# California Intersection Decision Support: A Systems Approach to Achieve Nationally Interoperable Solutions

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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

### **Task Order 4403 Final Report**

### California Intersection Decision Support: A Systems Approach to Achieve Nationally Interoperable Solutions

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#### I. Abstract

The overall IDS research plan was constructed to realize, in slightly more than three years, the requirements, tradeoffs assessment, and technology investigations necessary to define an IDS. Toward the end of the project we will combine our understanding of the problem definition, IDS technologies and our integration experience with a standard Caltrans intersection (with advanced controller) and design a deployable IDS demonstration that can be field tested.

**Key Words:** Intersection safety, LTAP/OD, cooperative systems, active safety, crossing path crashes, Infrastructure Consortium

#### **II. Executive Summary**

The Intersection Decision Support (IDS) project addresses the application of infrastructure-based and infrastructure-vehicle cooperative systems to address intersection safety. The Infrastructure Consortium (IC) comprises the US Department of Transportation (DOT), California DOT (Caltrans), Minnesota DOT, and Virginia DOT.

In defining this "best" IDS, we recognize that several potential dimensions are important. These dimensions include: (i) multiple views on the size of problem (be it by crash frequency, severity or fatality); (ii) grouping of cognitive or engineering causal factors, (iii) solution approaches can be addressed by certain technologies, and finally (iv) what can be cost-effectively deployed, in the near-term and also in the far-term. Our overall work plan addresses these tradeoffs, and in the end, we will arrive at a definition of a nationally interoperable IDS solution and an appropriate FOT.

To satisfy these dimensions, the project's mission is 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. We also investigate the use and usability of roadside-mounted dynamic message signs.

The effort reported here specifically addresses the common crash scenario in which a driver makes a left turn across the path of a vehicle approaching from the opposite direction (i.e., "Left Turn Across Path/ Opposing Direction" or LTAP/OD crash scenario). LTAP/OD crashes account for 27.3 % of all US intersection-related crashes, according to National Accident Sampling System<sup>1</sup> (2000) and Smith and Najim (2002), and two-thirds of all LTAP/OD crashes occur at signalized intersections. Before designing an IDS infrastructure system, the reasons for such crashes were considered including:

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- 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"), and
- obstruction of the driver's view by an opposing vehicle.

As an up-front exercise, we examined the GES and other data sources<sup>2, 3, 5, 7</sup> further to develop a taxonomy of crossing path crashes and to develop a profile of precrash scenarios and causal factors that contribute to such crashes, preparing the groundwork for engineering approaches in preventing crossing path collisions. The current study builds on and extends prior work by using data from the year 2000 GES to provide a profile and discussion of:

- crossing path crashes by junction type (i.e., non junction, intersection junction, or non-intersection junction);
- crossing path and other crashes at intersections by vehicle-level traffic-control configuration;
- crossing path and other crashes by speed limit;
- crossing path and other crashes by age and gender.

Findings and, in **bold**, implications for IDS:

1. Junctions are High-Risk Sites for Crashes

Crashes at junctions overall (defined as the connection of two roadways) represent about 60 percent of U.S. crashes, and most of these (or about 44% of all crashes) occur at intersections (a specific type of junction). Because junctions (and intersections in particular) represent a very small proportion of all streets and highways, they carry a much higher risk for crashes than other types of street or highway segments. Therefore, safety enhancements at such sites would be an efficient investment. Specifically, **IDS** 

countermeasures designed to prevent crashes at junctions in general, and intersections in particular, could efficiently address a significant share of all traffic crashes.

2. Crossing Path Crashes are a Significant Problem

Crossing path crashes represent 25 percent of all U.S. crashes. Types of crossing path crashes include:

- straight crossing path crashes (SCP) (8.6 percent);
- left-turn across path, opposite direction crashes (LTAP-OD) (6.7 percent);
- left turn across path, lateral direction crashes (LTAP-LD) (4.8 percent);
- right turn into path crashes (RTIP) (1.5 percent);
- left turn into path crashes (LTIP) (1.5 percent);
- other types of crossing path crashes (2.0 percent).

While each type of crash represents different pre-crash vehicle movements and a different mix of causal factors, each type could be reduced by using IDS countermeasures to support driver decisions at intersections and other junctions.

### 3. Most Intersection Crashes Occur at Controlled Intersections

We found that among intersection crashes, most (74 percent) occurred at intersections with some type of traffic control device in place including 46 percent at signalized intersections, 16 percent at two-way stop-sign intersections, 6 percent at four-way stop sign intersections, 5 percent at intersections with some other type of control. **IDS approaches should coordinate with existing traffic control devices.** 

4. Many Crashes Occur at Uncontrolled Intersections
 About one quarter (26 per cent) of intersection crashes occur at intersections
 with no physical traffic control devices. While statutory controls may apply

at these intersections, the GES codes them as "uncontrolled". If uncontrolled intersections have such light traffic that they don't even warrant a physical control device, there would probably be no justification for an IDS infrastructure installation, and it may be that collisions at intersections with no traffic control devices are best addressed by vehicle-based systems.

- Types of Crashes at Intersections Vary by Type of Traffic Control Crash types at intersections differ substantially by type of traffic control configuration.
  - The majority of crashes at <u>signalized</u> intersections are LTAP-OD, SCP, and rear-end crashes (73 percent).
  - The majority at two-way stop intersections are SCP and LTAP-LD (71 percent).
  - The majority at four-way stop intersections are SCP and rearend crashes (59 percent).

The differences represent the impact of traffic control on vehicle flow and reflect varying pre-crash vehicle movements. **IDS approaches will need to address the different patterns of crash types occurring with different traffic control configurations.** 

- 6. Driver Errors are Primary Causal Factors in Intersection Crashes Based on police reports, driver failure is the most frequently identified causal factor in crashes including failure to see crucial information (e.g., obstruction of view, driver distraction); and failure to correctly judge available information (e.g., misjudged speed of or distance to another vehicle). IDS is designed to address both of these cases by increasing the salience and relevance of information available to drivers about potential risks as they navigate the intersection.
- 7. Most Crashes Occur at Moderate Speeds

A substantial proportion of intersection crashes takes place at intersections where speed limits are relatively moderate:

- Almost 72 percent of crashes occur in intersections with speed limits of 40 miles per hour or less.
- An additional 21 percent occur at intersections with speed limits between 45 and 50 miles per hour.
- Only seven percent take place where the speed limit is 55 miles per hour or greater.

Even assuming that the average vehicle speed is higher than the posted speed, most intersection crashes are likely taking place at moderate speeds. This has implications for IDS algorithms for detection of conflicts and for providing information to drivers since vehicle speed is a predominant variable in these algorithms.

8. Older Drivers are Somewhat Over-Represented in Crossing Path Crashes at Intersections

Most drivers in all crashes were under age 65. However, drivers age 65 and older represented 11 percent crossing path crashes compared to 6.4 percent of non-crossing path crashes. There were virtually no gender differences by type of crash. These results suggest that IDS measures should be designed with potential functional limitations of older drivers in mind.

9. Many non Crossing Path Crashes Occur at Intersections

Rear end crashes make up about 32 percent of crashes at intersections, and crashes involving pedestrians and bikes about 3 percent. While the IDS project only addresses crossing path crashes directly, it is important to note the possible impacts of IDS measures on other types of crashes.

10. IDS May Reduce Risk Without Reducing Intersection Capacity
 Traditional engineering countermeasures currently address crossing path
 crashes and other crashes at intersections. However, these countermeasures

may reduce intersection capacity, for example, by adding left-turn (substituting left lanes for through lanes) or increasing effective lost time per signal cycle, they may have other adverse affects, or they may fail to adequately meet informational needs of drivers. **IDS countermeasures may be able to reduce risk for crossing path crashes at intersections by providing salient and relevant information to drivers while maintaining intersection capacity.** 

To culminate this effort, we developed and performed a demonstration at the FHWA Turner Fairbank Highway Research Center that shows how IDS may help drivers judge when they should not make a left turn in the face of an oncoming vehicle from the opposite direction (addressing the LTAP/OD problem). An important aspect of the demonstrated system was a dynamic "left turn prohibited" sign, designed with elements "looming" in order to enhance its conspicuity. This sign is activated by an approach timing algorithm using data about approaching vehicles obtained from several commercially-available sensors. We are used an IEEE 802.11a wireless LAN communication link – designed to be similar to the emerging second-generation Dedicated Short Range Communications (DSRC) standard – to show how complete knowledge of the intersection condition derived from the infrastructure-based sensors could be communicated in real time to approaching vehicles, where it could be used to trigger in-vehicle warnings or displays.

As illustrated in Fig E1, the demo sequence was: Subject vehicle (SV) approaches the intersection from the North. It has a (permissive) green signal, but no left turn protection, so the driver slows down to a stop to check if it is safe to make a left turn onto the Eastbound leg of the intersection. The SV driver's view of approaching traffic from the South is blocked by another vehicle, so that the driver cannot easily judge the speed or location of this approaching traffic, making it hard to decide whether or not to turn. While the SV driver is trying to determine

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whether the left turn is safe, other vehicles ("Principal Other Vehicles" – POV) are approaching the intersection from the South.

In order to help the SV driver prevent a collision or near collision, the PATH IDS system issues a warning to the SV driver by illuminating the dynamic "no left turn" sign. This sign's signal has a pulsing effect, which uses motion to speed the human perception of the warning signal. Also, there was a laptop computer display of the real-time motions of all the vehicles near the intersection, which was wirelessly transmitted from the roadside IDS to the car, illustrating how the complete "state map" information about the intersection could be made available to an in-vehicle display or warning system.



Fig E-1. Schematic of PATH IDS Demo

These efforts lead to a follow-on Task Order (and RTA) that culminates in engineering, testing and designing for a set of end-of-program demonstrations, probably in early 2005, and thereafter one or more approaches may be selected for Field Operational Test (FOT). An FOT will be a real application on a real site.

### **1.0 Background and Introduction**

The Intersection Decision Support (IDS) project is a product of the Infrastructure Consortium (IC), as part of a three-State DOT "Specialty Vehicle Consortium" – Caltrans (lead), Minnesota DOT, and Virginia DOT – June 1999 positive response to a request by the US DOTs ITS Joint Program Office to transform the focus from snow removal (and some emergency vehicle operation) to the more general class of vehicle-highway cooperative systems.

At the heart of the IC effort was an initial exercise to pose the following ten fundamental IDS research questions in advance, from which the IC derived requirements which drove the overall program plan. In the end, the IC will have answered these questions and defined al set of deployable IDS solutions.

### 1. Questions in Intersection Science.

- What does the existing data tell us about what we should focus on?
- At what types of intersections are improvements possible?
- What are the requirements needed to prevent crashes at intersections?
- How do we reliably analyze the crash configurations data?
- How do we use this data to help us understand the causal relationships and design countermeasures that have a high potential for success?
- Which crash configurations are most likely to be tractable within the time period of the project?
- To what extent do rural, urban and suburban share characteristics and to what extent should they be considered separately?
- What can be learned from epidemiological studies that are relevant to countermeasure design?
- 2. Questions in Surveillance Technology.
  - How do we know where the vehicles (and the drivers) are as they approach the intersection?

- How do we design sensors to give us adequate coverage?
- How accurately can we do that?
- How do we fuse information from multiple sensors to increase our level of confidence in the information?
- What is our level of confidence in the data?
- Are sensors vehicle based or infrastructure based? Or both?
- How well do they work under a variety of outdoor environments?
- Can sensors provide data soon enough to be able to use their information for countermeasure implementation?
- How far must sensors be located from the intersection?
- If sensors are vehicle based, what data is needed and how is it used?
- Can the sensors track high-speed vehicles on rural roads?
- Or deal with the vehicles and pedestrians in densely populated urban settings?

3. Questions in *Human Factors*. We cannot build or design a system for preventing crashes until we understand how humans react to intersection situations and what humans (and their vehicles) can and will do under these circumstances.

- How do we turn the sensor-provided data into useful information that drivers can use?
- What do drivers do at intersections that lead to crashes?
- What are the causes of driver error?
- How do drivers make decisions at intersections?
- How does situation awareness affect their behavior?
- How soon do we need to warn them so that they can react in sufficient time to prevent crashes?
- How do we communicate with the driver?
- How can we achieve an intuitive driver response, without special training?
- How do we best assist the driver to make the right decisions?
- What should be the nature of the driver interface?

- What should be the content of the information provided to the driver?
- How should that content be delivered to the driver?
- How do we deal with learned inattention?

4. Questions in *Wireless Communication*. Wireless communications is more than just information passing from vehicle-to-vehicle, or vehicle-to-infrastructure. It must incorporate the ability of widely dispersed intersections to pass information among each other (or even with central management facilities). Sensors may be dispersed along the approaches to an intersection; so sensor-to-intersection controllers or servers must be allowed.

- How will communications protocols facilitate such varying needs?
- How do we ensure that safety-critical communications take place robustly, especially with large numbers of vehicles entering and leaving the vicinity of the intersection?
- 5. Questions in System Architecture.
  - What are the necessary components of intersection decision support systems?
  - How do they tie together?
  - What data must pass between the subsystems?
  - What are the interfaces between the subsystems?
  - How do the infrastructure, the vehicles within the vicinity of the intersection and their drivers all interconnect to the driver decision-making support system?
  - Can this be described explicitly so that traffic engineers and vehicle manufacturers can plan their future systems accordingly?
  - Is there a single architecture that can capture all the needs of an intersection decision support system?

6. Questions in *Design and Implementation*. Countermeasures need to take into account our best understanding of how driver error, distraction, poor judgment and other human foibles act to contribute to intersection related crashes.

- Can these countermeasures be designed and built to reliably function in a variety of different environments?
- What portion of the countermeasure is infrastructure based and what portion is vehicle based?
- How can these cooperate?
- Can intersection collision countermeasures function on vehicles only (the autonomous model)?
- How reliable are these countermeasures for a variety of different scenarios?
- How do we design countermeasures that do not impede the traffic flow?
- 7. Questions in Evaluation and Validation.
  - How are the countermeasures best evaluated in environments that do not perfectly match the real world?
  - What validation procedures will be used to ensure that the evaluation experiments replicate real world conditions?
  - Can experiments be designed that allow for sharing of results across different intersection scenarios?
  - What do we want to learn from each of the experiments?

8. Questions on *Development of Driver Behavior Models*. Traffic models are needed to evaluate the effects of countermeasures on traffic flow and on road capacity. Most traffic models do not replicate the driver behavior at intersections.

- How do countermeasures at one intersection affect the flow at other local intersections?
- How can one understand and compare the effects of vehicle-infrastructure cooperative based countermeasures with vehicle-to-vehicle and vehicle-to-driver based countermeasures on traffic? Vehicle based systems may have profound effects on traffic behavior.

9. Questions on *Cost-benefits and Trade-off Analysis*. Limited budgets among DOT's and limited budgets among the vehicle buying public constrain the types of solutions that are possible. We must identify the underlying costs that are associated with the countermeasures.

- What benefits can be identified with the proposed countermeasures and how are their costs borne?
- How can we determine which countermeasures are most likely to reap the most benefits with the least new incremental costs?
- What costs are acceptable for IDS deployments at intersections of varying character (different traffic volumes and speed, crash histories, and urban/suburban/rural settings)?

10. Question on *Evaluation of Commercial-Off-the-Shelf (COTS) Technologies*. In order to ensure reasonable timelines on deployment, it is necessary to use COTS systems as much as possible. There are two levels of COTS systems that will be considered. The first represent new systems that take advantage of COTS subsystems, such as radar, imaging, GPS, wireless and display systems, but require new software that integrates these into a working system that serves as a part of a countermeasure. The second are represented by turnkey COTS intersection crash prevention systems that are on the market but have not received wide attention.

• Which COTS systems will satisfy IDS requirements?

As further context, the focus of IDS is on vehicle-to-vehicle crossing path collision (which includes straight crossing path, as well as turning movements). Two other participating universities have focused on intersection traffic control device violation (Virginia Polytechnical University, Virginia Tech Transportation Institute) and left turn assistance at stop-controlled minor roads intersecting with high-speed interregional corridors (University of Minnesota, ITS Institute). The PATH technical focus – requested by our IC partners and agreed upon us because, indeed it represents a major crash problem – is left turn movements with focus on urban and suburban applications. In particular, we concentrate on preventing crashes that occur when a driver makes a left turn onto a cross street, and is either hit head-on by an oncoming vehicle traveling in the opposite direction. Figure 1-1 illustrates the first scenario, dubbed Left Turn Across Path/Opposite Direction (LTAP/OD). The LTAP/OD scenario represents 27.3% of intersection crashes, and cuts across all causal factors.



# Fig 1-1: LTAP/OD Scenario. Blue Arrow Represents Subject Vehicle, and Red Arrow Represent Principal Other Vehicle.

Even with the specific IC-prompted interest in LTAP/OD, our overall effort is deliberately systems-oriented and transcended an infrastructure-only IDS solution. To begin, our point of view is that the national problem is the California problem, so we preferred not to focus *a priori* on a specific scenario or problem type. Our approach at inception was a systems-oriented one; therefore, we have investigated key enabling technologies, most notably *cooperative* infrastructure-to-vehicle (or vehicle-to-infrastructure) and vehicle-to-vehicle communication. We have also begun investigating the use and usability of roadside-mounted "driver-infrastructure interface" (DII). We have put these together preliminarily in a LTAP/OD

demonstration, given in June, 2003 at the FHWA Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia.

Based therefore on the ten fundamental questions, the agreed focus on LTAP/OD and our systems interest, we constructed an overarching three-year California IDS research plan in nine tasks A - I, shown below with a tenth task, Task M, which was agreed upon by the IC after the project began:

- Task 0: Management and Planning
- Task A: Delineate the Intersection Crash Problem
- Task B: Develop Top Level Requirements for Types/Classes of

   Intersection Crashes
- Task C: Conduct Enabling Research & Development
- Task D: Prioritize Classes of Intersection Crashes for Initial Study
- Task E: Conduct Countermeasure Trade-off Analyses
- Task F: Develop Detailed Requirements and Specifications for Each

   Countermeasure/Crash Class
- Task G: System Design and Development
- Task H: Conduct Subsystem Tests and Experiments
- Task I: Prepare for Countermeasure Demonstration
- Task M: Midterm Demo

This Task Order 4403 addressed the first year of the overall effort; hence, the final report addresses the following subset of the total task list, all covered the first year:

Task A: Delineate the Intersection Crash ProblemTask B: Develop Top Level Requirements for Types/Classes of Intersection Crashes

**Task C**: Conduct Enabling Research & Development Within Task C for this period, we focus particularly on the system architecture, human factors issues to include the DriverInfrastructure Interface (DII) and initial work in IDS communications tradeoffs. Task M: Midterm Demo

We describe output and results these tasks in the subsequent sections of this final report. The other tasks are addressed in out-years and subsequent task orders. Indeed, with the work reported herein, we have set the stage for subsequent tasks, with specific future accomplishments to conduct naturalistic driving data collection, perform driver modeling, develop an integrated IDS simulation approach, and to look at the applicability of a large set of already- or nearly-available "commercial off the shelf" systems toward meeting IDS requirements – all of which will be done in subsequent years, following a Caltrans-approved "rebaselining" (or rearrangement) of tasks, based on significant lessons learned from the work reported here.

#### 2.0 Delineate the Intersection Crash Problem

We recognize that identifying opportunities for crash avoidance as well as their potential countermeasures depends on understanding basic characteristics of each type of crash. Previous studies on crossing-path collisions have quantified numbers of target crashes, described crash characteristics, and identified causal factors using the 1990-1993 *National Automotive Sampling System* (NASS) *General Estimates System* (GES) crash database. Other work provides crash statistics using the 1998 GES crash database for different types of intersection crashes, determining the distribution of the major crash types, and identifying the dominant contributing factors by vehicle platform in each crash type.

Left turn movements, and in particular what is dubbed Left Turn Across Path/Opposite Direction (LTAP/OD) and Left Turn Across Path/Lateral Direction (LTAP/LD), urban scenario. According to the GES, the LTAP/OD scenario represents 27.3% of intersection crashes and cuts across all causal factors. Likewise, the LTAP/LD scenario represents 15.9% of all collision types. Even when delimiting the LTAP/LD to urban areas, we believe that our specific solution approaches may affect between 30 and 40% of all intersection crashes in the US.

We investigated these crash statistics in more depth because we believe that identifying opportunities for crash avoidance and their potential countermeasures will also depend on understanding (i) demographic characteristics of drivers, particularly age and gender and (ii) environmental conditions. Insight into (i) and (ii) will aid us considerably in grouping – of similar driver cognitive states, of similar potential engineering solutions, or of other types of aggregation pertinent to IDS design. The California effort has evolved to focus on the two specific cross-path scenarios: LTAP/OD, and LTAP/LT. In delineating the intersection crash problem, we will focus on these two scenarios, but will include other cross-path scenarios.

This section reports findings from two primary tasks and associated subtasks:

- Data Review
  - Intersection Traffic Safety Review
  - Review Existing Gap Acceptability Models And Design Parameters For Turning, Following And Braking At Intersections
  - A1.1.3 Review of Traffic Engineering Models
  - A1.2-3 Revisit Analyses in the Volpe "Crash Problem Definition..."
     by demographic and geographic characteristics.
- Draw Conclusions Regarding A1.2-3

For completion of this task we have organized material into three sections, written by different members of our project team. The sections are listed below, with original task names in parentheses. In the next section we summarize each of the three sections and then provide an overall summary and conclusion. As an up-front and context-setting part of the IDS effort, research on crossing path crashes was conducted using data from the General Estimates System (GES), a nationally representative sample of police-reported crashes in the United States. The end-result is straightforward: a synthesis and interpretation of the results will allow us to understand the problem, particularly as they reveal potential engineering approaches applicable to IDS.

Beginning in the early 1990s, a series of studies investigated the various types of CP crashes at intersections. Chovan<sup>9</sup> and colleagues investigated CP crashes using sets of collisions drawn from the Crashworthiness Data System (CDS). Wang and Knipling<sup>3</sup> used the General Estimates System (GES) to generate national estimates of intersection crossing path crashes. Najm and colleagues used a set of collisions from the CDS to study causal factors for various types of crashes, including crossing path crashes. More recent studies have extended earlier work. In particular, Najm and colleagues have developed a systematic taxonomy of crossing path crashes based on the GES coding system, and they have used the GES to develop estimates of the problem at the national level and to study potential causal factors.

