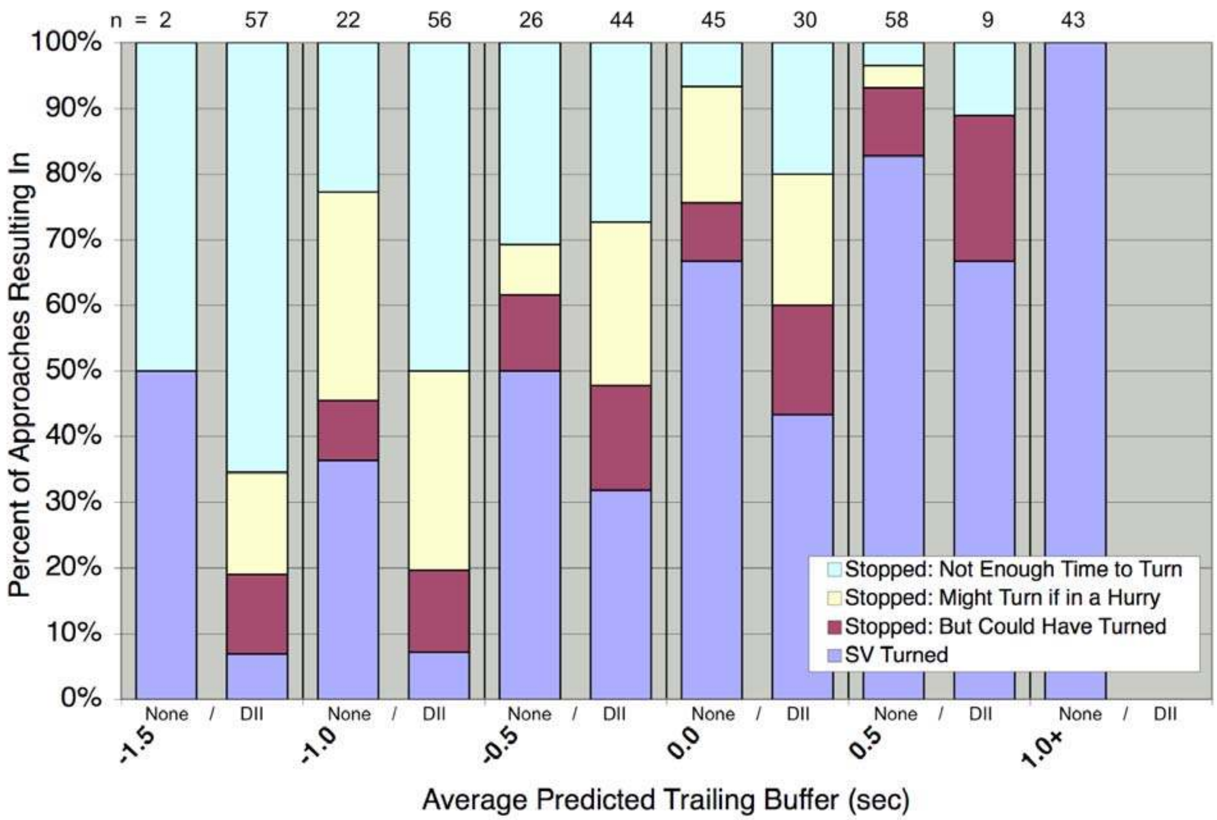


Figure 3-9. Decision to turn as a function of trailing buffer comparing DII to no warning.

The reduction in turning rate was most dramatic at the lowest levels of predicted trailing buffer (the closest calls). For trailing buffers between -1.0 and -0.5 seconds, the reduction in the percent of turns was almost 30 percent. Also interesting to note, in this same trailing buffer range, driver opinions also seemed to be influenced by the DII. The 30 percent reduction in the percent of turns made in front of the POV was accompanied by a 30 percent increase in the percent of time drivers rated the situation as "not enough time to turn."

3.4 Concluding Remarks

3.4.1 Trailing Buffer Prediction Model

The predicted trailing buffer model was based on the assumption that drivers are comparing an estimate of their own time needed to clear the intersection with an estimate of the oncoming vehicle's time to reach the intersection and padding that with some margin of safety. One glaring issue with the proposed trailing buffer model and the interpretation of these results is the fact that drivers made turns even though the predicted trailing buffer was less than zero (mathematically indicating a predicted collision). These results might be explained in two ways.

First, the margin of safety (trailing buffer) that drivers find to be acceptable might be overshadowed by normal driving variations or measurement errors. After all, the proposed trailing buffer measure is only a prediction being made 4 to 6 seconds before either vehicle even reaches the intersection. In reality, drivers may slow down, speed up, or otherwise fail to follow the predicted path, thus altering the potential outcome. When comparing the predicted the SV *t2i* from 4 seconds out, there was a standard deviation on the order of a half-second. Additionally, the POV, which had been instructed to maintain a constant speed, typically showed a deceleration while approaching the intersection. Although this deceleration was less than .02 g on average, this subtle effect (a behavior the POV drivers were not even conscious of) could still have accounted for another quarter-second of variation. However, if the safety margin (trailing buffer) was entirely within the noise, we would have expected to see a distribution of turns for predicted trailing buffers centered around zero. In this case, the turning distribution was weighted towards the negative end.