This section uses data from the Year 2000 General Estimates System to build on these studies. Specifically, we:

- Clarify the definition of crossing path crashes at intersections using terminology of the GES;
- Compare crossing path crashes at intersections to other types of intersection crashes and crashes in general;
- Describe types of crashes at intersections by <u>traffic control</u> <u>configuration</u>, providing a discussion of possible causal factors, traditional engineering countermeasures, and possible ITS countermeasures;

- Describe types of crashes at intersections by posted <u>speed limit</u>, providing a discussion of possible ITS countermeasures;
- Describe types of crashes at intersection by <u>age and gender</u>, providing a discussion of possible ITS countermeasures.

#### 2.1 Methods

Findings in this section are based on data from the Year 2000 *National Automotive Sampling System* (NASS) *General Estimates System* (GES) crash database. The GES is a nationally representative sample of police-reported crashes that includes vehicle types as well as severity of the crashes. The record includes about 50,000 sample cases each year. The GES includes variables recorded in standard police accident reports (PARs).

The GES uses sampling weights to generate national estimates of the number of different types of crashes. Furthermore, the GES is easily accessible and is well documented. However, the GES has several drawbacks. First, it relies solely on PARs. This means that it is limited by the range and quality of information that is recorded by police officers. For example, variables such as alcohol involvement<sup>4</sup> and driver distraction are almost certainly underreported. Second, since not all crashes are reported to the police, the GES record substantially underestimates the number of crashes in the U.S. The degree of underestimation is roughly inverse to the severity of the collision (i.e., underestimation is greatest for least serious crashes). A recent National Highway Traffics Safety Administration (NHTSA) report estimates that 21 percent of injury crashes and 48 percent of propertydamage-only (PDO) crashes are unreported. Finally, the GES includes no "exposure" data; i.e., using GES data alone, it is impossible to calculate rates per unit of exposure (e.g., per number of vehicles on the highway, per vehicle mile, per type of roadway segment, per weather or lighting conditions, and so forth) for different types of crashes or injuries. This means that any identification of causal factors in crashes based on GES data alone should be interpreted cautiously.

The GES includes variables at three levels: the accident, vehicle occupant(s), and the vehicle. Variables in this report include the junction (accident level), crash type (accident level but derived from vehicle level), traffic control device (accident level but derived from vehicle level), posted speed limit (accident level), and age and gender of driver (vehicle level).

### **2.2 Relation to Junction<sup>i</sup> (Variable V9 in GES)**

According to GES manuals, a junction is:

(*T*)he area formed by the connection of two roadways. It includes: (1) all at-grade intersections, (2) connections between a driveway access or alley access and a roadway which is not a driveway access or an alley access, (3) connections between two alley accesses or driveway access, or (4) a connection between a driveway access and an alley access.

These manuals also state that an *intersection*, which is the focus of the IDS project and this report, is:

<sup>&</sup>lt;sup>i</sup> The variable *Relation to Junction* separates road configurations into two categories: "noninterchange" and "interchange" areas, and then, within <u>each</u> of these areas, identifies "nonjunctions" and various types of junctions, including intersections. An interchange area" is defined as:

<sup>&</sup>quot;The area around a grade separation which involves at least two traffic ways. Included within its boundaries are: (1) all ramps which connect the roadways and (2) each roadway entering or leaving the interchange to a point 30 meters beyond the gore or curb return at the outermost ramp connection for the roadway."

The key point is that an interchange area or a non-interchange area is just that, an area, and may include within that area intersections, driveway accesses, alleyways, as well as roadway sections which are non-junctions. In 1998, only about 3 percent of all crashes are within interchanges, and, in this report "non-interchange" and "interchange" categories will be combined.

(A) type of junction which: (1) contains a crossing or connection of two or more roadways not classified as a driveway access or alley access, and (2) is embraced within the prolongation of the lateral curb lines or, if none, the lateral boundary lines of the roadways. Where the distance along a roadway between two areas meeting these criteria is less than 10 meters, the two areas and the roadway connecting them are considered to be parts of a single intersection.

An intersection is coded "when the first harmful event occurs within the area formed by the prolongation of curb or edge lines of the approach legs of the intersection." "Intersection-related" is coded "if the first harmful event occurs outside but near an intersection and involves a vehicle which was engaged or should have been engaged in making an intersection related maneuver such as turning." Most previous analyses have combined crashes at "intersections" and crashes that are "intersection-related." Intersection and intersection-related crashes are combined in the report.

#### 2.3 Distribution of Crashes

Table 2-1 shows the frequency and distribution of crashes by type of junction. "Intersection" (23.8 percent) and "intersection-related" (20.2 percent) are the two largest junction categories followed by "driveway, alley access" (10.6 percent) and others.

Table 2-2 presents frequency and distribution of crashes by types of junction in aggregate form. According to Plazak<sup>5</sup>, most crashes (59.7 percent) take place at junctions, and most of these occur at intersections (43.9 percent of all crashes). While only sixteen percent of crashes occur at non-intersection junctions, these are causing increasing concern in corridors near large urban centers. Crashes at intersections are the focus of this report.

Table 1-1. Frequency and distribut	ion of crashes by typ	e of junction			
(GES variable V9, Relation to Junction).					
Relation to Junction	GES Code	Frequency	Percent		
Non-Junction	0,10	2,572,747	40.3		
Junction					
Intersection	1,11	1,518,102	23.8		
Intersection Related	2,12	1,289,460	20.2		
Driveway, Alley Access, Etc.	3,13	676,824	10.6		
Entrance/Exit Ramp	4,14	163,990	2.6		
Rail Grade Crossing	15	56,686	0.9		
On A Bridge	6/16	15,329	0.2		
Other, Non-Interchange	7/17	96,173	1.5		
	8/18				
TOTAL		6,389,311	100.0		

Table 2-2. Frequency and dist	tribution of crashes b	y type of junction				
(GES variable V9, Relation to Junction, collapsing						
intersection and intersection-related into one level, and non-						
intersection junctions into another level).						
Relation to Junction	GES Code	Frequency	Percent			
Non-Junction	0,10	2,572,747	40.3			
Junction	All except 0,10	3,816,564	59.7			
Intersection	1,2,11,12	2,807,562	43.9			
Non-Intersection	All Other	1,009,002	15.8			
Junction						
TOTAL		6,389,311	100.0			

# Implication for the IDS project

Reducing crashes at junctions, and especially at intersections, will address a major portion of the US traffic crashes (59.7 and 43.9 percent, respectively)..

- Junctions, and intersections in particular, represent a small part of the total US roadways in the U.S., they carry disproportionate risk for crashes. Safety enhancements in such sites should be an efficient investment.
- Similarities between crashes at intersections and those at non-intersection junctions should be investigated. Countermeasures developed for intersections may have applicability to crashes at other types of junctions.

### 2.4 Crash Types (V23 in GES)

Crash type is derived from the Crash Type variable in the GES data (V23), which is a vehicle-level variable. When crashes are coded, they are mapped onto an Accident-Type Diagram (see Appendix A), and a number is assigned to each vehicle based on the (i) type of crash and (ii) role of the vehicle in the crash. For example, a vehicle that runs into the back of another vehicle that is stopped but poised to turn left is defined by crash type "20" while the other is coded "22" (vehicle stopped to turn left).

To reconstruct the crash for an individual incident in the GES data, it is necessary to view the pattern of crash types for the set of vehicles involved in the incident. In the example above, the vehicle-level code for each of a pair of vehicles would be "20" and "22," and the combination of these two would define the type of crash. For this example, this would be coded a "rear end" crash if any pair of vehicles is coded "20" or "22," regardless of their order in the database. Often, more than two vehicles are involved in a single crash<sup>ii</sup>. Most often, if there are more than two vehicles in a crash, and any particular pair of vehicles defines a crash type, then most other vehicles in the crash event will have a code indicating "unknown" or "other."

There are a fixed number of crash types precoded in the GES, and assigning a crash type is limited by the crash types provided. Najm and colleagues have used the

<sup>&</sup>lt;sup>ii</sup> In the 2000 GES, up to 11 vehicles.

GES categories to focus on five crossing path crashes, which is the focus of the current study. Crossing path crashes are identified by <u>pre-defined</u> combinations. For example, straight crossing path (SCP) crashes are defined if a pair of vehicles is assigned the numbers 86 and 87, or 88 and 89, respectively. Smith and Najm's taxonomy is as follows (with corresponding GES codes in parentheses):

- 1. Left Turn Across Path Opposite Direction Conflict (LTAP/OD) (68/69)
- 2. Left Turn Across Path Lateral Direction Conflict (LTAP/LD) (82/83)
- 3. Left Turn Into Path Merge Conflict (LTIP) (76/77)
- 4. Right Turn Into Path Merge Conflict (RTIP) (78/79)
- 5. Straight Crossing Path (SCP) Crashes (86/87 and 88/89)
- 6. Other

Two other possible crossing path crashes are defined in the GES crash diagrams. One is, "Turn into path, opposite direction" (defined by the crash numbers 81 and 82). This report follows the method of Najm and colleagues who combined this type with the category of "other crashes." Another type of crash defined in the GES taxonomy as a crossing path crash, but not included in the Najm and Smith taxonomy is described as "Turn across path, initial same direction" (defined by GES numbers 70/71 or 72/73). These crashes occur in substantial numbers (almost 3 percent of all crashes, and over 10 percent of intersection crashes), but they do not appear to fit the definition of crossing path crashes as addressed in the IDS project. Again, this report follows Najm and colleagues who included this type of crash in the category of "other non-crossing path crashes."

There are other possible additional crossing path crashes that have not specifically been identified within the GES codes<sup>6</sup>. For example, if a vehicle is entering an intersection and turning left, it might encounter another vehicle proceeding from the:

1. Opposite direction and turning left;
- 2. Opposite direction and turning right;
- 3. Lateral direction (left) and turning left; and
- 4. Lateral direction (right) and turning left.

Apparently, when such crashes are encountered in the GES sample, the GES codes them as "other crossing path crashes."

Because we are interested in comparing crossing path crashes at intersections with other intersection crashes, we have included all crashes defined by the GES, and have aggregated them into other, non crossing path types. These are (i) rear end crashes, (ii) crashes involving pedestrians and bicyclists, (iii) single vehicle crashes, and (iv) other (where we have included all other types of crashes).

Table 2-3 shows the frequency and distribution of crash types. One-quarter of <u>all</u> GES crashes are crossing path crashes, and the remaining 75 percent are non-crossing path crashes.

Table 2-3. Frequer	ncy and distribution of cr	rashes by type (Bas	ed on
GES variable V23)			
Type of Crash	GES Code(s)	Number	Percent
LTAP-OD	68/69	427,054	6.7
LTAP-LD	82/83	306,813	4.8
RTIP	78/79	94,306	1.5
LTIP	76/77	93,178	1.5
SCP	86/87 88/89	546,941	8.6
Other Crossing path Crashes	70/71 72/73 74/74 75/75 80/81 84/84 85/85 90/90 91/91*	127,587	2.0
Total Crossing path Crashes		1,595,879	25.0
			0.0
Rear End	20/33**	1,797,934	28.1
Pedestrian/Bike	13	385,471	6.0

Single Vehicle		1,319,798	20.7
Other Crashes***	All other types	1,290,228	20.2
Total Non-Crossing path Crashes		4,793,431	75.0
Total Crashes		6,389,310	100.0

\*When "other" is coded, each of a pair of vehicles has the same number.

\*\*All rear end-crashes are defined by combinations of codes between 20 and 33.

\*\*\*Other crashes include single driver, head on, and sideswipe.

Implications for the IDS project:

• One quarter of all crashes are crossing path crashes. This means that addressing crossing path crashes in effect addresses a large portion of the problem. Among crossing path crashes, SCP are the most common, followed by LTAP-OD and LTAP-LD.

#### **2.5 Crashes at Junctions**

For this analysis, we performed cross tabulations of "Relation to junction" and "Crash type variables." We collapsed non-intersection junction crashes and intersection and intersection-related crashes and calculated the percent for each crash for non-junction, intersection, and non-intersection junction separately.

Table 2-4 shows the varied distribution of crashes separately for intersections, nonintersection junctions, and non-junctions.

- Crossing path crashes are about 25 percent of all crashes, but they constitute more than 44 percent of all intersection crashes, and about 36 percent of all non-intersection junction crashes.
- Not surprisingly, only a small number of crossing path crashes are reported for non-junctions.
- A substantial proportion of all three types of junctions are rear end crashes.

• There are some similarities in the pattern of crashes at intersections and nonintersection junctions. Both LTAP-OD and LTAP-LD are among the top three in both cases. The major exception is SCP, which is most frequently reported in intersections and among the least frequently reported for nonintersection junction crashes.

About one-quarter (28.1 percent) of all crashes were rear-end crashes, and the percent at intersections and non-intersection junctions was about 32 and 26 percent respectively. In designing IDS countermeasures, it will be important to be aware of these crashes so that their rates won't be adversely affected. For example, a collision warning system for crossing path crashes might result in sudden or rapid stops, possibly resulting in additional rear-end collisions.

Crashes with pedestrians or bikes make up only about 6 percent of all crashes, and the rate is lower at intersections (3.0 percent) and non-intersection junctions (2.1 percent). However, pedestrian and bicycle collisions are much more likely to result in injury or death. For example, if drivers interpret the absence of a warning signal as an indication that it is safe to turn left at a signalized intersection but the system does not account for presence of pedestrians and/or bicyclists when issuing this signal, this might increase danger for pedestrians and bicyclists.

#### **Implications for the IDS project:**

- Since the distribution of crashes is similar for intersection and non-intersection junction crashes (except for SCP collisions), IDS technology may be applicable to non-intersection junction crashes—this should be kept in mind when developing a general architecture
- The majority of intersection crashes (56 percent) are <u>not</u> crossing path crashes. In designing IDS technology to prevent crossing path crashes at intersections, it is very important to not increase the frequency of non crossing path crashes.

• Intersection crashes may be similar in some ways to non-intersection junction crashes. Although non-intersection junction crashes will not be considered further in this report, it may be that approaches derived for intersection crashes will be applicable to non-intersection junction crashes.

						., 020		
			Interse	ection	Non-Inte	ersection	Total	
Crash Type			Number	Percent	Number	Percent	Number	Percent
LTAP-OD	2,602	0.1	Non-Junction	12.1	83,713	8.3	427,054	6.7
LTAP-LD	1,008	0.0	Number	Percent	112,366	11.1	306,813	4.8
RTIP	791	0.0	58,885	2.1	34,630	3.4	94,306	1.5
LTIP	592	0.0	54,782	2.0	37,804	3.7	93,178	1.5
SCP	3,036	0.1	499,568	17.8	44,336	4.4	546,941	8.6
OTHER CP	1,792	0.1	99,903	3.6	25,891	2.6	127,587	2.0
Total Crossing path Crashes	9,821	0.4	1,247,316	44.4	338,740	33.6	1,595,879	25.0
REAR END	627,46	24.4	904,749	32.2	265,720	26.3	1,797,934	28.1
PED/BIKE	280,96	10.9	83,547	3.0	20,955	2.1	385,471	6.0
SINGLE	1,015,6	39.5	189,387	6.7	114,799	11.4	1,319,798	20.7
OTHER	638,87	24.8	382,562	13.6	268,788	26.6	1,290,228	20.2
TotalNon- Crossing path Crashes	2,562,9	99.6	1,560,245	55.6	670,262	66.4	4,793,431	75.0
Total	2,572,7	100.0	2,807,561	100.0	1,009,002	100.0	6,389,310	100.0

Table 2-4. Crash types distributed by type of junction, GES

# 2.6 Crossing Path Crash by Traffic Control Device (TCD) (Variable A16N in GES)

The GES traffic control device (TCD) variable includes a list of possible trafficcontrol devices, including traffic control signals, stop signs, flashing traffic control signals, and yield signs. Najm and Smith<sup>7</sup> collapsed this variable into four categories: signalised intersections, stop sign controlled intersections, uncontrolled intersections, and other (see <u>Appendix B</u>). In the 1998 GES data (used in <sup>4</sup>) the TCD variable was coded at the accident level, i.e., there is a single coded value for each accident. First, as noted by Najm and Smith, the code fails to distinguish 2-way and 4-way stop sign controlled intersections. We might expect the crash patterns for the two types of intersections to be quite different. Second, there may be some ambiguity concerning the "no controls" category: "It should be noted that a number of intersections might have been coded as "No Controls" in LTAP/OD crash cases if the involved vehicles were traveling on a major traffic way without any controls and the minor crossing traffic way had a traffic control device such as stop sign (page 6, GES manual)." Najm and Smith postulate that this might account for the large number of intersections coded as "no controls".

Because of limitations posed by the accident level TCD code in the 1998 GES data, the present analyses were conducted using the 2000 GES data, which includes a single vehicle-level code for TCD, but also has available a vehicle-level TCD variable data (i.e., the TCD variable provides a separate code for each vehicle, which allows a more detailed analysis of TCD). An algorithm was developed in which a new, more detailed accident-level variable was derived from the combination of vehicle-level codes.

The relationship between the accident level TCD variable (termed the "original" variable) and the accident-level TCD variable as derived from the vehicle-level code (termed the "derived" variable), is given in Table 2-5. The following similarities and differences were observed. *First*, of 1,295,160 crashes at signalised intersections under the original TCD variable, a very high percent were coded as signalised under the new TCD variable. Few were assigned to other traffic control configurations. These should probably be considered coding discrepancies (i.e., errors) between the original and derived crash level TCD variables. *Second*, of 644,187 crashes at stop-sign-controlled intersections under the original crash level TCD variable, almost all were distributed between 2-way and 4-way stop

intersections, with 2-way intersections representing the largest number (458,456 versus 176,598). *Third*, almost all of the crashes coded as "other" TCD were also coded as "other" under the derived TCD variable. *Finally*, almost all crashes in the "no controls" category were also "no controls" in for the derived variable. This is contrary to the suggestion of Najm and Smith that many crashes in this category may actually have had controls on the minor crossing traffic way. Either these crashes in fact took place at intersections with no traffic control devices, or a high proportion of police reports fail to note traffic control devices that actually were in place.

Fable 2-5. Traffic control device: Vehicle level code by crash level						
code (Inters	ection crashes	s only, GES	2000).			
Crash Level		Crash level	derived from vehi	icle-level		
	Signal	2-Way Stop	4-Way Stop	Other	No controls	Total
Signal	1,291,150	891	0	2,960	160	1,295,160
Stop Sign	0	458,456	176,598	157	8,975	644,187
Other	562	1,152	0	143,343	706	145,763
No controls	0	0	0	4,146	718,305	722,451
Total	1,291,712	460,499	176,598	150,607	728,145	2,807,561

NOTE: A two-way stop can be further broken down by two-way stop with "<u>no</u> <u>controls</u>" on one roadway, and two-way stop with "<u>other</u>" on one roadway. The "other" could be flashing yellow, etc.

Table 2-6. Crash type by t	raffic con	trol devic	e, interse	ction cras	hes	
only, GES 2000						
		Type of T	raffic Control	Device		
Crash Type	Signal	Two-way	Four-way	Other	None	Total
		Stop	Stop			
(Number)	(1,291,712)	(460,499)	(176,598)	(150,606)	(728,145)	(2,807,561)
LTAP-OD	17.8	0.4	6.0	9.4	11.6	12.1
LTAP-LD	3.9	24.7	4.1	5.5	2.0	6.9
RTIP	1.3	6.3	1.2	2.1	1.1	2.1

LTIP	1.4	5.4	0.8	2.0	1.0	2.0
SCP	14.4	45.5	20.6	21.2	4.9	17.8
OTHER CP	3.4	5.4	5.5	3.9	2.2	3.6
Total Crossing path Crashes	42.1	87.6	38.2	44.2	22.9	44.4
REAR END	40.3	0.4	37.8	35.5	36.0	32.2
PED/BIKE	2.5	2.4	2.4	2.5	4.5	3.0
SINGLE	2.6	6.3	6.3	5.6	14.8	6.7
OTHER CRASHES	12.6	3.4	15.3	12.2	21.8	13.6
Total Non-Crossing path Crashes	57.9	12.4	61.8	55.8	77.1	55.6
Total	100.0	100.0	100.0	100.0	100.0	100.0

Of 2,807,561 estimated intersection crashes in year 2000, almost half (46 percent) were at signalized intersections, around one-quarter (23 percent) were at stop-sign-controlled intersections (16 percent and 6 percent for two-way stop and four-way stop sign controlled intersections, respectively), one quarter (26 percent) were coded as having no controls, and about 5 percent had other traffic controls (per Table 2-5).

The distribution of types of crashes was substantially different for intersections with different traffic control configurations. Crossing path crashes at signalized intersections constituted about 42 percent of signalized intersection crashes. Almost 88 percent of two-way stop sign controlled intersection crashes and around 38 percent of four-way stop sign controlled intersection collisions were crossing path crashes. At signalized intersections, the predominant type of crash was rear end (about 40 percent), followed by LTAP-OD, almost 18 percent) and SCP (about 14 percent). In contrast, at two-way stop sign controlled intersections, the predominant type of crash was SCP (over 45 percent), followed by LTAP-LD (around 25 percent), and then RTIP (about 6 percent). It is worth noting that LTAP-OD and rear end crashes constituted only 0.4 percent each of all crashes at two-way stop-sign-controlled intersections. The leading type of crash at four-way stop sign controlled intersections at four-way stop sign controlled intersection four-way stop sign controlled intersection four-way stop sign controlled intersection by 0.4 percent each of all crashes at two-way stop-sign-controlled intersections. The leading type of crash at four-way stop sign controlled intersections was rear end (almost 38 percent), followed by

SCP (more than 20 percent), and "other" (around 15 percent). Only 6 percent of crashes at four-way stop-controlled intersections were LTAP-OD crashes.

"No controls" is coded in the GES if at the time of the crash there was no intent to control (regulate or warn) vehicle traffic (i.e., an uncontrolled intersection). This code is used when there is no physical control device present. However, at such intersections, statutory controls may apply. For example, state laws often require that when two vehicles meet at an uncontrolled intersection, right-of-way goes to either (i) the vehicle arriving first or (ii) the one on the right.