A second explanation might come from a bias in the trailing buffer prediction model. There are two potential model flaws or opportunities for improvement. First, the model uses the mean turning speed and a mean deceleration rate; however, using the mean might not be appropriate in this application as drivers can make small adjustments in order to beat the POV to the intersection, resulting in large variations between the predicted trailing buffer and the actual trailing buffer. One alternative that should be explored in future work is changing the predicted trailing buffer model to use an 85^{th} percentile turning speed and deceleration rate instead of the mean. Using an 85^{th} percentile instead of the mean might weight the model to better account for drivers trying to beat the POV to the intersection.

The second, and perhaps the largest, source of error in the predicted trailing buffer model is the "inside the box" turning behavior, which has yet to be fully characterized. The model currently assumes a centerline to centerline turning arc requiring the SV to travel 16.8 m beyond the stop bar in order to clear the intersection. Using the regressed turning speed of 5.89 m/s, the mean intersection turning and clearance time was calculated to be 2.85 seconds. Although attempts were made to try to measure and validate vehicle movements inside the intersection box, none of the sensors used were reliable or accurate enough to capture the behaviors of the drivers. However, casual analysis of the video suggests that drivers often attempted to decrease their turning time (thus increasing the trailing buffer) by cutting the corner. Cutting the corner might reduce the travel path by as much as 5 m, easily providing an additional second of trailing buffer. Additionally, the SV turning speed was not constant. While this probably had a negligible effect at the RFS intersection which is fairly small, larger intersections might require additional model parameters to compensate for the SV acceleration during the turn.

3.4.2 LTAP/OD Warning Algorithm: Warning Criteria and Timing

Two warning algorithm parameters were explored in this research: the warning criteria and the warning timing. The warning criteria refers to the SV and POV approach conditions which may constitute an unsafe turn (such as the vehicle speeds and distances which used to calculate a predicted trailing buffer). As discussed earlier, the proposed predicted trailing buffer model, as a situational description used to describe driver turning behavior, is not perfect. However, the data collected in this experiment did show a 2.5-second (trailing buffer) range between the point where no one would turn in front of the POV and the point where almost everyone would turn in front of the POV. Within this range, the percentage of turns made in front of the POV increased fairly linearly and in direct proportion with the predicted trailing buffer. However, neither the percentage of turns nor the driver ratings measured in this study really provide conclusive evidence towards selecting a single specific warning criteria.

One important lesson learned from this experiment is that drivers routinely make turns that might be considered as, or result in, close calls. This study was hoping to find that drivers had some target for a comfortable amount of "spare time" (trailing buffer), below which they would choose to stop and wait for the POV to clear. However, this study suggests that drivers are willing to make turns in situations with almost no "spare time" or at least less spare time than could be accurately measured with the experimental setup. Additionally, even for turns made with the smallest predicted trailing buffers, the largest deceleration (if any) seen from the oncoming car was on the order of 0.09 g, which most likely corresponds to letting off the accelerator. When informally probed, the POV drivers would typically comment that there were some aggressive turns made by the SV, but there was nothing out of the ordinary. Further research is needed to refine the trailing buffer model and to correlate the predicted trailing buffer with subjective measures of the SV driver aggressiveness or, more importantly, POV driver comfort.

The second warning algorithm parameter studied in this experiment was the warning timing. The warning timing refers to the point at which the SV driver should be given the no-left-turn warning. Warning that come too early risk being seen as annoying, and warnings that come too late risk being ignored or otherwise rendered ineffective as the drivers will not have time to integrate the information and act upon the warning. This study found that overall, drivers were relatively insensitive to the timing of the warning activation for the speed and ranges tested. A warning that came when the SV was 16 m (2 seconds) from the stop bar was rated as too late over 50 percent of the time, whereas a warning that came when the SV was 24 m (3 seconds) form the stop bar was rated equally as too early and too late 20 percent of the time, respectively. Additionally, older drivers tended to favor earlier warnings.

Looking at an objective measure, the 16 m (2-second) warning came after the start of a typical driver's initial braking point, suggesting that the warning came after the driver had made an initial decision. Alternatively, the 24 m (3-second) warning appeared to come about a half-second before the typical driver's initial braking point.

One limitation of this study in discussing the warning timing lies in the fact that only a single SV approach speed was tested (approximately 20 mph or 9 m/s), and it is not inconceivable that there could be an interaction between the preferred warning timing and the SV approach speed. However, it is also true that the SV approach is constrained by the turning speed. Even if the SV approaches the intersection at 45 mph (20 m/s), the vehicle will still need to decelerate to a turning speed near 13 mph (6 m/s), and the warning point might not shift dramatically either in time or distance to the intersection. Still, further research is needed to better understand how the SV approach speed affects the desired LTAP/OD warning timing.

3.4.3 LTAP/OD DII Effectiveness

Subjectively, the driver reactions to the DII were overall positive. Drivers often commented that the sign influenced their decisions, stating that they might have gone if the sign had not illuminated, but instead decided to stop and wait for the POV to pass once the DII illuminated. Objectively, there was a consistent reduction (averaging about 20 percent) in the percent of turns made in front of the oncoming POV when the DII was illuminated for almost all values of the predicted trailing buffer. Drivers were free to violate the warning in this study, and the reduction in the percent of turns made when the DII was illuminated was purely voluntary.

However, it should be noted that these results are based on a small sample size of less than 400 cases over only 20 drivers taken in a highly contrived experimental setting. The results gathered in this study on the LTAP/OD warning effectiveness might show that the concept is promising, but should not be used as surrogate for compliance rate or as a basis for further benefit analysis. Compliance in operation is likely to be much higher than 20 percent, and would best be determined in future field operational tests.

APPENDIX B

B.1 Predicted Trailing Buffer Model Overview and Validation

The concept of trailing buffer was used in this project to describe the arrivals of both the SV and POV to the intersection. The trailing buffer roughly equates to a theoretical projection of how much spare time would remain if the SV made a typical turn in front of the POV. Thus, the trailing buffer model contained two components calculated at the warning point: 1) an estimate of the SV intersection clearance time and 2) an estimate of the POV's *t2i* (time to intersection).

The latter component is the more simple to estimate. Since the POV is assumed to be going straight through the intersection, its *t2i* can be calculated based on its speed and distance measured at the warning point. The SV intersection clearance time was modeled using the sum of the three phases (t_1, t_2, and t_3) shown in Figure B-1.

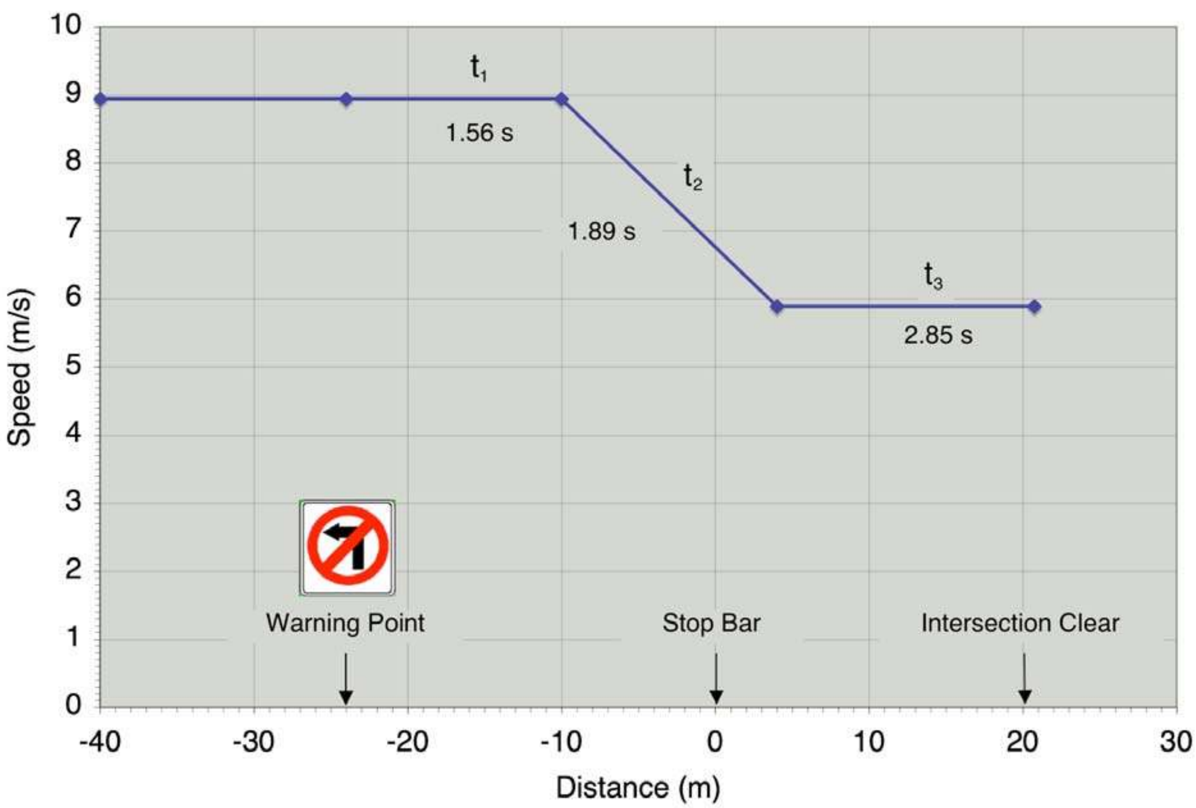


Figure B-1. Proposed model to calculate the SV intersection clearance time.

The SV intersection clearance model simply assumes that the SV will continue at its current speed (measured at the warning point) until it begins braking (at a constant average rate) to slow to a turning speed which is reached as the SV enters the intersection box. The turning speed is then maintained until the SV's rear bumper clears the intersection. In this model, the t_3 term becomes a constant based on the intersection geometry and the mean turning speed. The t_2 term is dependent on the initial SV speed, the mean braking rate, and the mean turning speed. Finally, the t_1 term can be computed using the initial SV speed and the braking point as computed in t_2.