The most predominant type of crash at an uncontrolled intersection is a rear-end (almost 34 percent), "other" (almost 25 percent), and LTAP-OD crashes (about 14 percent). "Other" is coded when the control device is other than a stop sign or 3-phase signal. The predominant types of crashes for this category were rear end (almost 36 percent), SCP (about 21 percent), and LTAP-OD (just over 9 percent). These intersections will not be considered further in this report. The IDS project is supposed to involve some infrastructure elements to support the IDS function. If uncontrolled intersections have such light traffic that they don't even warrant a stop sign or other control device, there would probably be no justification for an IDS installation. It may be that collisions at uncontrolled intersections or intersections with "other" controls are best addressed by vehicle-based systems.

The remaining types of intersections (signalized, two-way stop, four-way stop) will be considered with respect to (i) pre-crash scenario, (ii) causal factors, (iii) traditional engineering countermeasures, and (iv) potential IDS countermeasures. Because of the significant differences in patterns of crashes among these types of intersections they will be discussed separately. In discussing these we will make a distinction between subject vehicle (SV) and the principal other vehicle (POV). According to Ferlis<sup>8</sup> (2001), in crashes when one vehicle is turning, generally the SV is the turning vehicle.

Implications for the IDS project follow:

- Focus on both signalized and stop-controlled intersections will address almost 70 percent of all intersection crashes (almost 46 percent for signalized and almost 23 percent for stop sign controlled intersections).
- If all crossing path crashes at signalized intersections are eliminated by the deployment of IDS, it would eliminate about one-quarter (23 percent) of all intersection crashes. Similarly, it would be a reduction of 19 percent of all intersection crashes for stop-sign-controlled intersections.
- The mix of crashes is considerably different for different types of traffic control devices, suggesting that causal factors may operate differently by traffic control device and that different countermeasures may be needed or that they may need different application.
- Despite the difference in mix of crashes by traffic control device, an important task is to identify underlying factors for each type and location of crash.

#### 2.7 Discussion of Signalized Intersections

Three crash types, LTAP-OD, SCP, and Rear End, make up nearly three-quarters (73 percent) of crashes at signalized intersections. We will discuss these separately since pre-crash scenarios, causal factors, and countermeasures are different for each.

#### LTAP-OD (Left Turn Across Path—Opposite Direction)

Chovan and colleagues<sup>9</sup> studied LTAP-OD crashes using a sample of crashes from the Crashworthiness Data System (CDS)<sup>10</sup>. They identified two subtypes of LTAP-OD crashes:

- SV slows (but does not stop), begins the left turn, and strikes or is struck by the oncoming POV;
- (ii) SV stops, then proceeds with the left turn, and strikes or is struck by the POV.

The CDS includes a relatively small sample of "tow-away" crashes (i.e., crashes in which at least one vehicle was towed from the scene), and it is therefore not representative of the national experience. In addition, the CDS relies on police reports from the scene of the crash and interviews conducted with drivers some time after the crash. Therefore, observations drawn from crash data are limited.

In observations at urban intersections during the green interval and the greenamber-red transition, we observed a somewhat more complex set of turning patterns as drivers approached and entered an intersection to turn left:

- SV makes a full stop when a POV is approaching from the opposite direction, and then proceeds with various speeds, partially depending on the gap;
- SV makes a full stop even with no POV (possibly putting themselves in danger of rear-end crashes, since it would be apparent to other drivers that they could proceed);
- (iii) SV slows while waiting for a POV to pass and modulates their speed while waiting for an appropriate gap;
- (iv) SV slows even with no POV present;
- (v) SV makes no change in speed, especially when no POV is present; and
- (vi) SV accelerates through the turn, especially during the amber (attempting to "beat the yellow") or when one or more POVs approaching might delay the opportunity to turn.

Likewise, POVs exhibited variable behavior, including:

- POV slows (apparently attentive to vehicles approaching from the opposite direction) preparing to turn left as well as vehicles waiting during the red phase in the lateral direction;
- (ii) POV makes no change in speed; and

(iii) POV accelerates, especially during the late green or amber phase.

Certain combinations of SV and POV behavior seemed particularly relevant to creating potential conflict. Two phenomena were apparent during the green-amberred transition: In one scenario, drivers turning left would be delayed by POVs coming from the other direction, and then they would be forced to turn quickly in the latter part of the amber or early red. In the second scenario, drivers queuing to turn during the late green or amber would accelerate to make the turn before the red, or, if within the red, to make the turn before vehicles approaching laterally (on green) entered the intersection.

A report by BMI<sup>11</sup> (2001) described a review of selected intersections in California, Virginia, and Minnesota. At signalized intersections, LTAP-OD was the predominant type of crash. BMI described a "left-turn trap" in many LTAP-OD crashes in which "Left-turning vehicles with a yellow signal indication proceed into the path of oncoming traffic, because they believe that the oncoming traffic *also* has a yellow signal indication and will stop. However, oncoming traffic has a longer green phase, and a crash ensues. A similar phenomenon might occur if there are no sufficient gaps in oncoming traffic during the green phase, and left-turning drivers must wait for the amber or red phase to complete their maneuvers. However, oncoming motorists could enter on amber or red and create a conflict. Based on our own observations and those of BMI, we have hypothesized that the probability of crashes increases substantially in intervals near green-amber-red transitions.

Combinations of SV and POV behaviors could also produce a conflict or crash prior to the green-amber-red transition in cases where the left turning vehicle proceeds to turn left and either (i) misjudges the speed of the POV (i.e., misjudged the gap) or (ii) fails to perceive the POV.

Aside from general statements in the literature, we have not yet been able to find data pertaining to the timing of LTAP-OD crashes in relation to the signal phase.

Similarly, we have not been able to find reports pertaining to the timing of vehiclevehicle conflicts in relation to signal phase. Such information could be derived from structured observations of SVs and POVs at signalized intersections.

Najm and Smith used 1998 GES data to study contributing factors to crossing path crashes including violations, obscured driver vision, and driver distraction. About one third (32 percent) of drivers in LTAP-OD crashes received citations, with "Failure to Yield Right-of-Way" being the most frequent. Vision obstruction was coded in 5.5 percent of LTAP-OD crashes, and driver distraction was even lower.

Using police-generated crash reports, the BMI report cites three similar factors that affect a driver's decisions: i.e., obstructed line of sight, faulty perception (i.e., looked but did not see), and misjudgment (i.e., looked but misjudged the gap). Although valuable for helping to delineate the range of possible factors, the BMI report cannot be used to characterize LTAP-OD crashes in general. Unfortunately, being based on police reports, the GES is also limited for the purpose of understanding these variables as causal factors in crashes. Violations are given in only a minority of cases. Reported violations are often generic (e.g., 'violating right of way") and are applied inconsistently and without any detailed analysis of the crash. Vision obstruction and driver distraction are assumed to be incompletely noted by the police, and the GES data almost certainly produce underestimates of these problems.

An alternative source for studying vision obstruction or driver distraction, the CDS is based on a thorough investigation of crashes, and it may be more appropriate for understanding driver factors. However, the CDS is based on a much smaller sample, and as pointed out by Najm and Smith, multiple years of CDS data must be combined to allow adequate analysis of the impact of vision obstruction or driver distraction. Furthermore, even CDS detailed descriptions could be biased. CDS analyses are often based on interviews with drivers involved in crashes, and drivers' statements could be biased to deflect fault. For example, if a driver intentionally

waited for the amber or red indication to complete a left-turn maneuver or assumed that an oncoming vehicle would slow down or stop to avoid a crash, it is easier for the driver to say that he or she "looked but did not see".

One basic traditional engineering approach to reducing the frequency of LTAP-OD crashes at signalized intersections is a protected left turn signal phase. This measure is effective and will completely eliminate LTAP-OD crashes in the absence of a signal violation. However, this approach requires designating at least the left-most lane as a dedicated left-turn lane and implementing an extra signal phase. Also, it may decrease the overall capacity of the intersection, according to the BMI report. This approach is appropriate when there is a high volume of left turning traffic and when a dedicated left turn will not only reduce LTAP-OD crashes but may increase overall capacity by allowing left-turning vehicles to clear the intersection.

A second traditional engineering approach is to increase the duration of the amber or all-red interval. This approach may have limited application to LTAP-OD, particularly with a protected left-turn phase. Longer amber or all-red phases are considered to effectively reduce or eliminate dilemma zones that could exist on approaches to signalized intersections, but they also reduce intersection capacity. Longer amber and all-red intervals provide drivers with more time to make a decision to stop or to proceed through the intersection. Retiming the signal to provide sufficient green time may reduce running of red lights<sup>12</sup>.

Each of the traditional engineering approaches may lead to reduced intersection capacity, either through adding a dedicated left turn lane or through increasing total time required for signal phases. An alternative approach would be to provide information about potential risk to drivers as they near or enter the intersection; that is, IDS. If successful, this approach could provide information to drivers when risk is high, but allow optimum traffic flow at all other times.

The reports based on GES/CDS data and the BMI reports suggest several potential underlying causes of LTAP-OD: (i) obstruction of view (crucial information is not available), (ii) looked by did not see (did not recognize crucial information), (iii) misjudged gap (had information but was not able to interpret it accurately). While we do not feel there is adequate information in the literature to assign relative weights to these three, there is a potential common remedy, and that is to provide crucial information and to make that information salient. The IDS is being designed to help drivers make better decisions regarding obstructed lines of sight and driver judgments about gaps in oncoming traffic.

The two critical components of an IDS system are to identify risk or conflict and to provide information to the driver about the risk or conflict. For prevention of LTAP-OD crashes, algorithms for identifying risk or conflict will need to account for:

- highly variable (and even chaotic) behavior of SVs entering intersections to turn left;
- variable behavior of POVs approaching intersections;
- variation in SV and POV behavior connected with signal phase transitions;
- probable difference in speed of the SV and POV; and
- individual differences in drivers with respect to perception and reaction.

This significant challenge will require understanding of SV and POV behavior under both controlled conditions and under naturalistic roadway conditions. A special problem with LTAP-OD warnings at signalized intersections is adequate coordination of warnings to drivers with the signal phase.

## <u>SCP (Straight Crossing path) and LTAP-LD (Left Turn Across Path—Lateral</u> <u>Direction)</u>

SCP crashes account for about 14 percent of crashes at signalized intersections. In the SCP crash, the SV is proceeding straight across the path of the POV. Standard signal timing prohibits vehicles traveling in a perpendicular direction from being in the intersection at the same time, other then circumstances when a vehicle is allowed to turn right at a red light. Therefore, by definition, a SCP crash at a signalized intersection will take place only if at least one of the vehicles has violated the signal. The violation could take place at any point in the signal phase, but there appear to be two general cases.

In the first case, a SCP crash might occur at the green-amber-red transition if one of the vehicles (the SV) enters the intersection near the end of the amber or at the beginning of the red, and it encounters the POV just entering at the beginning of green (i.e., the SV driver attempts to "beat the yellow" by maintaining speed or even by accelerating, a very typical event). The likelihood of a crash <u>increases</u> if the driver of the POV attempts to get a "head start" or "jump the red." We hypothesize that crashes resulting from this scenario would most likely occur on the far side of the intersection from the viewpoint of the SV, since a delayed entry into the intersection would put the SV directly in front of the POV entering on it's green from the SV's right on the intersection far side. If true, this would have implications for which POV is the most important to warn.

In the second case, a SCP crash might occur during the red phase for the SV if the driver simply fails to see or to acknowledge the red signal or deliberately violates it. This event may be relatively rare. However, precisely because it is rare, it will be unexpected from the viewpoint of the POV, and it is therefore is hypothesized to carry relatively high crash risk.

There appears to be little data on the timing of SCP crashes to determine which of the two scenarios ("beating the yellow" versus "overt violation") is the more prevalent or whether these two scenarios are points on a continuum of behaviors. Studies on red-light violations suggest that most such violations occur at the beginning of the red phase and then drop sharply but continuously with each moment into the phase, according to two sources, Newton<sup>13</sup> (1997) and Retting, et al (1994). This suggests that entering patterns with respect to signal phase by SVs and POVs are defined by somewhat continuous (but only partially independent) probability distributions, with regions of the joint probability distribution defined by relatively high frequency but low risk and regions defined by low frequency but very high risk.

The LTAP-LD crash may be similar to the SCP. The difference is that the SV in the LTAP-LD crash may be slowing down for the turn or waiting for the vehicles in the opposite direction to clear. The LTAP-LD is less frequent (about 4 percent of crashes at signalized intersections) than the SCP. It is not clear whether this is because SV vehicles turning left are less likely to violate the signal, or whether the relative frequency of LTAP-LD versus SCP simply reflects the general traffic patterns that include less left turns and more driving straight through intersections.

Chovan and colleagues have conducted analysis of SCP crashes at intersections using data from the CDS. In their analysis, drivers who were attempting to beat the amber phase caused 16 per cent of the crashes, and drivers who were unaware of the signal presence and its status caused 41 percent of reported crashes. However, as mentioned above, the CDS is not representative of all crashes, and information from drivers could be biased or incomplete. Although information from the study by Chovan and colleagues can probably be taken to represent generic categories, reported percents should be extrapolated only cautiously to all SCP crashes at signalized intersections.

One potential countermeasure is to increase the duration of amber or all red intervals. Longer amber or all-red intervals are considered to effectively reduce or eliminate dilemma zones that could exist on approaches to signalized intersections. Presumably, longer amber and all-red intervals give drivers more time to make a decision to stop or to proceed through the intersection. This type of countermeasure

might be expected to reduce the type of SCP (or LTAP-LD) crash in which the SV is attempting to "beat the yellow" and/or the POV is attempting to "jump the red." However, there is some indication that longer intervals create more uncertainty as to whether a driver would stop or proceed through. This fact may contribute to a recent increased rate of rear-end crashes, according to Newton (1997). In sum, increasing the duration of amber or all red intervals may decrease intersection capacity as well as contribute to increased rear end crashes.

A second potential countermeasure is photo enforcement for red light running. This method, now adopted in numerous cities, involves automated detection of vehicles violating the red phase (i.e., vehicles entering at some pre-determined point after the beginning of the red phase), taking a picture of the vehicle, identifying the owner via the license number, and then citing the owner by mail. This method has proven effective in reducing the incidence of red-light running, it is less clear whether this method has had substantial impacts on reducing crashes involving red light running, per Retting<sup>14</sup>, et al (1994). Despite its promise, this approach is controversial because of privacy issues, and it is not clear whether red light running photo enforcement will be deployed on a scale large enough to impact SCP (and LTAP-LD) crashes on a national basis.

A potential IDS countermeasure for SCP (and LTAP-LD) crashes is aimed at detecting the potential "violator" and then warning either the violator or the drivers of the other vehicles. This type of warning is a mid-phase warning (i.e., after the all-red phase) designed to detect motorists who run a red light either intentionally or because they did not see the signal due to inattentiveness or obstruction by other vehicles or road geometry. Ferlis has conducted a detailed analysis of SCP crashes at intersections with respect to infrastructure-only and infrastructure-vehicle cooperative systems. A deployment model is developed that assumes sequential introduction of warnings first to infrastructure only-systems (i.e., warnings to all drivers) followed by roadside to vehicle communications (i.e., in vehicle warning systems). Based on the model developed by Ferlis, 88 percent of SCP crashes

could be addressed by providing warnings either to the "violators" or to other drivers entering the intersection. While having promise for preventing crashes when the SV driver violates during the mid-phase period, it is not as clear whether this approach would be effective for preventing crashes that occur closer to the phase transition. In general, IDS countermeasures offer the promise of preventing SCP and LTAP-LD crashes without reducing intersection capacity (as with increased time of signal phases) or encountering privacy issues (as with red light photo enforcement).

#### Rear End Crashes

Rear end crashes constitute about 40 percent of crashes at signalized intersections, which is almost as many as all crossing path crashes at intersections combined (about 42 percent). A rear-end crash occurs when one vehicle (lead vehicle) is struck from behind by another vehicle (following vehicle). The GES codes a number of scenarios. The lead vehicle may be stopped, moving with a constant speed, accelerating or decelerating. The following vehicle may also be moving with a constant speed, accelerating or decelerating. One possible scenario in a signalized intersection is that a rear-end crash occurs when a signal phase changes from green to amber to red, and the lead vehicle is stopped or decelerating while the following vehicle is moving with a constant speed, accelerating or decelerating. A second scenario is when vehicles intending to perform a left turn are stopped in the left lane waiting for a suitable gap in opposing traffic or for pedestrians crossing the lateral direction across the intended path. Therefore, the large percentage of rearend crashes at signalized intersections are probably due to a vehicle crashing into another when the latter vehicle is either (i) stopped or stopping for a red or amber light or (ii) waiting or slowing down to turn left or right (i.e., in situations involving uncertainty for the following vehicle). Based on the analysis of 1991 and 1992 CDS data, driver inattention and following too closely were causal factors in a majority of rear end crashes.

The IDS project is not intended to reduce rear-end crashes. Nevertheless, IDS measures at the very least should be designed to avoid contributing to the number of increasing rear-end crashes. Ideally, IDS measures would reduce rear-end crashes while also reducing crossing path crashes; i.e., it should not be assumed automatically that there will be a trade-off between crossing path and rear end crashes.

One of the basic types of information provided by IDS as currently conceptualized is one of warning; that is, of providing information when a potential conflict or risk develops as opposed to providing information when it is safe to proceed. Because of this approach, a successful IDS message would be followed by a change in a driver's speed or direction. While this change in response to warning should reduce the chance of a crossing path conflict or crash, from the viewpoint of a following vehicle, the behavior of the vehicle responding to the IDS information may include rapid changes in speed or direction which in turn creates uncertainty for the following vehicle and potentially contributes to a rear end crash.

Following are some steps that might be taken. First, observations could be made of "following" vehicles to determine patterns of behavior in response to changes in speed or direction of "leading" vehicles. Second, algorithms could be developed to model behavior of following vehicles. Finally, information from these two steps should be considered in designing and implementing IDS measures for avoiding crossing path crashes. Potential mitigating features might include IDS messages conveyed to both the lead vehicle and to all potentially affected vehicles.

At intersections controlled with two-way stop signs, nearly three-quarters of all crashes are attributed to SCP (45.5 percent) and LTAP-LD (24.7 percent). RTIP and LTIP account for a combined total of about 12 percent. This means that more than 82 percent of crashes at intersections controlled by two-way stop signs involve vehicles initially approaching one another from lateral directions. Remarkably, LTAP-OD and rear-end crashes account for only 0.4 percent each. Discussion here

will be limited to SCP and LTAP-LD, and since these two crash types at intersections controlled by two-way stop signs appear to be similar with respect to pre-crash scenarios, causal factors, and potential countermeasures, they will be discussed together.

An intersection controlled by two-way stop signs is one in which there are stop signs along one of two intersecting roadways (the "minor" roadway) and either no controls or just warning signs or signals on the other roadway (the "major" roadway). In this arrangement, most often the major roadways will have (i) more traffic and (ii) traffic with higher speeds than the minor roadway. Examples include a rural road intersecting with a state highway or a residential street intersecting with a major urban roadway. In some cases, the differences in traffic volume and speed might be dramatic. In addition, vehicles approaching the intersection from the minor roadway will be entering the intersection from a complete stop (assuming they stopped at the stop sign).

There appear to be two general scenarios. First, crashes may arise when a vehicle on the minor roadway stops at the stop sign and then enters a primary roadway, having to navigate higher traffic volumes, higher vehicle speeds, or both. Whether the vehicle entering the roadway from the secondary roadway is turning (either left or right) or proceeding straight through the intersection, the primary task is one of choosing an appropriate break in traffic (or "gap") on the primary roadway. Second, crashes may arise when the vehicle entering the intersection from the minor road simply does not see or acknowledge the stop sign, and enters the intersection without stopping first. While this event may be relatively rare it probably carries very high risk because it would be unexpected on the part of vehicles traveling on the major roadway.

Chovan and colleagues have conducted an analysis of SCP crashes at unsignalized intersections using the CDS. Of 100 crashes analyzed, 42 percent of drivers ran the stop sign, and the rest stopped and then proceeded. Three-quarters (74 percent) of

drivers were unaware of either the stop sign or the crossing traffic. It should be noted, however, that this analysis was done for intersections with stop sign controls but without distinction between two-way and four way placement of stop signs. Furthermore, the CDS has limitations already noted.

There are several traditional countermeasures for reducing crossing path crashes at intersections controlled by two-way stop signs. One countermeasure is to convert the intersection into a signalized intersection. However, a signal may create substantial delay along the major roadway, which may not be warranted if there is relatively low volume on the minor roadway. Furthermore, especially if the speeds on the major roadway are relatively high, a signal is likely to increase rear end crashes significantly. Another traditional countermeasure is installing signs that warn drivers on the major roadway of possible merging or crossing traffic. Other countermeasures could be focused on the minor roadway. "Stop Sign Ahead" warning signs and rumble strips are some of the ways to increase drivers' awareness of the stop signs ahead and flashing lights on signs. While possibly reducing the likelihood of running the stop sign, such countermeasures would not help drivers entering from the minor roadway in choosing an appropriate gap to enter the intersection.

Different IDS countermeasure might be employed for different presumed causal factors. For drivers running stop signs, IDS measures could be developed that detect vehicles that are likely to violate the sign and provide information to the vehicle before it runs the stop. Drivers would require information with sufficient time to stop the vehicle, and information would need to be salient enough to gain the attention of a driver who otherwise did not notice the sign. One potential risk would be increasing the risk for rear-end crashes, which is apparently very low under ordinary conditions at intersections controlled by two-way stop signs. Information that a vehicle was about to violate the stop sign could also be provided to the vehicle proceeding along the major roadway. The value of such information

for avoiding conflict with the violating vehicle would have to be weighed against the risk of increasing rear end or other crashes on a busy roadway.

For drivers on the minor roadway who have stopped and who are about to enter onto the major roadway, the major task is selecting an adequate gap and then successfully executing the entrance to the roadway. A critical task is to determine what gaps are sufficient and which are not. This is complicated by (i) individual differences in driver abilities and driving patterns, (ii) individual differences in vehicles performance, and (iii) uncertainty about the intended vehicle maneuver. (For example, for a vehicle intending to cross straight across the entire intersection, there are actually two gaps to measure: one for vehicles approaching from the left in the near lane, and one for vehicles approaching from the right in the lane). A critical issue is whether information should be communicated when there is risk (i.e., when gaps are narrow or infrequent), or alternatively when there are "safe" gaps. In the former case, there is danger that absence of a message might be interpreted as indicating a safe gap. In the latter case, there is danger that a message could be interpreted as a "green light," i.e., an indication that there is a protected period of time. These are critical issues for which careful research and consideration are required as IDS countermeasures are developed.