Rearranging the simple kinematic laws of motion, the equations used to compute the SV clearance time were as follows:

$$\text{SV Clearance Time} = t_1 + t_2 + t_3$$
$$t_1 = (d_i - (v_i * t_2 - \tfrac{1}{2} * a_{sv} * t_2^2)) / v_i$$
$$t_2 = (v_i - v_{turn}) / a_{sv}$$
$$t_3 = (\tfrac{1}{4} * 2\pi * r_{intersection} + l_{vehicle}) / v_{turn}$$

Where:

v_i = The initial SV speed measured at the warning point (m/s)
d_i = The warning point *d2i* measured from the intersection box (m)
v_{turn} = The mean SV turning speed
a_{sv} = The mean SV deceleration rate
$r_{intersection}$ = The radius joining the center of the SV turn lane to the center of the destination lane (7.5 m for the RFS Intersection)
$l_{vehicle}$ = SV vehicle length (5 m for the Ford Taurus sedan used as the SV)

From the equations above, there were two unknowns: 1) the mean SV turning speed and 2) the mean SV deceleration rate. To determine these values, the trials at the RFS intersection where the SV turned in front of the POV without stopping were examined. From this regression, the typical SV turning speed was 13.18 mph (5.89 m/s) with a standard deviation of 2.28 mph (1.02 m/s), and the typical deceleration rate was 0.16 g (1.61 m/s/s) with a standard deviation of 0.06 g (0.56 m/s/s). Unfortunately, the model could only be validated for t_1 and t_2 (which when added together simply form the SV *t2i*) because the intersection sensing was unable to detect the SV once it entered the intersection box. Several sensors were placed to attempt sensing of the SV once it cleared the intersection box; however, none of these sensors provided reliable or trustworthy data.

As shown in Figure B-2, the first two terms of the SV clearance time prediction model (for a warning point of 24 m from the stop bar) were plotted against the actual SV t2i. The prediction model predicted *t2i*'s from 3.2 to 3.9 seconds, while the actual SV *t2i* ranged from 2.5 to over 6 seconds. Finding underestimation, where the actual *t2i* as greater than the predicted *t2i,* could be normal and expected, as this would indicate that the driver was more cautious, slowed down earlier, or entered the intersection at a slower speed. Some of these errors might also be random or due to sensor or measurement noise. Further examinations of the worst cases of underestimation, where the actual SV *t2i* was greater than 4 seconds, showed that the differences between predicted and actual were most likely due to measurement errors.

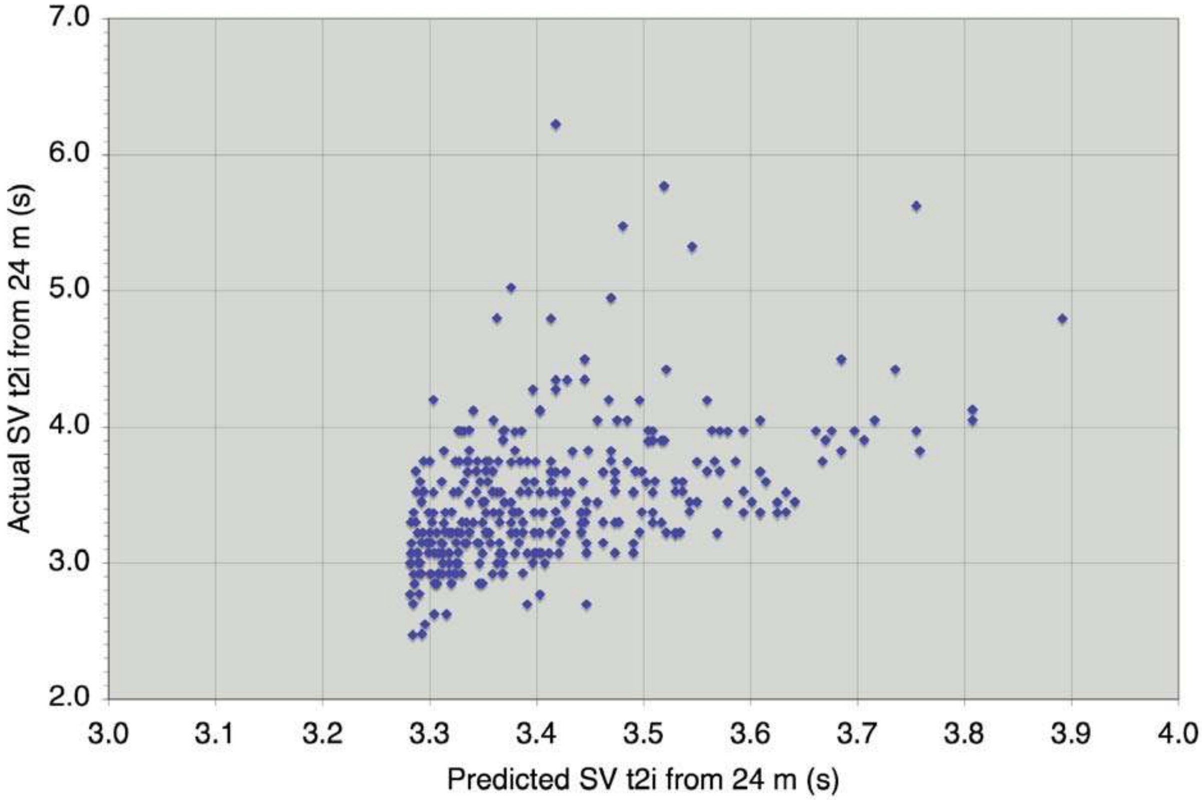


Figure B-2. Predicted SV *t2i* vs. actual SV *t2i.*

Conversely, finding overestimation, where the actual *t2i* was less than the predicted *t2i,* might suggest that the SV driver accelerated during the approach or entered the intersection at a faster than average speed. The worst cases of overestimation appeared to reflect this hypothesis; however, the magnitude of the maximum overestimation error in predicting the SV *t2i* was only on the order of 0.7 seconds.