#### **2.8 Discussion of Intersections Controlled by Four-Way Stop Signs**

At intersections controlled by four-way stop signs, SCP, LTAP-OD, and LTAP-LD crashes comprise around 31 percent of all crashes (21, 6 and 4 percent respectively). Rear-end crashes constitute nearly 38 percent of all crashes.

Notable differences in crash patterns compared with intersections controlled with two-way stop signs (especially in SCP, LTAP-LD, and rear-end crash rates) indicate possible differences in causal factors. However, these differences are not explicitly addressed in the literature reviewed.

#### SCP, LTAP-OD, and LTAP-LD

At an intersection controlled by a four-way stop sign, vehicles approaching along either of two intersecting roadways are supposed to come to a stop and then proceed. The rules concerning right of way are implicit. Generally, if two vehicles arrive at the intersection from different approaches, the vehicle that arrives first has the right of way. If two vehicles arrive (more or less) simultaneously, then the vehicle to the right has the right of way. Based on typical requirements for a fourway stop intersection, the two intersecting roadways will be closer in traffic volume and speed than will two-way stop controlled intersections.

At an intersection controlled by a four-way stop sign, a crash can occur when, (i) one or both of the vehicles run the stop sign (deliberately or otherwise) and (ii) two vehicles approaching laterally both stop at a stop sign and then proceed with one or both of the drivers being unaware of the other. A possible alternative scenario for an LTAP-OD crash is as follows: Two vehicles approach a four-way stop sign controlled intersection and stop (simultaneously or separated by a small period of time). The driver intending to turn left fails to indicate this intention. Two vehicles start concurrently and the turning driver attempts to turn left, which is unexpected by the driver that proceeds straight, and a conflict ensues.

The significant differences in distribution of crossing path crashes between fourway and two-way stop sign controlled intersections may indicate the presence of a different mix of causal factors. It is likely that the majority of crashes occur when one or both of the drivers run the stop sign, and or, there is confusion about right of way at the intersection. In the absence of a stop sign violation, all vehicles should be traveling relatively slowly in a four-way stop controlled intersection compared to a two-way stop controlled intersection, where vehicles along the major roadway are entering the intersection without having to stop. Therefore, it is less likely that issues of gap selection are major factors in crashes at four-way stop controlled

intersections compared to either two-way stop controlled intersections or at signalized intersections.

Installation of traffic signals in tandem with reduction of speed limits are some engineering countermeasures that have been used to reduce the rate of crossing path crashes at intersections with four-way stop signs. As in the case of two-way stop sign controlled intersections, installation of "Stop Sign Ahead" warning signs and rumble strips could be used to increase drivers' awareness of the stop sign downstream.

IDS systems may be employed to alert (i) the likely violators that a stop sign violation is imminent (ii) the drivers on lateral approaches about the possible violation. Certain factors are important in determining the warning point. These factors include (a) the approach speeds of both SV's and POV's (which could be highly variable); (b) decelerations of these vehicles, and (c) their distances to the intersection among other factors. In both above situations, the warning must be provided so the drivers are able to react to it. Reliable algorithms to determine the likely stop sign violators and the threshold to provide warning to the drivers are essential, as significant number of false alarms would reduce effectiveness and warnings will be rendered useless if issued too late.

#### Rear-End Crashes

The percent of crashes that are rear-end crashes at four-way stop controlled intersections (nearly 38 percent) is similar to that for signalized intersections (40 percent). The pre-crash scenarios are of course substantially different. At signalized intersections rear end crashes most likely occur when a leading vehicle is either stopping for a red light, or waiting to turn left turning a green or amber phase. It is not clear why the percent of rear end crashes should be so much higher at fourway stop controlled intersections than at two-two stop controlled intersections, expect it may reflect heavier traffic that would be expected at the four-way stop intersection. As with IDS warnings given for potential red light violators in a

signalize intersection, IDS warnings given to potential violators of a stop sign in a four-way stop sign controlled intersection could result in sudden reductions in speed, which might increase the probability of a crash with a following vehicles. IDS measures for preventing stop-sign violations should be designed with potential rear-end collisions in mind.

Table 2-7. Spee	d limit by	crash typ	e (intersec	tion crash	es only, G	ES	
2000)							
Speed Limit							
Crash Type	LE 25	25-30	35-40	45-50	55-60	60+	Total
(Number)	464,318	357,788	1,196,630	584,839	186,966	17,024	2,807,565
LTAP-OD	10.0	11.2	51.0	22.4	5.1	0.2	100.0
LTAP-LD	12.0	10.8	45.2	22.8	8.5	0.8	100.0
RTIP	13.1	14.0	42.4	22.0	7.8	0.8	100.0
LTIP	12.7	11.7	48.3	22.5	4.0	0.8	100.0
SCP	23.8	16.2	37.7	14.6	6.9	0.8	100.0
OTHER CP	23.6	14.3	41.3	15.0	5.6	0.2	100.0
Total Crossing path	17.2	13.6	43.5	18.7	6.5	0.6	100.0
Crashes							
REAR END	9.5	11.1	45.6	26.7	6.6	0.5	100.0
PED/BIKE	34.3	13.3	36.5	10.5	5.0	0.4	100.0
SINGLE	29.5	13.7	29.4	15.2	10.9	1.4	100.0
OTHER CRASHES	20.8	13.3	40.7	18.8	5.7	0.6	100.0
Total Non-Crossing	16.0	12.1	41.9	22.5	6.8	0.6	100.0
paul Crashes Total	16.5	12.7	42.6	20.8	67	0.6	100.0
i otai	10.5	14.1	72.0	20.0	0.7	0.0	100.0

#### 2.9 Intersection Crashes by Speed Limit (Variable A18 in GES)

A majority of intersection crashes take place where the speed limit is relatively low. For example, about three-quarters (72 percent) of intersection crashes take place at intersections where the speed limit is less than or equal to 40 miles per hour; an additional 21 percent take place where the speed limit is 45-50 miles per hour. Only 7 percent take place where the speed limit is 55 miles per hour or greater. Even assuming that the average vehicle speed is higher than the posted speed, this finding suggests that most intersection crashes occur between vehicles traveling at moderate speeds.

Implications for IDS are:

• This analysis shows that the vast majority of intersection crashes take place at locations where the speed limit is less than or equal to 60 mph, and a large majority take place where the limit is less than or equal to 50 mph. While actual average speeds may exceed the posted speed limit, the speed profile would still be fairly low after adjusting for drivers exceeding the speed limit. Observation studies may help to clarify the role of speed in intersection crashes and the profiles of speed to be expected in relation to the posted speed.

• These results have general implications for generating algorithms for crash detection, gap selection, crash warning, and ultimately, for the characteristics of IDS systems that are deployed.

#### 2.10 Intersection Crashes by Age and Gender

Older drivers are relatively over-represented in crossing path crashes compared to other crashes, as seen in Table 2-8. For example, older drivers are 10.9 percent of all drivers in crossing path crashes, compared to being just 6.4 percent of all drivers in other crashes. Younger drivers are over-represented in single vehicle crashes, again shown in Table 2-8. Focusing on crashes in which SV and POV have distinct roles, and it is possible to distinguish these roles in the GES (each of the major crossing path collisions except for SCP, and rear end collisions), older drivers were highly over-represented in LTAP-OD crashes, slightly over-represented in the other crossing path collisions, and slightly under-represented in rear end crashes. These patterns could be tested by combining more years of data for increased reliability.

Table 2-8.	Crash type by Age (GES 2000)							
	<=24		24-64		>=	=65	Total	
Crash Type	Number	Percent	Number	Percent	Number	Percent	Number	Percent
LTAP-OD	192,882	28.3	410,509	60.2	78,088	11.5	681,478	100.0
LTAP-LD	116,008	30.0	228,370	59.0	42,500	11.0	386,878	100.0
RTIP	33,402	28.4	69,822	59.3	14,546	12.4	117,770	100.0
LTIP	31,414	28.7	62,120	56.7	16,029	14.6	109,564	100.0
SCP	269,215	26.9	625,473	62.6	104,449	10.5	999,136	100.0
OTHER CP	45,407	22.7	137,170	68.7	17,229	8.6	199,806	100.0
Total Crossing path	688,328	27.6	1,533,464	61.5	272,841	10.9	2,494,632	100.0
Crashes								
REAR END	473,157	26.1	1,225,865	67.7	110,396	6.1	1,809,419	100.0
PED/BIKE	17,907	21.4	58,137	69.6	7,503	9.0	83,547	100.0
SINGLE VEHICLE	73,509	38.8	104,601	55.2	11,277	6.0	189,387	100.0
OTHER CRASHES	173,350	23.6	510,264	69.6	50,035	6.8	733,649	100.0
Total Non-Crossing	737,923	26.2	1,898,867	67.4	179,211	6.4	2,816,002	100.0
path Crashes								
Total	1,426,251	26.9	3,432,331	64.6	452,052	8.5	5,310,634	100.0

Table 2-9	D. Types of	f crashes for	drivers over	age 65 by	role in crash.	
		Role in Crash				
	S	V	PO	V	Tot	al
Frequency	Number	Percent	Number	Percent	Number	Percent
LTAP-OD	55,003	16.1	23,085	6.8	78,088	11.5
LTAP-LD	23,071	11.9	19,429	10.0	42,500	11.0
RTIP	7,982	13.6	6,564	11.1	14,546	12.4
LTIP	8,246	15.1	7,783	14.2	16,029	14.6
REAR END	50,979	5.6	59,417	6.6	110,396	6.1

Implications for IDS are:

- Older drivers are more heavily represented in crossing path crashes vs. other crashes at intersections.
- Younger drivers are over represented in single vehicle crashes.
- Where the distinction can be made in the GES data, older drivers are overrepresented as the driver of the SV compared to the POV.
- If a potential higher risk combination of drivers in crossing path crashes involves an older driver in SV, IDS designers should pay particular attention to make the system effective with respect to older drivers.

Table 2-10.	Crash Type, by Gender (GES 2000)						
		G					
	Ma	Male		ale	Total		
Crash Type	Number	Percent	Number	Percent	Number	Percent	
LTAP-OD	384,864	56.5	296,616	43.5	681,480	100.0	
LTAP-LD	209,143	54.1	177,735	45.9	386,878	100.0	
RTIP	64,858	55.1	52,912	44.9	117,770	100.0	
LTIP	59,959	54.7	49,605	45.3	109,564	100.0	
SCP	574,152	57.5	424,984	42.5	999,136	100.0	
OTHER CP	123,096	61.6	76,710	38.4	199,806	100.0	
Total Crossing	1,416,072	56.8	1,078,562	43.2	2,494,634	100.0	
hes							
REAR END	1,036,580	57.3	772,838	42.7	1,809,418	100.0	
PED/BIKE	52,640	63.0	30,908	37.0	83,548	100.0	
SINGLE	137,369	72.5	52,018	27.5	189,387	100.0	
OTHER	469,566	64.2	262,330	35.8	731,896	100.0	
Total Non-	1,696,155	60.3	1,118,094	39.7	2,814,249	100.0	
ath Crashes							
Total	3,112,227	58.6	2,196,656	41.4	5,308,883	100.0	

Female drivers were slightly over-represented in crossing path crashes, while male drivers were over-represented in single-vehicle crashes. The differences for crossing path collisions do not seem large enough to be important in designing IDS measures.

#### 2.11 Conclusions from Intersection Crash Data

Findings in this section include the following: (i) crashes at intersections represent a very high percent of all U.S. crashes, making intersections relatively high risk compared to other roadway segments; (ii) crossing path collisions represent 25 percent of all US police reported crashes, and almost 45 percent of crashes at intersections, making crossing path collisions a very substantial portion of the total crashes in the U.S.; (iii) patterns of crashes, including patterns of crossing path crashes, differ substantially by type of intersection (defined by traffic control device)-these differences reflect different underlying causal factors and require different applications of IDS measures; (iv) crossing path collisions at intersections take place at moderate speeds, which is important for algorithms for warning systems; and (v) older drivers are relatively over over-represented in crossing path collisions at intersections, but there is no over-representation by gender (by either male or female). IDS countermeasures need to account for these and other statistical findings, as well as findings from studies of vehicle movement and conflict at intersections, and studies of driver behavior at intersections. While there are significant challenges in detecting potential risk and providing appropriate information to drivers, IDS countermeasures show promise of addressing a significant portion of crossing path collisions at intersections.

## **3.0 Develop Top Level Requirements for Types/Classes of Intersection Crashes**

This section is a product of a brainstorm of a list of stakeholders and a viewpoint of their needs and roles. Each stakeholder has particular constraints, needs and objectives with respect to this system. Drivers and other users are particular stakeholders. Certain stakeholders are able to impose constraints on the qualification or acceptance process, including that their approval is a requirement for system acceptance. The eventual stakeholder perspective can be used as input to the system performance metrics.

#### 3.1 Stakeholder Matrix

IDS technology has many potential stakeholders: individuals, government entities, and companies in the private sector. Individual stakeholders include drivers and non-motorists (e.g., pedestrians and bicyclists). Government entities include legislative and administrative bodies (particularly departments of transportation). at local, county, and federal levels. Stakeholders in the private sector include companies that install or operate systems, equipment manufacturers, automobile companies (at least for vehicle-infrastructure cooperative IDS systems), and insurance companies. These categories of stakeholders represent a wide range of roles, concerns, and needs. Ultimately, success of IDS approaches will depend on the capacity to deliver cost-effective safety improvements. However, successful development and deployment of IDS systems will also depend on understanding the roles and addressing the concerns and needs of the various stakeholders. An initial list of potential stakeholders, along with roles, concerns, and needs, is summarized in Table 3.1 below. Please provide comments, additions, and corrections for incorporation into the matrix.

Stakeholders	Role(s)	Concerns/Issues	Needs
Vehicle operators	Target population that will	Safety	System must
	be directly affected		accommodate
	(positively or negatively) by	Travel delay	performance
	IDS deployment		characteristics of
		Travel costs	operators such as
			attention, perception,
			reaction time,
			cognition, and
			peripheral vision.
Other Intersection	Population of intersection	Safety	System must
Users:	users that could be affected		accommodate
Pedestrians	by IDS deployment	Travel delay	capabilities of these
Bicyclists	(directly or indirectly)		users and account for
Disabled persons		Compatibility with	differences in their
		ADA standards	performance (e.g.
			older adults, children)
		Comfort and ease of	
		use the intersection	System must
			accommodate or be
			compatible with ADA
			requirements
Legislative Bodies	Provide funding	Cost	Information on
			effectiveness, and cost
	Set transportation priorities	Cost-effectiveness	effectiveness.
	(e.g., importance of safety		
	in relation to other	Adverse effects	Information on the
	transportation needs).		societal burden of
			intersection collisions.
	Develop legislation related		
	to setting standards and		Clear, understandable
	guiding regulation.		descriptions of IDS
			systems, with
			explanation of
			function, costs,

Table 3.1. Draft list of Stakeholders, Roles, Concerns/Issues, and Needs

			benefits.
Local governments	Responsible for planning,	Effectiveness	Standards for
(Departments of	design, installation,		prioritizing potential
Transportation)	operation, and maintenance	Costs (e.g.	deployment locations
	of IDS system for local	installation,	(similar to warrants in
	roadways	operation, and	MUTCD)
		maintenance)	
	Responsible for funding		Means of evaluating
		Personnel training	effectiveness of IDS
	Interface with local		system as compared to
	constituencies (e.g., other	Potential exposure to	other intersection
	agencies, community	liability	measures (e.g. traffic
	groups)		signals)
		Increased potential	
		exposure to tort	Reasonable cost in
		liability. The larger	comparison to
		the portion of a	alternative methods
		driver task that is	
		yielded to an	Ease of operation and
		electronic system, the	maintenance
		larger the potential	
		exposure	Help with costs related
			to installation,
			operation, and
			maintenance of IDS
			systems is required.
			Set of procedures to
			determine where the
			installation of IDS
			systems is feasible and
			worthwhile, as well as
			a means of prioritizing
			the intersections for
			IDS deployment.
			Technical support in

			operations and
			maintenance.
State governments	Responsible for planning,	Effectiveness	Means of evaluating
(Departments of	design, installation,		effectiveness of IDS
Transportation)	operation, and maintenance	Costs (e.g.	system, as compared to
	of IDS system on state	installation,	other intersection
	highways	operation, and	measures (e.g. traffic
		maintenance)	signals)
	Development of operating		
	specifications and standards	Potential exposure to	IDS countermeasures
	(e.g., Traffic Control	liability	should be compatible
	Devices Committee)		with other
			countermeasures as
	Funding at both state and		well as with existing
	local level		traffic control devices.
Federal government	Major course of funding	Effectiveness in	The immediate need is
(Department of	for the development of	providing safety	to determine the
Transportation)	IDS.	benefits.	feasibility of IDS
			system and to identify
	Major player in	Cost in comparison	potential standards and
	development of IDS	to other	performance
	operating specifications	approaches.	characteristics.
	and safety standards.		
			The system must be
	Power to indemnify the		nationally deployable
	parties responsible to desigr		
	and deployment of IDS		The system should
	system of liability (e.g., as		address as wide a
	was done for some		range of crash types as
	pharmaceutical companies).		possible
			The system should not
			have adverse effects,
			such as substantial
			impacts non-cross path
			collisions, or reduced
			intersection capacity

Private System	In some locations,	Potential exposure to	Clear standards and
operators	installation, maintenance,	legal liability	regulatory guidelines
	and operation of IDS		for installation,
	systems.	Costs	operation, and
			maintenance.
			Opportunity for profit
Equipment	Manufacture equipment to	Effectiveness	Clear standards and
manufacturers	be installed at intersections		regulatory guidelines
	selected for IDS	Development costs	for installation,
	deployment. The presence	vs. profitability	operation, and
	and flexibility of the		maintenance
	manufacturers that are	Potential exposure	
	willing to commit their	to liability	Economic
	production capabilities to		considerations in
	make IDS equipment at the	Marketing	production of
	early stages of IDS		equipment.
	deployment are significant		
	factors in timely		Opportunity for profit
	proliferation of the IDS		
	systems.		
Automakers	During the early stages of	Development costs	Sources of funding
	IDS deployment, no		for research and
	equipment is expected to be	Ultimate return on	development
	installed inside vehicles.	investment	
			Specification of
	However, subsequent stages	Marketability	standards
	may require introduction of		
	devices to communicate	Level of responsible	Some protection from
	warnings to drivers inside	for maintenance and	liability
	vehicles. At these later	repair of the in-	
	stages, the automotive	vehicle intersection	Public acceptance.
	manufacturers are expected	collision avoidance	
	to play a significant role in	devices.	
	the development of in-		
	vehicle devices and		
	infrastructure-vehicle		

	communication standards.		
Insurance providers	Providing insurance for (i)	Safety benefits	The availability of a
	vehicles, (ii) system		standard set of
	operators, (iii) equipment	Potential adverse	procedures to
	manufacturers, (iv)	impacts	evaluate the possible
	automakers		risks.
		Level of reliability	
	Availability of adequately	(i.e., possibility of	Approved regulatory
	priced and sufficient	system failure)	status (e.g., MUTCD)
	insurance coverage could		
	be an important factor for		
	successful and timely		
	deployment IDS.		

### 4.0 Conduct Enabling Research & Development

#### 4.1 IDS Architecture

We have developed a general architecture to address the wide variety of intersection safety scenarios which we envision. This is intended to meet the minimum criteria of being nationally interoperable, with a clear near- to longer-term technology progression, where the architecture is at all times applicable. This architecture is intended to be flexible, agnostic with regard to infrastructure or vehicle deployment paths and, we believe, applicable to CICA.

We illustrate our architecture in Figs 4.1-1 through 4.1-3 below. At the top level is the driver, who can receive inputs from infrastructure or vehicle devices. These devices are actuated by the IDS system. The IDS system might be entirely resident in the vehicle (with example shown in the subsequent figure), entirely resident in the infrastructure (with the next example) or in the cooperative case, partially resident in both (in the last figure). Note that an important architectural concept is a state map generator, which represents the intersection dynamics (movements of all

approaching vehicles and state of the traffic signal). From that, a state map predictor can support a conflict predictor, a gap predictor (e.g., for use by Minnesota's LTAP/LD advisory system), and/or a stop predictor (e.g., for use by the Virginia traffic control device violation warning system). As illustrated in the figures, the information regarding the vehicle motions can be obtained from sensors in the vehicles and/or the infrastructure.



Fig. 4.1-1. Conceptual IDS Architecture


**Fig. 4.1-2: Example IDS Architecture Application Entirely in the Vehicle** 



Fig 4.1-3: Example IDS Architecture Application Entirely in the Infrastructure

# 4.2 Human Factors

The review covered in this section addresses the Human Factors aspects involved in the project of designing an IDS system. It aims at providing insight for the modeling effort, the data collection and countermeasures design.

In order to provide insight for the modeling task, two aspects are investigated, the identification of existing drivers' models at intersections and driver behavior description, specifically in terms of gap acceptance. The support to the data collection is realized through the identification of parameters to measure as well as a method to obtain necessary data. Finally, the countermeasure design inputs are

presented. These inputs are based on information about driver errors and prototypical systems.

This literature review focuses on driver behavior and underlying perceptive and cognitive aspects for two types of crashes, LTAP/LD and LTAP/OD. We refer to the driver of the Subject Vehicle (SV), who is usually considered as the driver who could benefit from a support or warning, and the driver of the Principal Other Vehicle (POV). These two types of crashes can be observed at different intersections, such as:

- Unsignalized intersections, with a major and minor stream and with a focus on the behavior of the driver coming from the minor stream. The SV driver is on the minor stream and has to give the right of way to the major stream
- Signalized intersections with permissive left turn, where the driver who wants to make a turn has to use his/her own judgment about when an approaching vehicle is far enough away to allow turning.
- Uncontrolled intersections, where a driver intends to make a left turn on a minor street from a major stream of traffic. The minor street may be controlled by a two way stop but the driver.

The two last cases have in common a driver making a left turn who is not required to stop before the turn. The driver's choice is dependent on the presence of oncoming traffic.

This section contains six subsections:

 Driver Errors at Intersections. We develop a taxonomy of driver errors at intersections. The two aspects explored in more detail are issues in understanding the right of way and in estimating the time gap. The specific case of older drivers is also highlighted.