Although there was no way to directly measure the actual trailing buffer, an attempt was made to estimate the actual trailing buffer to plot against the average predicted trailing buffer (see Figure B-3). The estimate of the actual trailing buffer was made by adding 2.85 seconds of estimated turning time to the point where the SV entered the intersection box to get the SV clearance point. The POV location and speed was then measured at this point. The correlation of the estimated actual trailing buffer and the average predicted trailing buffer is fairly strong and fairly close to 1:1. However, it is evident that trailing buffer predictions on the low end, between -1.0 and -1.5 seconds, were not so good.

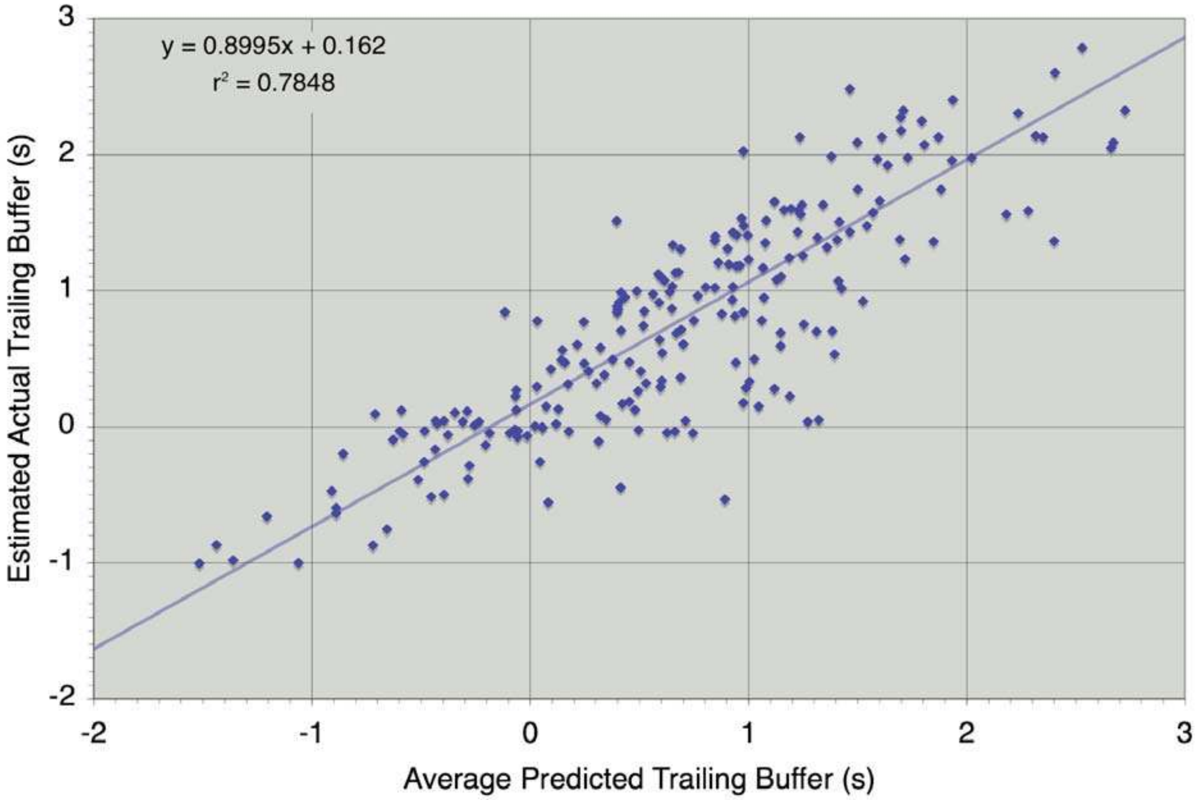


Figure B-3. POV deceleration rate during the SV turning maneuver.

B.2 Consent Form

Informed Consent for the Evaluation of a Gap Advice System

My name is Christopher Nowakowski. I am a researcher at the California PATH program, part of the University of California at Berkeley. I would appreciate your participation in my research study on driving behavior. The aim of this research is to observe driver's decision making behavior at intersections.

You will to come to my office at UC Berkeley's Richmond Field Station on a weekday between 9:00 a.m. and 12:00 a.m. or between 1:30 p.m. and 4:30 p.m. There we will show you the instrumented vehicle that you will use and describe the content of the test. This test will include a questionnaire on your driving practice and a test drive. You will be asked to drive through an intersection at the Richmond Field Station several times for a period of about 2 hours. During the entire driving test, video will be recorded. The cameras will be aimed at your face, front and rear traffic. If you are not allergic to latex, you will be asked to wear several dime-sized sticky markers on your forehead while driving in the experiment to improve the tracking accuracy of our eye-tracking equipment. If you agree to participate in the experiment, we will make an appointment for you to participate in the study.

If you agree to take part in the research, you must certify the following by signing this consent form:

1. You must provide a valid driver's license to show the experimenter.
2. Your driving record must be clear of any moving violations or DUI convictions for the past 3 years.
3. You must provide proof of insurance to the experimenter (as evidence of insurability).