- 2. Gap Acceptance. Gap acceptance research and theories are described in fair detail. We discuss the perceptive mechanisms involved in the detection of traffic at intersections and how this can influence gap acceptance. We perform some synthesis or translation of various data sources and fuse them onto a common nomograph, leading us to some insight to gap acceptance with regard to various influencing factors (e.g., age, gender, speed).
- Perception Reaction Time. We illustrate that the reaction time is a concept largely dependant on the precipitating event to which the driver responds. The three types of reaction that we explore in more detail are related to perception of traffic, traffic signals and warnings.
- 4. Countermeasures. In the context of our human behavior orientation, we discuss prior intersection collision warning and information prototypes and how they operate on the driver's cognitive system.
- 5. Synthesis. We conclude with a synthesis of the prior sections, upon which we develop guidance that this literature review has for the other tasks in the project and specific IDS design insights in particular.

With respect to driver model development, specific guidance has been provided through the literature on three modules:

- Perceptive module
  - Perception of other vehicles and scaling of their velocities
  - Perception of traffic signs
- Tactical
  - o a database about drivers' knowledge about intersection crossing:
    - Expectancies
    - Sequence of goals as the driver approaches the intersection and associated actions
    - Thresholds about gap acceptance, braking for stopping at the intersection, steering

- Decision making component matching the simulations inputs with the driver database
- Operational
  - Type of braking
  - Type of steering

With respect to countermeasure development, the literature review illustrates very well that driver performance problems are have a variety of origins, based largely on intentions. The types of crashes covered by IDS points to two types of factors: inadequate knowledge and infrastructure-related. Therefore, key elements would include:

- <u>Detecting driver intent</u>. The results from Lloyd<sup>15</sup> et al. (1997) are encouraging because they raise the possibility of measuring driver intent in complying with a stop sign. They indicate that braking behavior could be a cue for estimating the behavior prior to the intersection (e.g., type of turn or proceeding straight). The modeling effort from Chovan et al. (1994) is also encouraging in terms of possibility of identifying driver intention to turn at a signal-controlled intersection.
- <u>Consideration of driver characteristics and type of vehicles</u>. The field observation study conducted by Harwood<sup>16</sup> et al. (1999) illustrates that drivers of trucks require more time to make a left turn with lateral traffic present. All of the other researches on gaps acceptance cited also made the case that older drivers prefer longer gaps than younger drivers.
- <u>Cues for gap acceptance in LTAP/OD and LTAP/LD cases</u>. In the former case, drivers seem use distance rather than time to intersection or time gap. In the latter case, drivers seem to use a constant time gap rather than a distance.
- <u>Reaction time, or rather decision time, is a challenging dimension to assess</u>. This literature review illustrates that what is usually called *reaction time*, *perception reaction time*, or *perception decision time* is really a composite

of several sequences. Some of these can be assumed constant and others will vary based on driver expectancies, recognition and decision. Therefore, in considering reaction times (or similar measured) should consider variations in:

- Identification. The choice of the location of the display in the infrastructure will influence reaction time.
- Comprehension. Williams<sup>17</sup> et al. (1992) recommendation that the presentation of left turn only messages should be include the following considerations:
  - Red arrows use should be accompanied by an educational program
  - Green arrows should always be used for protected left turns.
  - Circular red and green arrows should not be shown simultaneously.
  - Auxiliary signs are difficult to see at night and can be confusing or superfluous.
- Decision. Staplin S. and Fisk A.<sup>18</sup> (1991) illustrate that information redundancy improved understanding rate and decision time

With respect to data collection, there is very little from the literature that is intersection-specific – at least to the degree of fidelity and modeling we believe is necessary to fully understand driver perceptual and cognitive issues. As a result, we have constructed (again, partially from direct literature but also from our recognition of the holes in the literature, or indirectly) the following itinerary:

One of the first issues to arise is the problem of measuring cross traffic flow with an instrumented vehicle. Therefore, this type of measurement will not be realized in the field but on an instrumented intersection which can measure traffic on each of its legs and synchronize this information. A left turn at traffic light scenario can also be difficult to observe as the experimenter has no control over the light cycle, presence of other traffic, or when the subject reaches the intersection. In order to

overcome this, driver behavior at intersections such as the one described in figure 6 B will also be observed.

Here is a primary list of elements that will be investigated during the data collection include:

- Observe scanning during the approach of the intersection for supporting the location of the display in the infrastructure
- Test gap acceptance when driver can revise their judgment
- Look at the stop vs. non stop decision using distance and oncoming vehicle speed instead of only time to intersection as what cited by Chovan et al. (1994)
- Take age and sex into consideration
- Investigate gap acceptance with lateral traffic in experimental set up, looking at distance and traffic speed

# 4.2.1 Driver errors at intersections

Understanding and describing driver behavior becomes a challenge when one tries to identify driver errors in determining crash causal factors and countermeasures. Access to data related to crashes is usually based on crash statistics and restricted to general characteristics of the involved drivers, such as gender, age, type of vehicle driven (Kim<sup>19</sup> et al. 1999). Very rarely are the actions and maneuvers that led to a crash addressed. The investigation of pre-crash actions and maneuvers usually relies on either focus groups involving officers who respond to crashes or drivers involved in crashes (Wierville<sup>20</sup> et al. 2002, Larsen and Kines<sup>21</sup> 2002). They therefore rely on subjective sources. Another approach adopted for understanding why crashes occur consists of linking general characteristics with known issues of specific group, such as age linked with perceptive and cognitive deficits (Hakamies-Blomqvist<sup>22</sup> 1996).

Wierville et al. (2002) proposes the following definition of driver error based on Reason's seminal work: "... the failure to achieve a sequence of mental or physical activities through a thought-out plan-of-action. For example, within the driving environment, an error is committed when a driver does not successfully stop for a red traffic light because he or she depresses the accelerator instead of the brake pedal. (p. 1)". The authors also distinguish between unsafe acts that are intended or unintentional. After an extensive review of several taxonomies about driver errors and investigation of crashes, the authors proposed a taxonomy of contributing factors affecting the driving performance (see Figure 4.2-1).

#### Inadequate knowledge, training, skill

- Lack of understanding or misunderstanding of:
  - Traffic laws
  - Vehicle kinematics, Physics
  - Driving techniques
  - Driver capabilities, limitations

#### Impairment

- Fatigue and drowsiness
- Use of illegal drugs, alcohol
- Health related
  - o Illness
  - Lack of use of, incorrect use of medication
  - o Disability, Uncorrected disability

#### Willful Inappropriate behavior

- Purposeful violation of traffic laws, regulation
- Aggressive driving
- Use of vehicle for improper purposes
  - Intimidation
  - As a weapon

#### Infrastructure, Environment problems

- Traffic control device related
- Roadway related
  - Alignment
  - Sight distance
  - delineation
- Weather, visibility related

## Driving performance problem

- Failure to perceive or perceive correctly
  - o General
  - Due to distraction
  - Due to inattention
  - Incorrect assumption
- Incorrect cognitive processing
- Failure to act

•

Incorrect action

# Figure 4.2.1: Taxonomy of contributing factors affecting driving performance, p 210 in Wierville et al. 2002

The taxonomy is interesting because it illustrates the diversity and origins of the problem of degraded driving performance and classifies it into several major categories: inadequate knowledge, training, skill, impairment, willful inappropriate behavior and the infrastructure/environment problem.

The scope of IDS addresses mainly two of these categories, inadequate knowledge and the infrastructure/environment problem. In the first, the two major aspects on which we focus are the lack of understanding or misunderstanding of the traffic law and the vehicle kinematics. For the last category, we mainly address infrastructure problems with sight distance.

# 4.2.2 Understanding of signals

Williams et al. (1992) conducted a mail survey in Texas about the understanding of left-turn signal indications and auxiliary signs. They investigated four different types of display configurations (concerning the number and location of traffic heads) for drivers in a left turn bay, and tested a total of 40 scenarios of feasible left-turn signal/auxiliary sign combination. They collected 894 surveys composed of the 40 scenarios and demographic information about the person who filled the questionnaire. Their results are percentages of incorrect responses. Tables 4.2-1and 4.2-2, respectively, display the percentage of incorrect answers for the different combinations of green and red phases.

Table 4.2-1: Understanding of green phase for left turn (in Williams et al.
1992)

Display Meaning	Signal display	Sign	Number of	% incorrect
			Responses	
	(G) (G) (G)	none	84	50
Cincular mean	GRR	LEFT TURN SIGNAL	73	42
protected only	@@@	LEFT TURN SIGNAL	96	65
	GG	PROTECTED LEFT ON GREEN	89	43
	GRR	none	107	47
Green arrow	$\underline{G}(\mathbb{R})$	none	83	17

protected-only	₫ @@	none	109	16
	G R R	LEFT TURN SIGNAL	81	17
	Q (G) (G)	LEFT TURN ON ARROW ONLY	82	20
	<u>G</u> R R	none	96	9
	₫ @@	none	95	27
	<u>G</u> R R	LEFT TURN SIGNAL	103	17
	Q Q Q		103	31
	GRR	LEFT TURN SIGNAL	92	14
	Q (Q) (Q)	LEFT TURN SCHAL	69	23
Circular rad and	$\mathbb{R} \subseteq \mathbb{R} \mathbb{R}$	none	79	23
green arrow	$\mathbb{R} \subseteq \mathbb{R} \mathbb{R}$	LEFT TURN SCHAL	93	34
	<u>⊊</u> ® ®	none	80	20
Green arrow	GRR	PROTECTED LEFT TURN ON GREEN ARROW ONLY	86	5

The presence of the circular green is often interpreted as a permissive rather than a protected left-turn, even when there is an auxiliary sign. The green arrow seems to be better understood than the green circle, as an indication of a protected left turn. The use of the green arrow with a circular red also seems confusing to drivers.

Display	Signal Display	Sign	Number of Responses	% incorrect
Meaning				
	₽ @ @	none	110	33
Red arrow	<u>₽</u> @ @	LEFT TURN SIGNAL	75	52
	<u>₽</u> @ @	none	107	29
	<u>₽</u> @ @	LEFT TURN SIGNAL	91	31
	RGG	none	103	24
Red circle	RGG	LEFT TURN ON ARROW ONLY	95	21
	RGG	none	87	13
	RGG	NO TURN NO RED	68	28

 Table 4.2-2: Understanding of red phase for left turn (in Williams et al. 1992)

The red arrow appears to be more confusing than the red circle, probably because drivers interpret the red arrow as an indication rather than a prohibition. The other reason advanced by the researchers is that red arrows are not widespread in Texas.

Williams et al. (1992) observed that the factors most influencing the number of wrong answers were years of driving and age. The drivers with the smallest numbers of incorrect responses had been driving for 11 to 20 years, and drivers aged 26 to 35 had the lowest percentage of incorrect responses. Drivers 65 years of age and older presented the highest percentage of incorrect answers (35%).

Staplin and Fisk (1991) investigated older drivers' difficulties with intersections. They assumed that elderly drivers were over represented in intersection car crashes due to the complexities inherent at intersections. As a driver approaches the intersection, he/she has to make a decision about his/her right of way over oncoming traffic. Making this decision requires integration of different pieces information from different sources (signs and signals). The underlying causes were identified to be perceptive and cognitive problems. "Perceptive" can be defined in terms of visual acuity and contrast sensitivity lost. "Cognitive" relates to working memory and information processing.

In order to test this assumption, the authors ran an experiment on a driving simulator with two groups of subjects, one composed of 25 young drivers (age 18-49, mean age = 36.8) and one composed of 30 elderly drivers (65 to 80, mean age = 70.6). They presented each individual with two sets of signals (e.g., green arrow, green ball) and signs (e.g., left turn signal, protected left on green arrow) combination. Each set was composed of 12 signals and signs. One set conveyed the message that a driver approaching this intersection and making a left turn had the right of way to oncoming traffic, or "go" information, while the other set had "no go" information, where drivers were to leave the right of way to oncoming traffic. Two cases were investigated. In one case, the sign and signal were presented together; in the other case, the sign was presented 5 sec before the signal/sign combination. Subjects had to perform a secondary task in order to recreate a situation close to driving, where attention has to be divided between several tasks. Subjects had 10 sec to answer, beginning at the point where the signals become visible.

The results of this study showed that elderly drivers were in all cases significantly slower than the younger drivers to decide whether they could go, and that the difference between elderly and younger drivers was of about a half second. There was no significant difference between the different modalities of information presented for either group. The assumption that presenting information in advance would aid older drivers was not shown true, as this did not help older drivers to make a faster decision in the end. Another very interesting result from this study is that both groups better interpreted "go" messages than the "no go" messages. The mean percentage of correct answers was of about 80% for the "go" situation, while it was about 55% for the "no go" situation. This raises serious questions about

driver understanding of MUTCD-compliant signs meant to establish to drivers the right of way.

### 4.2.3 Estimation of Gaps

Larsen and Kines (2002) reported on an extensive investigation of crashes in Denmark by a multi-disciplinary team constituted of a road engineer, vehicle inspector, police superintendent, physician and two psychologists. They investigated a total of 17 head-on collisions and left-turn crashes. For two of these crashes, they considered that the POV behavior contributed to the crash by making it difficult for the SV driver to estimate the amount of time available for the maneuver. The main problems they identified for left turning drivers are attention errors and misjudgment of the time available to complete the maneuver. None of the cases they investigated was due to a driver who misunderstood the right of way. Older drivers were over represented on these types of crashes.



3 Driver is still looking out for road users from the right, and forgets to look to the left again

# Figure 4.2-2: Example of a "look did not see" crash, p.377 in Larsen and Kines (2002)

Figure 4.2-2 illustrates an example of "a look did not see crash". The interpretation of the authors is that the driver forgot to look to the left when ready to merge on the

major road. Another interpretation is that when the driver first looks to the left and sees that there is no car, he infers that the lateral direction is clear and focuses all of his attention to the right. Supplementary information that would be interesting to have about this crash is whether there was traffic coming from the right justifying the "continuous" surveillance to that side. The authors classify the cause of this the crash as inattention. Another explanation is the application of an inappropriate heuristic such as, "If there is no traffic from the left when I look from before the intersection, then there is no threat from the left".

## 4.2.4 Older drivers

In the research reported in the two previous sections, most mentioned age as a factor toward understanding right of way at intersection and estimation of gap. In fact, older drivers are over represented on the basis of miles driven in intersection accidents, left-turn accidents and gap acceptance accidents. Garber and Srinivasan (1991), looking at data from VDOT, noticed that the differences in left turn involvements by age group approximately doubled between the age bins of 45-49 and ages above 79. Right-turn involvements increased between those two age groups, too, but only slightly.

Hakamies-Blomqvist (1996) described the risk factors at intersections with regard to age-related changes. She identified the task demand based on what she terms "functional domains" of perception, attention, motor performance, and interactions with other drivers/vehicles (see Table 4.2-3). This list is quite exhaustive and does not imply that each elderly driver exhibits all of these age-related changes. However, it does illustrate that older drivers' difficulties lie on perceptive, attentional and motor issues.

Table 4.2-3: Risk factors in intersection driving: task demands and age related	
in cognitive performance, (p. 97 in Hakamies-Blomqvist (1996))	

Functional domain	Task demand	Age-related change	
	• Detect objects at large	• Visual field shrinking	
	visual angles	• Decrease in dynamic	
	• Perceive movement	acuity	
	• Estimate the velocity of the	• Less accurate velocity	
Perception	vehicles in sight	estimation	
reception	• Estimate the speed of self-	• Estimates of the speed of	
	performed action	self-performed actions	
		may not be updated to	
		account for age-related	
		slowing	
	• Divide attention between	• Difficulties in tasks	
	the different directions to be	demanding divided	
	scanned and vehicle	attention	
	handling	• Difficulties in selective-	
Attention	• Select, focus att. to, and	attention tasks; slowness in	
	switch att. Between the	switching attention	
	task-relevant aspects of the	• Difficulties in ignoring	
	traffic and traffic	irrelevant information	
	environment ; ignore		
	irrelevant information		
	• Perform complex vehicle-	Motor slowing down	
	handling movement	• Seriality in the	
	sequences swiftly within	organization of vehicle-	
Motor performance	the given time gap while	controlling movements	
	attending to the traffic	• Disproportionate slowing	
		in complex task	
		environments	

	•	See the other vehicles and	•	As above
Interaction with		accurately predict their	•	Slowness in approaching
other		behavior		the crossing falsely
drivers/vehicles	•	Behave in a predictable way		interpreted as a signal of
drivers/venicles				the intention to respect
				the right of way

# 4.2.5 Gap Acceptance

An intersection requires several actions from the driver: (i) detect the presence of the intersection, (ii) detect and interpret traffic control (interpret timing if traffic light), (iii) anticipate other vehicle acceleration/deceleration, (iv), detect and anticipate oncoming, cross traffic, (v) overcome obstruction, and (vi) negotiate the turn (Caird and Hancock<sup>23</sup>, 2002). The detection and interpretation of the type of control provides information about who has the right of way and when to exercise this right. In some situations, the indication of right of way is not sufficient. For example, in the case of a permissive left turn signal, the driver who makes a left has the right of way over crossing traffic but not over an oncoming vehicle. The driver then must rely on his/her own perceptive system to determine the possibility of turning before or after an oncoming vehicle.

This section deals with two main scenarios: (i) left turn involving lateral traffic, a maneuver that corresponds to crashes of the type LTAP/LD, (ii) left turn involving on-coming traffic, maneuver corresponding to LTAP/OD. In the latter case, we will distinguish between left turn involving no traffic control and left turn operated under a green light. Before we detail of these scenarios, we will define the notion of gaps and lags.

# Gaps and lags: definition

Gaps and lags are two terms often referred when describing gap acceptance. The difference between the two terms in illustrated in Figure 4.2-3.

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Fig 4.2-2: Difference between gap and lag

A gap is the time gap between two vehicles on the major road. A lag is the portion of a gap that remains after a SV first arrives at the stop line or first begins to move onto the major road.

The estimation of a critical gap is the key parameter when addressing crossing paths at intersections, and where one of the traffic streams has to leave the right of way to the other. The concept of critical gap has been investigated in the study of traffic flow patterns and in the estimation of intersection capacity. Brilon<sup>24</sup> et al. (1999) describe the critical gap, t<sub>c</sub>, as the "*minimum time gap in the priority stream that a minor street driver is ready to accept for crossing or entering the major stream conflict zone.*" (p. 162). Furthermore, they define the follow-up time, t<sub>f</sub>, as "*the time gap between two successive vehicles from the minor street while entering the conflict area of the intersection during the same major street gap.* (p. 162). "

One of the main differences between the use of gap and lag between traffic engineers and human factors researchers is the type of traffic crossing these describe. Indeed, traffic engineers pioneered research with crossing path traffic safety and the notion of major and minor stream. Most of their focus has been on Straight Crossing Path (SCP), whereas human factors researchers tend to describing the oncoming traffic, i.e. a situation where the driver needs to cross the path of the oncoming vehicle and does not necessarily have to stop before to proceed. Instead, the driver must use his/her own judgment to decide whether to give in to the right of way.

We will examine in more detail the computation of gap and distinguishing factors based on the origin traffic, e.g., lateral or opposite. We will also investigate driver action – stopped or moving – prior to the turning movement.

# Left turn with lateral traffic

This maneuver will be considered when it involves a traffic control of the type, "Stop sign" or "Yield". In other words, the turning vehicle has to come to a stop or near stop and give the right of way to cross traffic (see Figure 4.2-4 below).



Fig 4.2-3: Left turn with lateral traffic

#### 4.2.6 Perception of Vehicles Arriving from a Lateral Direction

This situation is best investigated for an unsignalized intersection between a minor and major stream such as a vehicle coming from the minor stream where the driver must stop, then scan for threats within the crossing stream of vehicles. In the majority of cases, perception of vehicles approaching from the lateral direction is easier than the perception of oncoming traffic. This is because a lateral vehicle represents a motion across the field of view of the driver<sup>25</sup>. However, there is an exception to this case.

Uchida<sup>26</sup> et al. (2001) investigated the specific case of vehicles arriving at an intersection at a constant angle. This situation puts approaching vehicles on an exact collision course. Because the angle between the vehicles remains constant, a driver perceives the other approaching vehicle as a static object until perhaps too late. This phenomenon is illustrated in the Figure 4.2-5 below. To arrive at the figure, the authors conducted an experiment on a driving simulator with 18 volunteers. The protocol consisted of driving with a cruise control on at 60 km/h, traveling through a set of intersections located every 300m. The authors tested three conditions: a vehicle appearing on a collision course, a vehicle appearing in a non-collision course and no vehicle appearing. Targets appeared either right or left at three different degrees: 60, 45 and 30 degrees. In order to ensure that drivers were looking straight ahead they were instructed to recognize a letter appearing in the center of a screen in front of the vehicle buck.

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# Fig 4.2-4: Mean distance from subjects' vehicle to the intersection when the target vehicle was detected in Uchida et al. (2001)

As illustrated in the figure above, the vehicles not in a collision course were detected much earlier than the vehicles on a collision course for all conditions except when the target vehicle was at 30 degrees to the left. Apparently, the pillar was hid the laterally approaching vehicle.

# 4.2.7 Gap Acceptance and Sight Distance

Harwood et al. (1999) addressed the issue of design policies for sight distance at stop-controlled intersections, with a focus on gap acceptance. They reviewed the AASHTO design standards and proposed to investigate factors not taken into account for computing the sight distance on the major road: the speed reduction of the drivers on the major road, assumed to be 15%, and the perception-reaction time of the driver from the major road when a vehicle enters from the minor road.

The AASHTO recommendation for computing sight distance is the following equation:

where:

ISD = sight distance (m) along the major road from the intersection required for SV to depart from a stop line, accelerate to 85% of the major-road design speed and complete a left turn without being overtaken by the POV 2 traveling at the major road design speed and decelerates of 15% Q = distance (m) traveled by POV 2 h = distance (m) along major road traveled by POV 2 (see paper for complete description of factors for Q and h).

Based on this equation, AAHSTO in 1994 recommended distances (shown in Table 4.2-4) based on different speed designs.

Design speed (km/h)	Required ISD (m)	Corresponding time gap (s)
30	65	7.8
40 (25 mph)	90	8.1
50	120	8.6
60	160	9.6
70	205	10.5
80(50 mph)	255	11.5
90	310	12.4
100	380	13.7
110	455	14.9

Table 4.2-4: Intersection sight distance	e criteria for AASHTO in 1994 (in
Harwood et :	al. 1999)

As a side note, the same distance is used for either LTIP or RTIP. These distances and time gap do not cover the case of the LTAP/LD.