All of the information that I obtain about you during the research will be kept confidential. I will not use your name or identifying information in any reports of my research. I will protect your identity and the information I collect from you to the full extent of the law (this does not include subpoena). Should you be involved in an accident while driving the study car, the videotapes taken may be subpoenaed as evidence. Liability and Physical Damage insurance for this vehicle will be provided by the University of California during your participation in the research.

After this project is completed, I may make the information collected during your participation available to other researchers or use the information in other research projects of my own. If so, I will continue to take the same precautions to preserve your identity from disclosure. Your identity will not be released to other researchers.

If you are injured as a result of taking part in this study, care will be available to you. The costs of this care may be covered by the University of California depending on a number of factors. If you have any questions about your rights or treatment as a participant in this research project, please contact the University of California at Berkeley's Committee for Protection of Human Subjects at 510/642-7461, subjects@uclink.berkeley.edu."

Your participation in this research is voluntary. You are free to refuse to take part, and you may stop taking part at any time. There is no direct benefit to you from the research. I hope that the research will benefit society by improving our knowledge about driver behavior and using this knowledge to improve the development of advanced transportation concepts and prototypes.

You will be paid a total of $30 for your participation in installments of $10 per hour of participation.

If you have any questions about the research, you may call me, Christopher Nowakowski, at (510) 231-5756.

I have read and understood this consent form. I agree to take part in the research.

______________________________ ____________
Signature Date

B.3 Driver Background Questionnaire

Driver Information

Age: .... Gender: ....

For how many years have you been regularly driving? ....

What is the type of vehicle you are currently driving?

Make: ....

Model: ....

Annual Mileage:

❑ Less than 5000 ❑ 5000 - 10,000 ❑ Greater than 10,000

What Percentage of your driving includes the following?

.... Freeways

.... Rural Highways

.... Suburban/Residential (Walnut Creek, Peninsula)

.... Urban/City (downtown Berkeley, Oakland, or San Francisco)

What percentage of your driving is done during the Day/Night?

.... Day

.... Night

What percentage of your driving is to Familiar/Unfamiliar destinations?

.... Familiar Destinations

.... Unfamiliar Destinations

B.4 Driver Opinions on Intersections Questionnaire

Driving Opinions

Do you think that urban/city driving can be difficult or problematic?

❑ Often Difficult ❑ Sometimes Difficult ❑ Not a Problem

What factors cause the most difficulty? *(Please check any that apply)*

❑ Intersections Complexity

❑ Other Drivers

❑ Pedestrians

❑ Other: ....

Estimate the speed of other vehicles is…

❑ Often Difficult ❑ Sometimes Difficult ❑ Not a Problem

What situations cause the most difficulty in speed estimation?

❑ Left Turn with Oncoming Traffic

❑ Left Turn with Lateral Traffic

❑ Right Turn

❑ Merging

❑ Overtaking

❑ Other: ....

Would you like to be contacted about participation in future driving-related studies organized at California PATH? *(Answering "Yes" in no way obligates you to participate in future studies.)*

❑ Yes ❑ No

B.5 Driver Health and Vision Questionnaire

Driver Vision and Health

Do you wear corrective lenses when you drive?

❑ Glasses ❑ Contacts ❑ None

If so, How long have you worn glasses/contacts? ....

Are you: *(Please check all that apply)*

❑ Myopic (Near sighted)
❑ Hyperopic (Far sighted)
❑ Astigmatic
❑ Presbyopic (Far sighed due to aging)
❑ Other: ....

Have you had corrective eye surgery (e.g., LASIK)?

If so, what procedure? ....

When? ....

Are you currently taking any medications? ❑ No ❑ Yes

If yes, please describe?

....

If yes, for how long? ....

Do any of the medications you are currently taking contain warnings against driving while on that medication?

❑ No ❑ Yes

4.0 SUMMARY AND CONCLUSIONS

4.1 How do drivers approach left-turn intersections?

The Berkeley instrumented-vehicle field test (section 2.0) was the only data collection that really examined the left-turn approach in detail from the SV driver's point of view. This study first broke intersection approaches into two categories based on the presence or absence of a lead vehicle, concluding that the presence of a lead vehicle more or less dictates the SV's approach. If there is no lead vehicle causing interference, then the SV approach yielded three interesting categories of behavior:

1. The SV turns without stopping, dropping to a minimum speed between 5 and 7 m/s.
2. The SV slows to let a POV clear, dropping to a minimum speed between 2 and 4 m/s.
3. The SV must stop prior to or within the intersection.

In some cases, a driver's intent to follow any of these trajectories might seem apparent from as far back as the moment their vehicle enters the turn lane (40 to 60 meters from the intersection stop bar). However, this study also concluded that the approach and turning decision are fluid and constantly being re-evaluated with an expectation of a change in conditions (e.g., the signal may change from green to amber). Drivers are, in essence, prepared to change their decision and stop at a moment's notice. Typical reaction time to an event such as a traffic signal change was observed to be fairly rapid, on the order of 0.4 seconds.

Furthermore, driver behavior is constrained by (and fast reaction times are aided by) vehicle dynamics. Typical approach speeds when entering the left-turn lane ranged from 9 to 13 m/s (20 to 30 mph), but the fastest typical turning speeds ranged from 5 to 7 m/s (11 to 15 mph). This means that during the left-turn approach, drivers are already on the brake, slowing the vehicle down. Any reaction that is needed to an unexpected event, a signal change, or an IDS countermeasure, is simply an adjustment of the brake pressure already being applied.

Similar observations were made during the RFS instrumented-intersection experiment (section 3), and the mean turning speed as the SV entered the intersection (when it turned without stopping) was within the same 5 and 7 m/s range that was found in the Berkeley instrumented-vehicle field test. In both studies it was very difficult to accurately predict from the SV approach whether the driver intended to stop and wait for the POV to pass or whether the driver intended to turn in front of the POV without stopping.

4.2 How long does it take drivers to traverse an intersection?

Both the roadside observations (described in previous IDS reports) and the Berkeley instrumented-vehicle study (section 2.0) investigated the question of SV turning time, and both studies concluded that the important factors dictating turning times included the intersection geometry, the SV approach behavior (turned without stopping or turned from a stop), and the presence of pedestrians.

The most accurate measures of SV turning time came from the roadside observation video analysis, which had a clear view of the SV as it both entered and exited the intersection. Thus, the turning time clock started when the SV was observed to start moving and ended when the SV's rear bumper was observed to clear the intersection. The mean turning times reported in this analysis varied from 2.6 to 4.4 seconds by intersection, with slightly faster turning times being associated with turning without stopping behavior (an overall mean of 2.5 s with a standard deviation of 0.5 s). The presence of pedestrians increased the overall mean turning time to 4.6 s and increased the standard deviation more than threefold (to 1.8 s).

The Berkeley instrumented-vehicle study also examined the turning time, with results ranging from 5.2 to 7.8 seconds; however, there were differences between studies due to the measurement techniques. The instrumented-vehicle study started the clock when the driver released the brake pedal (taking into account a reaction time not measured in the roadside observation) and ended when the crosswalk was visible in the rear-facing camera (which likely adds some extra distance to the turning time measurement). Nevertheless, the instrumented-vehicle study was able to conclude that neither age nor gender played a significant role in determining or predicting the turning time.

Although the RFS instrumented-intersection experiment (section 3.0) was unable to directly measure turning time, it was noted that typical driver behaviors, variations in turning speed or trajectory (such as cutting the corner) when making a left turn, had the potential to introduce quite a bit of error (on the order of 0.7 seconds) into the predicted outcome.

Overall, the implications for IDS are positive. First, any prediction or warning algorithm does not need to take an individual driver's age or gender into account, which is good news given the relative difficulty in obtaining this information. Second, any warning or prediction algorithm will need to be tuned to its particular intersection installation, since turning times vary so widely among intersections. Further research is recommended to develop the quantitative basis for that tuning, based on intersection characteristics.

4.3 What "gaps" in the oncoming traffic are typically accepted or rejected?

One of the primary, and perhaps the most difficult, questions tackled by each of the data collections was the question of "gap" acceptance. Unfortunately, it is difficult to directly compare results across the various studies due to differences in the definition, measurement, and computation or prediction of "gap." One initial problem in the definition of gap comes from the fact that there are two distinct cases: 1) where the SV has stopped in the intersection and is waiting for an appropriate gap and 2) where the SV is still approaching the intersection and making the decision to turn without stopping or to stop in the intersection. The latter case brings in the unique challenge of defining gap with a moving SV, where decisions are being made before the vehicle even reaches the intersection. One solution that has been proposed to standardize the definition and measurement of "gap" is the concept of "trailing buffer." The trailing buffer simply subtracts a prediction of the POV's arrival time from a prediction of the SV's time required to clear the intersection, resulting in a measure equating to the amount of spare time (should the SV decide to turn in front of the POV), which could be calculated at any given point in the approach. The prediction models would take into account both cases of stopped and moving SV.

The roadside observation study (described in a previous IDS report) explored the question of gap acceptance in two separate analyses. In the radar-based analysis, the POV distance and speed were measured as the SV crossed the point of conflict, and thus, only the accepted gaps were considered. Furthermore, the results don't consider individual vehicle cases or individual driver willingness to accept gaps smaller than those presented. Nevertheless, converting the results to the common measure of "trailing buffer," the study concluded that 20 percent of the LTAP-OD turns were made with predicted trailing buffers of less than 1 second, increasing steadily to at least 70 percent of the turns being made with predicted trailing buffers less than 5 seconds.

In the video-based analysis of the roadside observation study data, the POV time-to-intersection (T2I) was measured *post hoc* on the video and includes any speed adjustments made by the POV driver during the intersection approach. Both the accepted and rejected gaps were recorded; however, the results still don't consider individual vehicle cases or individual driver willingness to accept gaps smaller than those presented. For this analysis "gap" was defined as the POV T2I at the moment the SV began its turn. The distribution of gaps which occurred during these data collections could be described by a log-normal distribution with about 38 percent of the gaps being less than 3 seconds, 50 percent being greater than 3 seconds but less than 9 seconds, and the remainder being greater than 9 seconds. All gaps below 3 seconds were rejected by drivers and all gaps above 9 seconds were generally accepted by drivers; however, there were intersection effects, probably due to the actual intersection geometry and traffic conditions. The gaps corresponding to overall gap acceptance rates of 15^{th}, 50^{th}, and 85^{th} percentile were 4.2, 6.3, and 9.6 seconds. Converting these results to trailing buffer (by subtracting a mean turning time of 3.3 seconds), the trailing buffers corresponding to overall gap acceptance rates of 15^{th}, 50^{th}, and 85^{th} percentile would be 0.9, 3.0, and 6.3 seconds.