Harwood et al. (1999) conducted a field observation of right and left turn movements at 13 stop-controlled intersections, inkling 5 three-legged intersections and 8 with four legs. In their study, a stop existed on the minor road and none was present on the major road. The authors used to method in determining the critical time gap by applying the Raff method, and alternately by performing a logistic regression. The Raff method consists of determining the "cumulative distribution of the percentage of rejected gap and the complement of the cumulative distribution of the percentage of accepted gaps." The critical time gap is the crossing point of the two distributions. The results of the two methods are presented in the Table 4.2-5 for right/left turn maneuvers and for three types of vehicle that performed the turn from the minor road: passenger car, single unit truck and combination truck.

Vahiala tura	Critical gap (s)		
vemere type	Raff method	Logistic regression	
Right-turn maneuvers			
Passenger car	6.3	6.5	
Single unit truck	8.4	9.5	
Combination truck	10.7	11.3	
Left turn maneuvers			
Passenger car	8	8.2	
Single unit truck	9.8	10.8	
Combination truck	10	12.2	

 Table 4.2-5: Critical gaps for right and left turns (in Harwood et al. 1999)

The authors compared their results with those from two other researchers, Lerner<sup>27</sup> (1995) and Kyte et al. (1996). The main difference between Lerner and the authors' work is that Lerner did not find a significant effect of the type of maneuver (right, left turn or crossing) while both Kyte et al. and Harwood et al. find a difference. The difference in time gap was 1.7 sec by Harwood et al. while it was found to be 0.9 sec by Kyte et al. Harwood et al. explained this difference by differences in traffic density between the intersections that each team observed. Therefore, when

traffic density is higher, drivers would be willing to accept shorter gaps. The common point to these studies is that passenger car drivers seem to be looking for a time gap of about 7 sec. The other interesting point is that drivers of different types of vehicle require different time gaps for the same maneuver.

The other aspect of the turning maneuver investigated by Harwood et al. addresses the acceleration profile of the turning vehicle and the deceleration of the vehicle traveling on the major road. They focused on cases where the gap or lag accepted was 10 sec or less. The results show that the reduction of speed ranged from 0 to 80%, with a median value of 31%. The average deceleration speed from maximum to minimum speed was 0.68 m/s<sup>2</sup> (2.2 ft/s<sup>2</sup>). Approximately 2/3 of the speed reduction occurred before the intersection. The observed average acceleration rate for passenger car drivers entering the major road was 1.49 m/s<sup>2</sup> (4.9 ft/s<sup>2</sup>) for going from 0 to 40 km/h (0-25 mph).

Based on these results, Harwood et al. proposed the following sight distances:

Table 4.2-6: Recommended sight distance for right and left turn (in Harwood
et al. 1999)

Major-road design speed	Recommended sight	Sight distance from
(km/h)	distance (m)	AASTHO (m)
30	65	65
40	85	90
50	105	120
60	125	160
70	150	205
80	170	255
90	190	310
100	210	380
110	230	455

## Left turn with opposite traffic

The two cases that we consider for this literature review are illustrated in Figure 4.2-6 below. Figure 4.2-6 A illustrates the situation of a permissive left turn, where the SV driver must consider both the traffic signal and the presence of oncoming traffic in deciding whether it is possible to turn. Figure 4.2-6 B illustrates the case where the only source of information the driver has to consider is oncoming traffic.





Chovan et al. (1994) describe the dynamics of the SV and POV for this situation (see Figure 4.2-7). They distinguished the case were the SV stops or does not stop prior to turning. Based on the work of Ueno and Ochiai, they consider that the stopping/not stopping decision depends of the time headway between the POV and the SV turning path when the SV is at the start of the turn. The threshold for stopping would be time gaps less than 3 sec, and drivers would not stop if the time gap exceeds 8 seconds.



Figure 4.2-6: Illustration of Ueno and Ochiai threshold for determination of SV stopping decision

In other words, the sequence of decisions from the driver would be to first decelerate to prepare for the turn, and upon reaching the start of the turn, decide whether to proceed or not based on the POV time to intersection. The SV driver adjusts his/her vehicle's braking to either stop at this point, maintain speed or accelerate to turn.

## 4.2.8 Perception of Oncoming Vehicles

The perception of an on-coming vehicle depends of mechanisms of identification of the vehicle, estimation of the distance of the vehicle from the driver (observer), and eventually the perception of the relative speed between the driver and the oncoming vehicle. The perception of relative velocity and closing rate has been investigated by Hoffman and Mortimer (1996). Their model is based on the perception of the change in visual angle,  $\theta$ , as illustrated in Figure 4.2-8.



Figure 4.2-7: Illustration of Hoffman and Mortimer Model

The mathematical expression of the model is given in equation below:

$$\dot{\theta} = -\frac{d \cdot R}{R^2}$$

In the above, R and d are the range and the width of the forward car respectively,  $\dot{R}$  is the perceived range-rate,  $\theta$  and  $\dot{\theta}$  represent the visual angle and the rate of change of visual angle respectively. At  $R < \sqrt{|\dot{R}/0.00164|}$  from the equation (1) and just-noticeable increments of  $\delta R/R = 0.12$ , drivers scale perceived range-rate in a practically linear relationship to R. Applying this model to a scenario where the SV is stopped and waiting for an on-coming traffic, the relative velocity can be perceived when the POV (for a width of 1.8 m) is at about 80 meters from the intersection.

## 4.2.9 Left Turn without Stopping

Chovan computed the distance required to slow down,  $D_{slow}$ , based on a curve radius of that would be taken at a maximum speed of 9.95 m/s (26ft/s), for speed ranging from 25 to 55 mph. They also computed the distance available,  $D_{available}$ , which corresponds to the available distance plus 4.5 m (12 ft), since drivers initiate their turning maneuver once they are in the intersection.

Subject Vehicle		Normal Deceleration		Maximum available time to react		
Velocity V <sub>0</sub>		(a=.31g)		$(t_d)$		
Mph	m/s	$D_{slow}(m)$	D <sub>available</sub> (m)	Had braking	Emergency	
				(a=.5 g)	braking (a=.7g)	
25	11.1	12.9	17.5	0.3	0.9	
30	13.3	24.32	28.9	1	1.6	
35	15.5	37.8	42.4	1.8	2.3	
40	17.8	53.4	57.9	2.5	3.1	
45	20	71	75.6	3.2	3.8	
50	22.2	90.7	95.4	4	4.6	
55	24.4	112.3	116.8	4.7	5.3	

 Table 4.2-7: SV does not stop (From Chovan et al. 1994 p28)

Based on work performed by Sivak et al., Chovan et al. concluded that to have 90% of drivers able to integrate the information of a warning there should be 2 sec available for the driver to respond. In that case, it seems that collision under 35 mph would be difficult to address with a warning system as the time to react is less than 2 sec, even in the emergency braking case.

## 4.2.10 Left Turn after Stopping

Most human factors research to address the left turn after stopping case has been conducted either on driving simulator or on the road experiments. Note that this research is quite challenging if conducted in natural settings, as it requires synchronization of data collected between vehicles arriving from two opposite sides of the intersection.

Hancock and Caird (1992) focused on the assessment of the appropriate time to turn left with variable oncoming traffic speed and time gap size. They conducted an experiment on a driving simulator with 40 subjects total, 10 in each group (51 to 84 years old). Subjects were randomly assigned to groups defined by the type of vehicle on the oncoming traffic (motorcycle, small car, big car, delivery truck). They used seven approach speeds (10 to 70 mph) and seven time gaps (3-9 seconds). They concluded that decisions do not depend only on velocity or gap size but on some cue extrinsic to these parameters. Drivers that turned left across trucks were almost uniformly successful when the inter-vehicle time exceeded six seconds. For gap-sizes between 3 and 5 sec, successful turn and no turn decisions were equally split. At higher velocities, a pre-dominantly no-turn decision is made. Older drivers seem to be more conservative than young. Both young and old drivers do not initiate turns upon oncoming velocities, gap size or distance; rather, they use higher order information extracted from these parameters, like time to arrival or rate of frontal expansion.

Staplin<sup>28</sup> (1995) conducted a series of investigations on measures in left turn gap judgments. He compared several tests, placing drivers in situations involving accepting or rejecting time gaps. Three of the tests were conducted in a lab and used a television display, video projector display and cinematic display. The last test was in the field. Volunteers were placed in the passenger seat of a vehicle stopped at an intersection. A confederate vehicle would approach the intersection at speeds of either 60 mph or 30 mph. The volunteers had to express the minimum gap they would accept for making a left turn. The results of the test are compiled by us into the nomograph of Figure 4.2-10.

Because the author compared three groups of volunteers, young-middle ages, young-old and old-old, we divide results similarly. This allows us to examine the extent of the variability of answers. Each rectangle describes the range of distances were a vehicle would be considered a threat, assuming that the distribution is normal and using the standard deviation for the top and bottom part of the zone.

We also display the data in terms of distance. In examining Figure 4.2-10, we see that with the exception of the younger group, the velocity of the oncoming vehicle did not seem to influence the choice of the least safe gap. However, if the same data are interpreted in terms of POV time to intersection, then it appears that the faster the POV, the smaller the time to intersection.

Finally, the third interesting aspect of our nomograph is our addition of the threshold for scaling relative velocity based on the Hoffman and Mortimer model (see earlier). This shows that drivers would make their decision on velocity before being able to perceive the relative velocity. This could explain why the velocity of the target does not play a role in the driver gap decisions, as drivers would have to use distance rather than time. To underscore, this is what they seem to be doing in determining gap, at least with the lateral traffic case.

The other study plotted on figure 10 was conducted by Alexander<sup>29</sup> et al. (2002) on a driving simulator and for British right turn situation (corresponding to the American left turn). The only data provided is the mean gap or lag accepted by drivers. Another interesting point is the order of the accepted gaps. The lag, which would have been the first opportunity to turn, was usually rejected and that the first gap was more often chosen. It is also interesting to note that the median accepted gap size is smaller for the first gap, and it slightly increases for the other gaps (see Figure 4.2-9).



Figure 4.2-8: Number of gap accepted based on order of gap occurence and median gap accepted by order of occurence in Alexander et al. (2002)



Figure 4.2-9: Summary of research on time-gap acceptance for LTAP/OD

Lerner<sup>30</sup> (1994) cites the results of an experiment that investigated gap acceptance for young and older drivers. Older drivers required longer gaps than younger drivers; the gap duration accepted 50% of the time for the youngest group was 6.74 sec and 7.85 sec for the oldest. The mean point at which the youngest group judged an approaching vehicle to be too close for initiation of the maneuver was 5.32 sec for the youngest and 5.86 sec for the oldest. The data suggests that drivers require gaps that are somewhat larger than the time durations it actually takes them to perceive initiate and complete a maneuver. This may reflect a margin of safety drivers allow beyond the time it normally takes to execute a maneuver. However, it may also be that the driver integrates the fact that they have to accelerate to the speed of the oncoming traffic if they are merging with this traffic.

### **4.2.11** Perception Reaction Time (PRT)

The concept of Perception Reaction Time (PRT) is wildly used for describing driver behavior. Its range of application covers driving tasks such as reaction to the stop light of the leading vehicle to reaction to a traffic light change. Very often now the literature also distinguishes between different driver states in terms of either attention or awareness. For example, a driver can be surprised or non-alerted (Olson<sup>31</sup> 2002).

Olson (2002) defines a perception-reaction time as the "interval that starts when some object or condition enters the driver's visual field and ends when the driver has initiated a discernible response (e.g., foot on the brake pedal or the hands start to turn the steering wheel, or both)." (p. 45). An important addition to this definition is to consider that the object or condition is not only entering a driver's Field of View (FOV) but rather a driver Useful Field of View, which is the area of the FOV where a driver can extract information in one fixation, without head or eye movement. Another important point to take into consideration is that a driver alternates between two modes: anticipation and reaction. When in an anticipation mode, driver behavior is oriented toward a goal and that in order to reach this goal, the driver will focus on specific information. However, as the driver is looking for specific information, he/she will still be open to other information. For example, a driver who desires to make a left turn at an intersection is probably going to look at the traffic signal, the on-coming traffic and potential pedestrians. The main idea here is that it is not only a matter of information being within a driver's FOV necessary to obtain a response, but that the information as to be either relevant for the current task being conducted, present in a range of general expectancies, or that the information has to make sense for the task being performed.

 Table 4.2-8: Deduction of driver perception-response time based on assumed

 components from literature (p. 54 in Olson, 2002 from McGee et a. 1983)

Flement	Percentile of drivers						
Ekment	50	75	85	90	95	99	
1 Perception							
a. latency	0.24	0.27	0.31	0.33	0.35	0.45	
b. eye movement	0.09	0.09	0.09	0.09	0.09	0.09	
c. fixation	0.20	0.20	0.20	0.20	0.20	0.20	
d. recognition	0.40	0.45	0.50	0.55	0.60	0.65	
2. Decision	0.50	0.75	0.85	0.90	0.95	1	
3. Brake reaction	0.85	1.11	1.24	1.42	1.63	2.16	
Total A (1a-1d+2+3)	2.3	2.9	3.2	3.5	3.8	4.6	
Total B (1a-1d+2+3)	2	2.5	2.8	3.1	3.4	4.1	
Total C (1a-1d+2+3)	1.8	2.1	2.3	2.6	2.9	3.6	

Table 4.2-8 illustrates that a reaction time should be sequenced in different steps and that some elements of the sequence are assumed to invariant while others vary, like the recognition or the decision steps (shaded in the table). Factors greatly influencing the reaction time are the *event* which the driver detects and recognizes and the *response* which the driver produces. In the case that there could be several potential answers, the decision time will likely be long. Olson advises a cautious application of the data in table 8 in the sense that an individual who performs slower in one of subelement (e.g. recognition) does not necessarily perform slower for another (e.g. brake reaction).

#### 4.2.12 Reaction Time Related to Traffic Perception

Naylor and Graham (1996) intended to verify whether the time necessary to decide to decide to make a left turn, also called j value, and set to 2.0 sec in the forties by AASHTO, is valid and account for older driver. The j value is the time required for a stopped driver to scan left and right, determine if it is safe to proceed, and then to depress the accelerator. The authors conducted observations at four stop-controlled intersections (2 T and 2 four leg intersections, one of each in an urban area and one of each in a rural area) recorded on video. They categorized drivers into old and young groups. All told, they recorded data for 52 drivers for each type of intersection, 26 young and 26 old, and 13 males and females in each age group (with 208 observations total).

The overall mean decision-reaction time for all drivers was 1.24 sec, with a standard deviation of 0.50 sec. The range of decision time was from 0.27 to 3 sec. The 85<sup>th</sup> percentile value of the decision-reaction time was 1.73 sec. The younger group had a mean decision-reaction time of 1.16 sec while the older group had a mean decision-reaction time of 1.32 sec (significant at 0.05). Even though the difference is statistically significant, 0.16 seconds of difference between young and old does not seem to be a huge difference. The mean decision-reaction for the urban locations was 1.17 sec and 1.31 sec for rural locations. The highest frequency occurred between the intervals of 1.2 to 1.39 sec. They found that 93.3% of the drivers had decision-reaction times less than 2 sec. The authors proposed to replace the j value by the decision reaction time required for this type of maneuver.

Lerner (1994) distinguished between the definition of PRT from the "manual", i.e. once stopped, time required to begin the search, make the decision, then initiate forward movement and the actual behavior of the driver. This is because the driver begins scanning on approach, and he/she may not stop completely. He/she may instead show multiple starts and stops, and he/she may continue scanning well into the maneuver. Lerner conducted an experiment with age groups, 20-40 (n=25) 65-69 (n=27) and 70+ (n=29). Subjects drove their own vehicle equipped with video data collection through 14 intersections on a 56-mile route, including left and right turns and straight crossings. Data were recorded only for trials where there was no conflicting traffic at the time of the decision.

Older drivers did not require more time than younger drivers to search and proceed at intersections. The younger group actually took 0.2 sec more than the older to initiate movement. Older females were significantly slower than older males. This difference was not seen for the younger group. Lerner's presumed 2.0 sec PRT appears to work well for all age groups. Lerner considered that the intersection problem may be related to perceptual failure (i.e., "looked did not see"), attentional limitations, visual complexity, comprehension of traffic control devices and vehicle control capability. He concluded that PRT is not a problem.

### 4.2.13 Reaction Time to Traffic Signals

Olson (2002) addresses reaction time to the onset of the amber phase. The motivation for studying this specific reaction time is to support the setting of the duration of the transition period. There are two specific characteristics to this reaction time. The first is that a driver expects the chance that the signal is going to turn to amber. The second one is that once the light turns amber, the driver has to determine whether to stop or proceed through the intersection. Therefore, the times presented in Table 4.2-9 account for the detection, recognition and decision to stop.

Intersection Approach	Average time	Standard deviation	85% time	
Intersection Approach	(sec)	(sec)	(sec)	
University Drive	1.28	0.82	2	
Southern Ave. (day)	1.49	0.62	1.9	
Southern Ave. (night)	1.43	0.73	2	
U.S. 60	1.38	0.60	2.1	
First Ave	1.24	0.51	1.8	
Sixth street	1.55	0.70	2	
Broadway Blvd. (day)	1.16	0.48	1.5	
Broadway Blvd. (night)	1.09	0.44	1.5	
All approaches	1.30	0.60	1.8	

Table 4.2-9: Response time of approaching driver to the onset of the yellow phase of traffic signals (in Olson, 2002, from Wortman and Matthias (1983))

## 4.2.14 Reaction Time and Warning

Olson (2002) proposes eight factors affecting the perception reaction time: i) detection, ii) identification, iii) decision, iv) response, v) driver expectancy, vi) night vs. day, vii) chemicals and drivers fatigue, viii) age and sex.

The first five are among the most important to consider for the design of a warning. *Detection* addresses issues such as location of the device to make it as conspicuous as possible. *Identification* concerns the meaning of the information provided by the display. Some information formats are processed fasters than others (e.g. icons vs. text) given that they make sense in the current driving context. *Decision* refers to the choice of action to apply and whether to apply this action. For example, a warning gives information about a hazard that can be avoided either by braking or steering; the driver will have to decide between the two. Another consideration if the display provides the action to take is that the driver will decide whether or not to
comply with the system advice. *Response* is the time taken for activating the vehicle control. Finally, *driver expectancy* reflects the understanding the driver has of the current driving situation. If a warning violates a driver's expectancy, it may lead to a longer processing time.

Another dimension to consider for reaction time and warning is the possibility to provide a warning in a time and fashion that allows the driver to act in a timely manner. In this regard, Lloyd et al. (1997) observed driver behavior with an instrumented vehicle in order to identify the sequence of action that a driver accomplishes when reaching a stop sign-controlled intersection in order to determine the possibility of using a warning system based on the available time. The approach of the authors is that the warning should be presented after the driver normally makes control input (e.g. take the foot of the throttle, brake), as this reduces the amount of false alarm and nuisance. Their results show differences based on the direction the driver will follow at the intersection: 92% of the drivers who will go straight take the foot of the accelerator 6 sec prior to the intersection, while only 70% of those making a turn do so at the same time.

Differences in control input based on the intersection maneuver (straight, right or left turn) are also observed for braking behavior. To illustrate, 6 sec prior the intersection, 82% of the drivers proceeding straight applied brakes, 63% of the drivers turning left had did so, and only 34% of the drivers turning right applied brakes. An explanation for the discrepancy between the two turning movements is that drivers intending to make a right turn might plan on creeping at the intersection. The authors concluded that driver input to the vehicle primary control can be used for both evaluating drivers compliance with the intersection and intended maneuver, except for the steering maneuver, which occurs too late in the intersection approach.

Chovan et al. (1994) also gave attention to this matter. Their focus is on LTAP/OD conflicts, and their approach consists in modeling the timing between the SV and

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the POV. They performed kinematic calculations with timing and when the SV driver is expected to take an action for turning. They compare the time a driver needs to accomplish a left turn, about 2.43 sec for a typical intersection, with the minimum gap drivers are willing to accept with an oncoming vehicle, about 3 sec. Even though the difference between the clearing time by the SV vehicle and the time to intersection of the POV is almost a half second of spare time. This interval is too short to be accepted by a driver. Therefore, the authors' advice is to use the slowing time for computing when to provide a warning rather than the clearance time.

#### 4.2.15 Driver Models

We have identified two driver model approaches which might be applicable as frameworks for IDS. The first driver model approach is centered on the decision making aspect and contains some references to other cognitive structure. The second model proposes a framework of perceptive, cognitive and motor processing.

#### Computational model of driver decision making at an intersection

This model is based on the fundamental theory of Naturalistic Decision Making, first introduced by Klein (1989) as the Recognition-Primed Decision (RPD) model (see Figure 4.2-11). This model addresses how experienced operators make decisions in situations characterized by time constraints, uncertainty and high stakes. The theory postulates that an experienced operator will recognize a situation as typical, based on four cues: relevant cues for that situation, expectancies, plausible goals and plausible courses or action. The first step of the decision will consist of identifying the typical elements of the situation. Once the familiarity of the situation is established, the operator will choose a single course of action and apply it. As issues arise, the course of action will be adapted. If the situation is not initially recognized, the operator will engage in a search of information. As a side note, a complementary approach to this theory is the decision field theory developed by Busemeyer and Townsend<sup>32</sup> (1993). The authors illustrate that time constraints and dynamic environments are not as important as the initial idea that a decision maker has about what the decision should be. If a decision maker has a preferred alternative, he/she will likely look for elements that support it. In a timely constrained time environment, this strategy allows the decision maker to reach a solution rapidly. The flaw of this strategy is that if a situation is atypical but not identified as such by the decision maker, the decision may not be appropriate, and the decision maker may have difficulties identifying the problem. In the case of non typical situation, a novice could fare better than an experienced individual because the novice would have a better chance to consider all of the cues, while the experienced individual would focus mainly on the cues that appear to be relevant for the preferred alternative.



Figure 4.2-10: Recognition-Primed Decision model (in Stanard<sup>33</sup> et al. 2001)

Stanard et al. (2001) conducted a Cognitive Task Analysis (CTA) with experience and novice drivers in order to identify the general and specific issues underlying a decision making while approaching an intersection. The results of this CTA are reported in the Table 4.2-10.

# Table 4.2-10: Components of the decision making context at an intersection controlled by a traffic light (in Stanard et al. 1991)

Goals	Cues	Expectancies	Course of action
<ul> <li>Don't break the law</li> <li>Don't get caught</li> <li>Don't hit anything or be hit</li> <li>Minimize driver time</li> <li>Preserve momentum</li> <li>Maintain traffic flow</li> <li>Avoid sudden stops</li> </ul>	<ul> <li>Light color</li> <li>Distance to light</li> <li>Auto speed</li> <li>Presence of cop</li> <li>Pedestrian presence</li> <li>Presence of a lead car</li> <li>Presence of cross traffic</li> <li>Other vehicles actions:</li> <li>Slowing lead</li> <li>Turning on-coming</li> <li>Turning cross traffic</li> </ul>	Lead car actions: Going through light Stopping Not moving Light Going to change Not going to change Can't make it before it changes Pedestrian moving	<ul> <li>Accelerate</li> <li>Decelerate</li> <li>Stop (controlled)</li> <li>Stop (hard break)</li> <li>Maintain speed</li> <li>Change lanes</li> </ul>

In order to address the experience stored in long term memory (LTM) and how typical an experience is, the authors use the Hintzman's multiple-trace memory model. The principle of that model is that each experience is coded as a unique trace in LTM. During the recognition process, each trace in memory is compared to the given situation. The recognition process produces a similarity value for each trace. Then, a combination of the similarity values forms an "echo" representing the typicality of the situation. During the decision cycle, the cues present in the environment are stored in short-term memory (STM) and then used to compute a similarity value with each traces present in LTM. Based on this, the model generates expectances that are confirmed or validated. In the former case, then the course of action is implemented, in the latter case, the driver reassess the situation and initiate the cycle again.

The authors are currently pursuing their effort of developing the computational model of Recognition-Primed Decision. They use Micro Saint and IMPRINT as simulation tools.

# Cognitive Simulation of the Driver

COSMODRIVE (Bellet and Tattegrain-Veste<sup>34</sup> (2003)) is fuses theories and methods in two fields, cognitive psychology and ergonomics applied to transportation studies for the theoretical framework, and Artificial Intelligence for the implementation. The focus of this model is directed toward the driver, so no vehicle constraints or dynamics have been integrated so far. The aim of the model is to reproduce driver behavior in any type of road environment (urban, rural highways, highways) and for any type of driver's experience and/or familiarity with the environment by simulating the processing of a driving scene by a driver.

The approach underlying its design has been to first define a functional structure describing the principal stocking structures and information processing. Second, a specification of the nature of the computational mechanisms (here the cognitive processes) has been realized. Third is the description of the data structures (knowledge and representation) on which operate these processes. Once these three steps have been followed, the choice for an implementation method has been done, in this case, it is object modeling oriented that had been chosen.



Figure 4.2-11: General Architecture of COSMODRIVE

Figure 4.2-12 displays the seven modules that compose COSMODRIVE. Each module is in charge of a specific activity. The strategic module is in charge of the navigational aspect (i.e., itinerary organization) and general objectives generation.

The tactical module is an internal representation generator of the road environment. The main processes presented at this level are road environment categorization and recognition, decision-making and anticipation. Finally, the operational module is composed of a set of autonomous operational units specialized in the elementary driving tasks, such as lateral or longitudinal control. These three modules are the ones classically used for driving activity description. Four modules have been added to this classical architecture. The perception module allows the integration of human characteristics for driving scene processing. The emergency management module is activated when an emergency situation is perceived and proceeds to acquire the tactical and strategic module attention resources. This switch is made possible by the module of resources management and control. All of these modules function by the way of a limited amount of resources that they share.



Figure 4.2-12: COSMODRIVE tactical module (in Bellet, to be published)

Figure 4.2-13 represents an expansion of the tactical module. This module interacts primarily with the perception module. This interaction is realized in two fashions based on the visual channel. There is an integration of events as well as a voluntary exploration of the environment. These two basic operations allow the simulation of both reaction (cognitive integration) and anticipation (exploration). The strategic module feeds the tactical module with "general" goals. Of great importance is also the module of management and control, as it regulates the resources available to the processes. The other module that exchange with the tactical module is operational. This interaction is related to the realization of action decided at the tactical level, concerning lateral and longitudinal control.

Within the module, three structures can be distinguished: i) cognitive processes, such as categorization, decision making, representation generation, ii) mental representation, split between a current state and anticipation state and finally iii) a knowledge base.

The role of the processes is to "interface" the data "sampled" in the road environment with the knowledge that a driver has and to manipulate these two sources of information for controlling and adapting his/her behavior. The different actions executed by these processes are: i) generate and update a current representation of the driving scene, ii) mobilize the appropriate knowledge to process the situation, either via a categorization process or a place recognition process, iii) make decisions about the behavior to adapt, and iv) anticipate the future behavior.

The driver knowledge database is organized into two sets. One set is made of general knowledge about driving. This knowledge is organized along a hierarchy based on driving environment, mainly urban, rural and highway. Each of these categories are themselves divided in more subcategories depending on other environment features (such as the number of lane for a highway for example). The other set is knowledge a driver has of a specific place. The smaller units of this hierarchy are called driving schema. For example, in the highway category of the general knowledge set, there is a schema for exiting a highway. Part of the schema is the procedure to do so, like moving into the right lane at a certain distance from the exit. The driver may also know a specific exit which is on the left of the highway and then the schema he has for this exit is made of rules for this specific exit, integrating some marks from this specific environment (to be on the left lane at a certain point).

The mental representation of the current driving situation is a transitory stocking structure. The selected schema is instantiated in the current representation and then provides the guide to manage behavior by specifying the information to be considered, the one necessary prior to undertake an action. This instantiation also integrates the information persent in the environment and leads to the construction of an internal model of the situation. Most decisions are based on the status of the information present in the mental representation. Only a certain amount of information can be considered at a time and the status of the information, in terms of validity, decays over time.

# 4.2.16 Countermeasures

Chovan et al. (1994) proposed active crash avoidance concepts for LTAP crashes. These concepts are based on the time available to prevent the crash and range from warning system to fully automatic control. In the case of LTAP, warning systems are to be used during the intersection approach. As the driver approaches the intersection and the time available for reacting decreases, then it becomes necessary to consider partial automation. The next step is a fully automatic system. The authors recommend warning SV drivers when they do not have the right of way and there is oncoming traffic. The type of message could be a warning to brake or to not steer. An alternative solution is to warn the POV to slow down or stop for a SV on his/her way. The authors also present concepts for the partial and full automation.

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However, as the goal of IDS research is to identify concepts that could be used in the infrastructure, we will not go in the detail of these concepts here. Another type of countermeasure that we will not discuss here either is the adaptation of the infrastructure, as proposed by Wierville et al. (2002) for example.

The prototypes that we could identify through the literature search are all at the very early stages of being either tested through experiments or designed. We identified three different interventions in the driver's environment aiming as either warning or supporting a decision at an intersection.

#### Information redundancy

Staplin and Fisk (1991) proposed to facilitate older drivers' decisions by gradually providing information about the nature of the right of way at the intersection. In a driving simulator, they presented an auxiliary sign in advance of an intersection and this sign again as the driver was reaching the intersection in combination with the traffic light. They found that redundancy improved the decision time for both young and old drivers. However, the decision accuracy for older drivers for the case of "no go" messages did not improve. Unfortunately, the authors do not provide information about the distance of the redundant information to the intersection.

#### Approach of intersection at same velocity

This concept consists of increasing the conspicuity of the vehicles approaching an intersection at a constant angle. Uchida et al. (2001) conducted an experiment on a driving simulator with 18 volunteers. Based on the result of a prior experiment, they determined a critical point where the POV has to be detected by the SV driver. They added a fence that covered the sight of the POV leg until 2 and 3 sec before the critical point. The results indicate that the fence allows an earlier detection of the POV, the best result being with the 3 sec experiment.

# Information about other traffic at the intersection

Inman V. and Shafer T.<sup>35</sup> (2001) presented several prototypes of countermeasures to be installed in the infrastructure and provide information about other traffic at the intersection (see Figures 4.2-14 and 4.2-15).

Figure 4.2-14 illustrates information on the possible options available to the SV driver upon reaching the intersection. In this example, the driver can make a right turn and proceed straight, but a left turn maneuver leads to a traffic conflict. The device presented by the authors would serve the purpose of assisting SV adjusting his/her behavior to the presence of gap at the intersection and attract attention on specific areas to search.



Fig 4.2-13: Advance information about conflicting traffic at the intersection (in Inman and Shafer, 2001)

The other type of intervention proposed by Inman and Shafer is to provide a warning about the presence of a violator at the intersection, as illustrated in Figure 4.2-15.



Figure 4.2-14: Traffic warning presented in the infrastructure (in Inman and Shafer, 2001)

# 4.2.17 Synthesis

# Insight for driver model development

The two models reviewed in section 5 provide some foundations about realistic information processing by operators like drivers. However, they do not cover specifics like the time each step of the process takes, or how much information can be processed at once. This information will have to be either estimated or identified in other sources as the development of the model progress. Below is a list of steps for the development of the driver model in three major modules:

- Perceptive module
  - o Perception of other vehicles and scaling of their velocities
  - Perception of traffic signs
- Tactical
  - o a database about drivers' knowledge about intersection crossing:
    - Expectancies
    - Sequence of goals as the driver approaches the intersection and associated actions

- Thresholds about gap acceptance, braking for stopping at the intersection, steering
- Decision making component matching the simulations inputs with the driver database
- Operational
  - Type of braking
  - Type of steering

The literature review will provide a base for the development of the driver model, but some of the elements listed above will have to be identified through data collection and more extensive review. The application of the model will address the creation or recreation of scenarios in which drivers made errors that led to a crash. A good candidate for this type of scenario is the example that was presented from Larsen and Kines, where the driver omitted to check again a side of the intersection and how this could be prevented with the developed countermeasures.

# Insight for countermeasure development

The driver's error taxonomy developed by Wierville et al. illustrates very well that driver performance problems are have a variety of origins, based largely on intentions. The types of crashes covered by IDS points to two types of factors: inadequate knowledge and infrastructure-related. Therefore, key elements would include:

 <u>Detecting driver intent</u>. The results from Lloyd et al. (1997) are encouraging because they raise the possibility of measuring driver intent incomplying with a stop sign. They indicate that braking behavior could be a cue for estimating the behavior prior to the intersection (e.g., type of turn or proceeding straight). The modeling effort from Chovan et al. (1994) is also encouraging in terms of possibility of identifying driver intention to turn at a signal-controlled intersection.

- <u>Consideration of driver characteristics and type of vehicles</u>. The field observation study conducted by Harwood et al. (1999) illustrates that drivers of trucks require more time to make a left turn with lateral traffic present. All of the other researches on gaps acceptance cited also made the case that older drivers prefer longer gaps than younger drivers.
- <u>Cues for gap acceptance in LTAP/OD and LTAP/LD cases</u>. In the former case, drivers seem use distance rather than time to intersection or time gap. In the latter case, drivers seem to use a constant time gap rather than a distance.
- <u>Reaction time, or rather decision time, is a challenging dimension to assess</u>. This literature review illustrates that what is usually called *reaction time*, *perception reaction time*, or *perception decision time* is really a composite of several sequences. Some of these can be assumed constant and others will vary based on driver expectancies, recognition and decision. Therefore, in considering reaction times (or similar measured) should consider variations in:
  - Identification. The choice of the location of the display in the infrastructure will influence reaction time.
  - Comprehension. Williams et al. (1992) recommendation that the presentation of left turn only messages should be include the following considerations:
    - Red arrows use should be accompanied by an educational program
    - Green arrows should always be used for protected left turns.
    - Circular red and green arrows should not be shown simultaneously.
    - Auxiliary signs are difficult to see at night and can be confusing or superfluous.
  - Decision. Staplin S. and Fisk A. (1991) illustrate that information redundancy improved understanding rate and decision time

# Insight into data collection protocol

The aim of the data collection is to support the driver modeling and the countermeasure development tasks. Because there is either no precedent or the literature indicates discrepancies, we will develop our own data collection protocol.

One of the first issues to arise is the problem of measuring cross traffic flow with an instrumented vehicle. Therefore, this type of measurement will not be realized in the field but on an instrumented intersection which can measure traffic on each of its legs and synchronize this information. A left turn at traffic light scenario can also be difficult to observe as the experimenter has no control over the light cycle, presence of other traffic, or when the subject reaches the intersection. In order to overcome this, driver behavior at intersections such as the one described in figure 6 B will also be observed.

Here is a primary list of elements that will be investigated during the data collection include:

- Observe scanning during the approach of the intersection for supporting the location of the display in the infrastructure
- Test gap acceptance when driver can revise their judgment
- Look at the stop vs. non stop decision using distance and oncoming vehicle speed instead of only time to intersection as what cited by Chovan et al. (1994)
- Take age and sex into consideration
- Investigate gap acceptance with lateral traffic in experimental set up, looking at distance and traffic speed

# 4.3 Driver-Infrastructure Interface (DII)

## 4.3.1 Measuring DII Effectiveness

While the ultimate measure of IDS effectiveness would be a reduction in intersection collisions and fatalities, the effectiveness of a DII alone might be measured through its ability to exert influence over driver behavior. In essence, the driver interface is the opportunity to communicate the information gathered by the IDS to the drivers. The information might reduce the need for sudden maneuvers such as lane changes or hard braking, reduce the selection of unsafe gaps, or reduce the rejection of safe gaps while attempting a turning movement.

In defining measures of effectiveness for driver interfaces, it is helpful to break down the information processing task into its three phases: perception, decision, and action. First, the driver must *perceive* the situation, locating the state of any intersection controls (traffic signals) and detecting any threats (vehicles, pedestrians, or obstacles). Second, the driver must interpret the situation and *decide* on an appropriate course of action. Finally, the driver must execute the appropriate *action*. A breakdown in any of these tasks can lead to poor decisions, unsafe maneuvers, and potentially, crashes. The goal of a DII would be to aid the driver in either the perception of the intersection situation and in the interpretation or decision making stage. Thus, the effectiveness of a driver interface can be established by looking at how easily the driver interface is perceived and how well the information provided is interpreted.

The perceptual effectiveness of a driver interface may be characterized along the following criteria:

 Salience or probability of detection is influenced by two factors: location and conspicuity, where conspicuity refers to the ability of an object to attract the attention of a driver when viewed peripherally. 2. Visibility and readability refer to the ability to be seen and read, when looked at directly, without negative side effects (such as glare). This measure of effectiveness encompasses attributes such as color, brightness, and font size.

The effectiveness of a driver interface on influencing the interpretation or decision making stage may be characterized along the following criteria:

- 1. The usefulness of the message content and the comprehension of that message are the most important criteria. In this case, comprehension refers to both whether the driver understood the message being given and whether the driver understood that the message was targeted at him/her.
- Message consistency will also influence both the salience and comprehension of the warning system. There is consistency with other traffic control devices and policies in the intersection, between the DII, and among the various implementations of IDS assistants and warnings targeted at different crash scenarios.
- 3. Message timing will play an important role in the effectiveness of influencing a driver's decision since driving is a time-critical activity.

A final category of driver-related MOEs might fall under the heading of driver acceptance and compliance which includes characteristics such as the following:

- The perceived reliability and usefulness of the system will play an important role in its overall effectiveness. Attributes such as the accuracy of providing alerts the driver agrees versus nuisance alarms will contribute to trust in the system. If the system cannot achieve trust, drivers will not comply with its recommendations.
- 2. A perceived decrease in driving workload or an increase in driver comfort may also be indicative of an effective CICAS.

### 4.3.2 DII Design

The placement or location of a DII influences both the probability of detection and whether or not the driver comprehends that the sign is targeted at them, and thus much thought and research has gone into the selection of a location for a potential DII. The first factor influencing the placement of a LTAP/OD DII was expectancy. According to the MUTCD Section 2B.17 (Turn Prohibition Signs):

If No Left Turn (R3-2) signs are used, at least one should be placed either over the roadway, at a left corner of the intersection, on a median, or in conjunction with the STOP sign or YIELD sign located on the near right corner.

We hypothesized that by the time drivers reached the intersection and were trying to decide whether or not a gap in the oncoming traffic was sufficiently large, their vision (and attention) would be focused on the oncoming traffic, and not on the overhead traffic signal. Therefore, placing the DII on the far left corner of the intersection below the traffic signal (see Figure 4.3-1) would put the sign closer to the driver's center of attention, increasing the chances that the driver would detect the sign when it is activated.



# Figure 4.3-1. PATH West Coast Intelligent Intersection with a LTAP/OD DII on the left corner under the signal.

With regard to DII criteria, foremost is that it had to be instructive to the driver of the SV. In the present case, that of a LTAP/OD the instruction is to abort a turn intended or in progress on the grounds that an unseen POV threatens to collide with the SV.

Other criteria included:

- Placement: the sign needed to be placed where the driver's eyes would likely be directed and where an imminent turn could be stopped.
- Look: the DII needed to show a familiar icon within the array of po0ssible signs approved within the MUTCD.
- Temporal facility I: The DII needed to be 'off', and thus invisible, until needed.
- Temporal facility II: The DII needed the capability of sudden turn-on.
- The DII requires its own power in order to respond to a trigger signal delivered either in hard wire or by wireless means.
- The DII must compete with the gamut of distracting visual features of an intersection; thus it must exhibit salience and attention-getting qualities along with its familiar instructional quality.

We considered a number of option including speed limit signs with variable speed indicators, in-pavement flashing signals to supply a visual barrier, and augmented traffic signal approaches (e.g. Left turn red arrow).

The most generally useful of the solutions proved to be a modestly refined (to become active) left-turn prohibition sign (MUTCD R3-2), illustrated in Figure 4.3-2. The sign is to be placed just above eye level at opposite corner of the intersection. (For the LTAP/OD case, it will be on the left-hand far corner, whereas for the LTAP/LD case, it could be placed on either intersection; optimization for the exact placement has not yet been thoroughly investigated.) These are the ones of the candidate locations (e.g. which also include overhead at the signal, in advance of the intersection) that the driver of the SV is most likely to scan in advance of a turn.

We have designed the sign to be self-luminous when active (using LEDS) and thus to be neutral and icon-free when not. An additional refinement, that we project will increase its salience and attention getting qualities, will be to arrange for the red circle/slash that covers the left turn arrow, to be continuously active during the 'on' phase. The circle/slash under our design will, periodically (at 1-4 Hz), increase in scale from the standard size shown in geometrical specifications for the R3-2 to a 50% increase in the thickness of the elements. This latter activity will, we conjecture, make the sign especially visible amongst the distracters that can be found at any intersection for the reason that the motion inherent in its elements and the looming nature of that motion, should be especially suited to signaling the faster and more sensitive pathways in the visual nervous system.



24 x 24 ft. (600 x 600 mm)

Figure 4.3-1. Left Turn Prohibited Sign, to be Adapted to Active DII

# 4.4 IDS Communications Tradeoffs

With regard to the roadside-vehicle communication necessary to enact an in-vehicle driver interface, we have developed a "State Map" concept (described in Section 4.1) wherein information from the roadside is transmitted to a computer, which can exist either at the roadside or within the vehicle. In either case, a LTAP/OD IDS algorithm – probably the same or similar version – can operate at either locale. The critical enabling technology is Dedicated Short Range Communication (DSRC), and the concomitant development of protocols which allow safety critical information to be transmitted to ad hoc and ever-changing networks of cars within the intersection.

Therefore, wireless communication technologies may play a key role in the development of an IDS. Wireless communication increases the amount and quality of the information that the IDS system receives. Even in an Infrastructure-based implementation, the IDS application may gather critical information from the vehicles and deliver targeted warnings via wireless communication. The IDS communication subsystem provides two services:

- Neighborhood state map building, i.e. to acquire information of the surrounding environment;
- Message delivery, i.e. to deliver warning or support messages.

The IDS application makes its decisions based on the current knowledge of the surrounding environment (e.g., the application warns others that a vehicle is violating the red signal if it knows that the signal phase is red and the vehicle is not predicted to stop). This knowledge is traditionally acquired via sensors. We plan to consider communication as well as sensors in the information collecting/sharing. We envision this approach to be able to overcome some sensors' limitations (e.g., it may be difficult for sensors to detect a vehicle coming from an intersecting road if there are buildings or trees near the intersection).

Wireless communication easily solves the "line of sight" problems coming with sensors: the infrastructure may send a message containing a list of vehicles approaching the intersection. As soon as the IDS application makes a decision (e.g., it decides to warn a red traffic signal violator) it needs to communicate with the driver. This may be done in many different ways such as using DII or in-vehicle displays. Communication is needed to deliver these messages from the IDS application to the right device.

We will organize our enabling research around two communication architectures, a distributed architecture (see Figure 4.4-1) and a partially centralized infrastructure supported (PCIS) architecture (see Figure 4.4-2).



Fig 4.4-1. The Distributed Architecture

The Distributed Architecture aims to realize the networking service through the peer-to-peer interaction of wireless communication enabled vehicles alone. The PCIS architecture presupposes the existence of a roadside infrastructure. Both the architectures are going to use some sort of radio. The car will be equipped with wireless on-board-emitter (OBE) while the infrastructure will have a wireless roadside-emitter (RSE).



Figure 4.4-2. The Partially Centralized Infrastructure Supported Architecture

We are interested in the Distributed Architecture because it provides a degraded mode of operation in the event of failure of the roadside infrastructure. It may also enable large parts of rural America to enjoy IDS benefits without requiring the ubiquitous deployment of DSRC infrastructure across the nation.

Our interest in the PCIS architecture is due to the unpredictable evolution of the invehicle wireless market, the potentially greater operational benefits of partial centralization, and the possibility of public agencies mobilizing enough investment to drive at least a limited deployment of roadside DSRC infrastructure. Both communication architectures are going to provide the two basic services we discussed at the beginning of this section: message delivery and neighborhood state map building.

In the distributed scenario the OBE-equipped vehicles broadcast information about themselves and listen to the other vehicles messages. They fuse the information received via communication with the information gathered from the sensors.

In the infrastructure assisted scenario the vehicles behave in a similar way. While the vehicles send their messages, the infrastructure listens and collects them. The infrastructure fuses the information in these messages with the information it gathers from its sensors (these are probably more precise than the ones that can be mounted in a vehicle). The infrastructure-enhanced map can then be broadcast back to the vehicles. At the same time the infrastructure may react to driver hazards or support their decisions.