While the roadside observations were insensitive to the SV approach, the Berkeley instrumented-vehicle field test (section 2.0) examined both accepted and rejected gaps for drivers approaching an intersection, based on whether the gap was accepted and the driver turned without stopping or whether the gap was rejected and the driver slowed or stopped. Estimates of the POV speed and distance were provided by the instrumented SV's forward looking radar. Although the driver population was more homogenous in this study, the sample size was very small and limited to only those gaps in traffic randomly presented during the test. The mean accepted trailing buffer resulting in a turn without a stop was 4.3 seconds (± 3 s), and the mean rejected trailing buffer resulting in a stop was 0.5 seconds (± 2.5 s), showing considerable overlap between the ranges of accepted and rejected gaps.

The RFS instrumented-intersection experiment (section 3.0) examined both accepted and rejected gaps on an individual basis, presenting each driver with a series of gaps spanning from always rejected to always accepted. However, the study was conducted on a closed test track, without pedestrian traffic, with only one approaching POV, and with a permanently green signal for the SV and POV. These almost ideal and artificial conditions presented to the SV probably account for the fact that results showed a much narrower range, on the order of only 3 seconds of predicted trailing buffer, between gaps with 0 percent acceptance and gaps with 100 percent acceptance. The experimental conditions (as well as on-going questions about how exactly to compute "trailing buffer") also probably account for the fact that, overall, drivers were fairly aggressive in the study, finding a more than 50 percent turn rate when the predicted trailing buffer was just under a half-second, increasing to a 100 percent turn rate when the predicted trailing buffer was over 2 seconds.

4.4 When are decisions being made by the SV driver?

Both the Berkeley instrumented-vehicle field test (section 2.0) and the RFS instrumented-intersection experiment (section 3.0) examined the question of decision point. In the context of an IDS system, the decision point is one of the most critical elements as it directly dictates the timing or onset of any warning. In the field test, the concept of decision point was examined by contrasting the SV approach curves for cases where the SV turns without stopping and cases where the SV driver decides to stop for an approaching POV. In comparing these two conditions it was possible to discriminate between the two behaviors beginning approximately 17 m (or 2 seconds) from the stop bar. Given that a difference in the vehicle approach was already detectable at 2 seconds from the stop bar, it was expected that the decision to stop had already been made at least a half-second prior to then.

The RFS study further built upon these findings and experimentally tested DII warning onsets at 2, 3, and 4 seconds from the stop bar. Overall, the study surprisingly found that drivers were more or less insensitive to the warning point, which probably relates to the earlier conclusions regarding the fluidity of the decision point. The optimal warning point for all drivers was found to be around 3 seconds before the stop bar. There was also a slight age bias as older drivers didn't mind the warning being earlier and younger drivers didn't mind the warning being later.

4.5 Can a conflict between the turning SV and POV be accurately predicted and warned?

Overall, drivers in the RFS instrumented-intersection experiment (section 3.0) were relatively receptive to the concept of a LTAP-OD DII, and the presence of a DII reduced the turn rate by an average of 20 percentage points (being more effective as the predicted trailing buffer decreased and less effective as the predicted trailing buffer increased). However, there are at least three issues which require further research before the implementation of any field operational test could be considered.

First, there are still significant questions regarding how, exactly, the trailing buffer should be calculated. While the trailing buffer measure appears to be correlated with turning rate, the formulas used to predict SV and POV arrival times still need some fine tuning because this research has shown that warnings must be given 2 to 3 seconds before SV even arrives at the intersection. Thus, questions arise such as whether the predictions about the SV movements and turning time be based on mean speeds or on the 85^{th} percentile speeds, where the later policy might reflect more aggressive driver behavior. Furthermore, there are questions regarding the tolerance of errors or variability. A 4-second intersection approach can easily result in a half-second of variability (standard deviation) simply based on driver behavior. Crossing the intersection (turning times) also resulted in at least a half-second of variability on the low end, suggesting that any algorithm may start off with errors on the order of 1 second simply due to the variability in driver behavior before measurement errors are even accounted for.

Second, the question still remains about how to select the warning criteria. All of the studies in this section found overlapping ranges of accepted and rejected gaps. Although the gap acceptance rate increases as the trailing buffer increases, there was no natural cut-off point or obvious policy on which to base the warning criteria. Fortunately, drivers tended to agree with the DII alert more as the warning criteria was set at lower trailing buffers. In effect, the presence of the DII not only deterred drivers from making a turn, but it also influenced their opinion as to what constituted an unsafe condition.

Third and finally, the roadside observation studies showed that there were significant differences among intersections in parameters such as turning time, traffic volumes and available gaps, and approach speeds. Fortunately, although driver behavior varied widely, it was found to be somewhat linked to vehicle dynamics, and some variables such as the posted speed limit will have little effect. Even with increased speed on the approach, vehicle movements will still be related to the maximum turning speeds, which are governed by the intersection geometry. Still, these differences suggest that any LTAP-OD alert algorithm will need to be fine-tuned to its intersection, and more research is needed to develop the quantitative data to provide the foundation for defining handbook guidelines for the alert parameters.

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