In order to conduct enabling communications research, the first step is to select the radio technology we are going to use for the OBE and RSE.

Many different wireless radios are currently available on the market. Every one of them offers unique advantages and disadvantages. This report introduces a set of evaluation parameters and the group of the most promising wireless technologies available on the market. Using the evaluation parameters we will comparatively evaluate this group of technologies and, in the conclusion, we will suggest one technology as the platform for the development.

In the following sections we address the following research questions:

- What are the enabling technologies available for IDS?
- Which parameters should we consider to evaluate them?

• Given these parameters, which technology best fits the IDS application requirements and why?

#### 4.4.1 Description of Available Technologies

# 5.8 GHz DSSS / MC-DSSS

The idea of spread-spectrum radio transmission was proposed by the military who was seeking ways to prevent radio signals from being monitored or blocked by hostile parties. With direct-sequence spread spectrum (DSSS) the signal is passed through a spreading function and distributed over the entire band. DSSS avoids interference from conventional radio transmitters by configuring the spreading function in the receiver to concentrate the desired signal but spread out and dilutes interfering signals. Spread-spectrum radio is good at dodging interference from conventional sources, as signals that stay in one narrow area of the frequency band and don't move; however, its performance does not degrade gracefully with amount of interferences. When the interferences reach a saturation level the throughput suddenly drops to zero.

As described in publications by WiLAN<sup>36</sup> and Altera<sup>37</sup>, direct-sequence spread spectrum (DSSS) radios combine data signal at the sending station with a higher data rate bit sequence, or chipping code, that divides the user data according to a spreading ratio. The chipping code is a redundant bit pattern for each bit that is transmitted, which increases the signal's resistance to interference. If one or more bits in the pattern are damaged during transmission, the original data can be recovered due to the redundancy introduced by the chipping code. This radio sequence is used by many different systems (e.g. 802.11b, Bluetooth).

There are many DSSS radios available on the 5.8 GHz band, with different channel width, modulation schemes, ranges, and bandwidth (usually between 56 kbps, and 6.176 Mbps). In particular the Multi Code DSSS technology, described in the US Patent bearing this title<sup>38</sup>, offers a 10 Mbps data rate and a 10 km range.

#### IEEE 802.11b

This standard uses the DSSS introduced in the previous section. It works in the FCC allocated 2.4 GHz – 2.4835 GHz band. Under 802.11b, devices communicate at a rate of 11 Mbps whenever possible. If signal strength or interference is disrupting data, the devices will drop back to 5.5 Mbps, then 2 Mbps and finally down to 1 Mbps. Though the radio may occasionally slow down, it keeps the network stable and reliable. 802.11b has a short range (1,000 ft / 305 m in open areas, 250 to 400 ft / 76 to 122 m in closed areas).

The 802.11b standard specifies a Complementary Code Keying (CCK), a set of 8bit code word, which can be easily distinguished at the receiver side even with presence of substantial noise and multi-path interference, to decode all data sent over the air. These symbols encode 4 bits (5.5Mbps rate) or 8 bits (11 Mbps rate) and they are sent using QPSK to achieve a symbol rate of 1.375 Mbps. The data rate of 1 and 2 Mbps uses the original 802.11 DSSS techniques (Barker Sequence coding, BPSK/QPSK at 1MSps rate).

The performances degrade gracefully, since because of dynamic rate shifting, the rate is dynamically adjusted to the background noise level.

# CANOPY

The Motorola Canopy Wireless radio technology is currently used by Wireless Internet Service Provider (WISP) to offer wireless connectivity. It operates in the unlicensed national information infrastructure (U-UNII) band, 5.25 to 5.35 GHz and 5.725 to 5.825 GHz, but it can be adapted to work on the 5.85-5.925 GHz band, reserved to ITS applications. The Medium Access Control method is Time Division Duplex / Time Division Multiple Access (TDD/TDMA). The modulation type is high index BFSK, optimized for interference rejection. Motorola claims that, because of this modulation scheme, the signal to interference ratio can be kept under 3dB. The range goes up to 2 miles in the 5.2GHz band and up to 10 miles in the 5.79 GHz band. The transmit power meets the regulation of the FCC U-NII bands (< 43 dBm).

#### Bluetooth

Bluetooth is a new wireless technology, which operates in the 2.4 GHz ISM (Industrial Scientific Medicine) band. In most of countries, it operates at frequencies ranges between 2.400GHZ and 2.4835GHZ. Bluetooth is designed to replace wired connectivity between different personal electronics (e.g. connectivity between personal computer and printer, personal computer and digital camera and so on). It provides Omni-directional connectivity between devices, and supports point to point and point to multi-points connections.

Wireless technologies like IrDA has been deployed for numbers of years, but they didn't gain users' popularity because of their "line of sight" communication, and their point to point connection. Bluetooth has overcome these problems. When Bluetooth-capable devices come within range of one another, they start discovering each other, and try to offer services to each other. Users do not need to establish and maintain devices connection. Devices within the communication range form a personal-area network (PAN) or piconet.

To minimize power consumption of devices, the Bluetooth standard limits devices communication range to be within 10 meters. To minimize interfaces from other piconets, Bluetooth subdivides the spectrum into 79 channels and uses a spread-spectrum frequency hopping modulation technique that we have previously described. In this technique, a device randomly chooses frequencies within a designated range, and switches from one channel to another on regular basis. In the case of Bluetooth, the transmitters change frequencies 1,600 times per sec. Thus it is unlikely that two devices use same channel at the same time, and even they do, the interference lasts only for a tiny fraction of a second.

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The maximum data rate per channel is 1 Mbps and the bit error rate is in the order of  $10^{-5}$ .

# DSRC

Recently the spectrum from 5.850 to 5.925 GHz (5.9 GHz) has been allocated in the United States "to enhance the safety and the productivity of the transportation system" (see <<u>http://www.leearmstrong.com/dsrc/dsrchomeset.htm</u>>). The ASTM (American Society for Testing and Materials) standardization committee E17.51 is working on the development of the standard of 5.9 GHz **DSRC** (Dedicated Short Range Communication). DSRC is a short to medium range communication service that supports both Public Safety and Private operations in roadside to vehicle and vehicle-to-vehicle communication servicommunications by providing very high data transfer rates in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important. The preliminary DSRC standard proposes max data rate up to 27 MB/s with 7 licensed channels, and up to 1000 meters transmission range.

# 802.11a

The Institute of Electrical and Electronics Engineering (IEEE) has developed 802.11a standard for the next generation of enterprise-class wireless LANs. It offers greater scalability, better interference immunity and significantly higher data rate than 802.11b. 802.11a has the same MAC (Media Access Control) layer and similar communication range as 802.11b.

The 802.11a operates in the 5GHz Unlicensed National Information Infrastructure (U-NII) band, which is not as highly populated as the 2.4 GHz band of 802.11b. Therefore, it has lower external interference than 802.11b. Moreover, Forward Error Correction (FEC) was added to the 802.11a specification to improve the

reliability and utilization of the channel, which reduces amount of retransmissions due to data loss.

To offer much higher data rate, 802.11a uses Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme. 802.11a standard subdivides the spectrum into 8 non-overlapping 20 MHz wide channels. Each channel is again subdivided into 52 subcarriers with each sub-carriers being approximately 300 KHz wide. OFDM allows transmitters and receivers to send and receive multiple data symbols on different sub-carriers in parallel. This significantly increases the amount of information that can be communicated in a time unit.

As stated in LAN 802.11a white paper<sup>39</sup>, this operates in the 5GHz U-NII band. In United State, frequency operational ranges are 5.15 - 5.25 GHz, 5.25 - 5.35 GHz and 5.725 - 5.825 GHz. The Standard subdivides the spectrums into 8 non-overlapping channels with 52 subcarriers each. It uses OFDM for its modulation scheme. It has maximum data rate up to 54 Mbps. It has communication range up 10,000 ft.

# 802.11g

The Institute of Electrical and Electronics Engineering (IEEE) 802.11g standard committee is currently finalizing the standard. Consumers now can purchase prestandard 802.11g wireless cards in stores, and companies claim that they can easily convert these cards to the finalized standard by updating the firmware. 802.11g is designed to operate at the same spectrums as 802.11b, but offers as much data rate as 802.11a.

802.11g is backward compatible with existing 802.11b, and they will be able to operate concurrently with each other at the same regions. 802.11g has the same modulation scheme as 802.11b. In addition, it has adapted OFDM modulation from 802.11a, which allows it to achieve maximum throughput of 54Mb/s. Some test

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results have shown that, in static environment, 802.11g offers better data rate and coverage area than any existing Wavelan technologies<sup>40</sup>. However, 802.11g has the same limited amount of channels as 802.11b, so it is not as scalable as 802.11a which offers more than twice amount of channels.

802.11g operates in the 2.4GHz ISM band. The 2.40GHz to 2.483GHz bandwidth are divided into three non-overlapping channels. It has communication range up 10,000 ft.

#### 4.4.2 Evaluation Parameters

There are many available radio technologies with really distinct performances. In this section we are going to describe the evaluation parameters we are going to use to select a particular radio technology.

The evaluation parameters are selected based upon the IDS application requirements.

One of the first evaluation parameters is **range**. The IDS application needs to start to track a vehicle when this vehicle is approaching the intersection. It is important that the range of the radio is not too low; otherwise, the IDS application will not have enough time to gather data, perform computations and issue a warning. It is not good to have a too large range as well because in that case an intersection may be interfered by vehicles at neighboring intersections. We can filter out this information, but the filtering consumes computing resources and communication bandwidth. The range is directly proportional to the number of vehicles that are able to communicate with the infrastructure. For this reason, the range is inverse proportional to the radio performance (i.e. large range => channel congestion => poor radio performance). The range choice is going to be based finally on the IDS

application requirement that has not been determined yet. Approximately, this range is going to be between 3,000 and 6,000 ft.

Another important evaluation parameter is **reliability**. Since the communication will deliver warnings, reliability is important. While we are listening via Internet to a broadcast radio it is critical if we lose 1 ms of music. Human ears cannot distinguish whether there has been an interruption. On the contrary, we cannot tolerate to lose a safety critical warning. A value of  $10^{-6}$  bit error rate should be enough (a higher reliability would be even better). Sengupta has introduced the interesting concept of variable reliability in order to guarantee a higher reliability to important messages (e.g. a warning message) and lower reliability to less important (e.g. the sensor reading of a vehicle at the border of the IDS application tracking zone).

Another evaluation parameter is **latency (or delay)**. A safety message is useful only for a short time. Large delay causes the vehicle unable to respond in time for the hazard. Thus safety messages have to be delivered with a bound on delay. Different radio technologies offer different bounds on latency. The maximum tolerable latency depends on the application itself. Even if this requirement has not being stated yet, it should be in the order of 10 ms. In Sengupta (2003) the concept of latency and reliability are bound together.

The last parameter we are going to consider is **data rate**. The radio needs to offer a bandwidth big enough to support the communication protocol we are developing. Every vehicle and the infrastructure need to be able to communicate in a given time even in congested situation. Based upon the preliminary sketches of the algorithm we are developing, work performed by Krishnan and Kellum<sup>41</sup> and ARINC<sup>42</sup> and on some mathematical and statistical modeling by Sengupta, it seems that a 1Mbps data rate is required and a higher rate is recommended.

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Given a particular environment it is important that the radio technology has a good **multi-path resistance**. The vehicles reflect the wireless signals and the radio receives the same signal many times with time shift and decreasing amplitude. The direct and reflected signals interfere with each other, making harder the successful reception of the original signal. The situation is worsened by the fact that the direct signal (most powerful) is often blocked by a string of vehicles between the sender and the receiver. Some radio technologies have introduced new techniques to deal with the problem, but some not. It is important for our choice, to select a technology with a high resistance to multi-path.

Finally, we are going to consider **interference likelihood** of the spectrum. The radio spectrum is dramatically congested. Many part of it are shared by many applications and standards. Even if a radio technology has a good range, is reliable, has a bound on the maximum latency and a high bandwidth it may not be usable because the part of the spectrum it uses may be congested. The interference likelihood should be small today as well as in the future. We do not want to deploy our application on a part of the spectrum that is almost unused today but it is going to be so crowded 5 years from now that our application will not be able to work.

We did consider other parameters such as the **size** of the device, the **power consumption** and the **antenna** requirements that are of critical importance on the vehicle side of the application. We are not going to list them in our evaluation in the next section because all the technologies we considered meet these requirements.

#### 4.4.3 Technology

We consider the aforementioned off-the-shelf wireless technologies and we evaluate them following the criteria described in Section 4.4.2. The results are summarized in Table 4.4-1.

Radio	Range	Reliability	Latency	Data Rate	Interference	MP
technology	(ft)	(BER)		(Mbps)	likelihood	resistance
5.8 GHZ	>	10-6	Fair	10	HIGH	GOOD
DSSS	10,000					
802.11b	1,000	10-6	Fair	11	HIGH	GOOD
CANOPY	10,000	10 <sup>-6</sup>	Fair	10	HIGH	GOOD
Bluetooth	30	10 <sup>-5</sup>	Bad	1	LOW	BAD
802.11a	10,000	10-6	Fair	Up to 54	HIGH	GOOD
802.11g	10,000	10-6	Fair	Up to 54	HIGH	GOOD
DSRC	10,000	10-6	Not	Up to 27	NULL	GOOD
			standard			
			ized yet			

# **Table 4.4-1: Evaluation Results**

As stated in the previous section, the IDS application requirement on range has not been finalized, but almost all technologies fall in the interval that we have specified. The only exceptions are Bluetooth, whose short range makes it completely unsuitable, and 802.11b, that may not meet the finalized requirements.

As far as reliability and multi path resistance are concerned, all the alternatives but Bluetooth, have an error rate smaller or equal to the selected one and a good resistance to multipath.

Bandwidth is not a concern, all the radios offer at least 1 Mbps. 802.11a and DSRC seem to be preferable because of the higher bandwidth:

The only parameter where the technologies differentiate themselves is the interference likelihood. The only two technologies with acceptably low interference likelihood are Bluetooth and DSRC. However Bluetooth cannot be used because of

its short range, low reliability and poor multi-path resistance. We note that DSRC is going to work on a part of the spectrum licensed specifically for transportation safety applications, so interference should be minimal.

Because of its high bandwidth, small error rate, and strong resistance to multi-path, DSRC seems to be the ideal candidate for a wireless technology for IDS applications. However the DSRC standard is not yet completed and it is currently impossible to use this platform.

The DSRC standard closely follows the 802.11a standard. It should therefore be straightforward to migrate a system working with 802.11a radios to DSRC radios when they will be available.

In conclusion, we recommend developing the IDS system on top of 802.11a radios, because they have small bit error rate, correct range, really high data rate, good resistance to multipath and high compatibility with the soon to be available DSRC radios. We suggest a strategy of switching to DSRC radios as soon as they become available, as we believe this will be relatively straightforward.

#### 4.5 Modeling and Simulation

The IDS project includes a significant modeling and simulation component. Hence, we have considered the relevance of previous work on modeling and simulation of intersections to our ongoing IDS research.

We recognize the importance of "testing in the computer", particularly when we are developing notional systems and assessing their effectiveness under a variety of presumed – and very dangerous – scenarios. Hence, our goal is an intersection simulation tool that incorporates realistic models from outside sources as well as those developed within the IDS program. This simulation tool will be provided to

IDS program (as well as US DOT and US DOT-designated) users as an invaluable part of system development and assessment.

Intersection safety does not appear to be a traditional subject of study using simulation. The problem is noted in Pursula and Matti<sup>43</sup> (1999):

Traffic safety related questions have been quite a hard problem for simulation. In traditional simulation programs the drivers are programmed to avoid collisions. Thus, they do not exist. Some trials for analysis of conflict situations through simulation can be found (Karhu<sup>44</sup> 1975; Sayed<sup>45</sup> 1997), but a general approach to the problem and widely used safety simulation tools are still missing. Traffic safety simulation belongs to the field of human centered simulation where the perception-reaction system of drivers with all its weak points has to be described. This kind of approach is sometimes called nanosimulation in order to separate it from the traditional microscopic simulation.

Our review of TEXAS and other intersection simulations has confirmed this statement.

# The TEXAS Model

The TEXAS Model was developed in the 1970s by Lee, Rioux and Copeland<sup>46</sup> to study traffic flow at intersections. The model has some limitations for intersection safety studies, but it also provides some basic principles which we can reuse in our simulation.

#### Limitations of TEXAS

First, the model is oriented towards studies of performance, rather than safety. It is microscopic, with simple models of individual vehicles, rather than nanoscopic,

with detailed, high fidelity models of vehicles their motions. For instance vehicles follow their set paths exactly, in the exact center of lane.

Second, the driver model is too simplistic. To reduce computational resource requirements for 1970s-era hardware, many assumptions were made (see in particular pp. 290-291 to Lee, et al; 1977):

- the driver can predict future position and velocity of self and others
- the driver has perfect information about what others are doing
- the driver can accurately calculate the necessary acceleration or deceleration to perform a maneuver
- drivers follow deterministic logic in their decision-making, and do not change their minds
- "left turning vehicles will not move part of the way into the intersection when the signal turns green."
- drivers enter intersection only if it there is a clear path
- at most one driver enters intersection during amber phase
- drivers do not run red lights, and obey all traffic laws
- perception reaction time is a single parameter that applies in many algorithms (p.223-4)

Most of these assumptions are unwarranted for our study.

Third, detection of collisions and conflicts is too simplistic (p. 222):

[D]river-vehicle units within the intersection are furnished information only about the other driver-vehicle units on the same intersection path. Therefore, only rear-end collisions on the same intersection path are detected ... Other types of collisions that may possibly occur in the intersection are not detected by SIMPRO as the intersection conflict checking procedure is designed to prevent collisions with vehicles on other intersection paths.
In addition, the conflict checking procedure happens before the simulation starts, and is purely geometric in nature, with no attention to dynamics or human variability. There is no consideration of gap judgment for conflicting (opposing or crossing) traffic (only for lane change). We expect gap judgment to play a major role in our study.

Finally, there is no provision for ITS devices on vehicles or in the infrastructure, except for actuated signals.

### Relevance of TEXAS

TEXAS does provide us with a useful classification of intersection design parameters and geometries. Also, it has formulas and algorithms for calculation of occlusion, paths through the intersection, speed restrictions for paths, and path conflicts.

### The HUTSIM Model

HUTSIM <<u>http://www.hut.fi/Units/Transportation/HUTSIM/</u>.> was originally specifically for signal control, but has developed into a more general urban traffic simulation. Like TEXAS, it is oriented towards studies of performance, rather than safety. The models have been calibrated using macro level measurements (flows, queues), and may not accurately represent the motions of individual vehicles.

### *Sim Traffic*

SimTraffic <<u>http://www.trafficware.com/simtraffic.htm</u>.> is advertised as a replacement for CORSIM, and, correspondingly, emphasizes large scale simulations. In particular, it has been used for studies of delay, emissions, queues. It does not appear to be useful for safety-related nanosimulations. Also, it does not seem to model any ITS components.

# 5.0 Midterm Demo

### 5.1 Background and Concept

The concept PATH demonstrated is an IDS system designed to warn drivers when it is unsafe to make a left turn in the face of an oncoming vehicle. Using multiple detection and sensing devices [including laser scanners (lidar), microwave radar, inductive loop detectors and in-vehicle global positioning systems (GPS)], the IDS system can identify and track other vehicles approaching the intersection in real time. Combined with motion data for its own vehicle, the central processing unit (CPU) uses signal timing and phasing data sent from a traffic controller at an intersection to run a decision- making algorithm. When conditions are unsafe for making a permitted left turn, a dynamic "no left turn" sign that pulses (or "looms") and displays a warning to the driver. An alternate path to deployment is the IEEE 802.11a, wireless communication device, that would allow direct communication between one vehicle's CPU and approaching vehicles, thus creating a "smart" intersection that can provide information directly to in-vehicle devices. The flow of information can be seen in Figure 5-1.



Fig 5-1: Data Process Flow for PATH IDS system.

We implemented three objectives as the target goals for the demonstration:

- Develop an infrastructure-supported decision support system to prevent LTAP/OD crashes that would be viable in the near-term;
- Illustrate a robust system architecture the would be able to gather the data from the infrastructure and synthesize the information to form a digital map or "State Map" of the intersection;
- Transmit the "State Map" via an 802.11a wireless communication device to a vehicle to show how the infrastructure information could be provided to future in-vehicle warning systems.

Our demonstration scenario is illustrated in Figure 5-2 with block diagrams representing approaching vehicles. The subject vehicle (SV) approaches the intersection on the southbound leg. The SV has a permissive green and slows to a stop so that the driver can check whether it is safe to make a left turn onto the Eastbound leg of the intersection. Directly opposite from the SV is an occluding vehicle that is stopped in a protected left-turn lane, also waiting to make a left-turn. However, the traffic-signal phase for the occluding vehicle is a red left-turn arrow. The SV driver has his or her view obstructed and cannot decide whether to turn.

At the same time, a principal other vehicle (POV) is approaching on the northbound leg of the same street at roughly 10 to 20 mph. The POV driver plans to go directly through the intersection without stopping because the driver has a "green" light. Both SV and POV will arrive at the intersection at the same time.

To help the SV driver prevent a collision or near collision, the IDS system would issue a warning to the SV driver using a pulsing signal produced by a driverinfrastructure interface (DII) device near the intersection. The SV driver should notice that the DII has a pulsing signal, using motion to speed the human perception of the warning signal.



Fig 5-2: LTAP/OD Crash Scenario.

The PATH IDS demonstration system uses a combination of three warning sensors. Two pairs of remote sensors (Denso Lidars and Eaton Vorad Radars) above ground and seven inductive loop-shaped detectors (or loops) embedded in the pavement are used to detect the presence of an SV as well as traffic downstream from the intersection. Extracting useful information from the loops means that the PATH team chose to use the National Transportation Communications ITS Protocol (NTCIP) within the 2070 advanced traffic controller.

Besides loops, radars, and lidars, differential global positioning satellite (GPS) data from the SV and POV vehicles are also used to relay the approximate position of the vehicles relative to the target intersection. With the combination of the three sensors and GPS, a rich and robust amount of information can be extracted about each approaching vehicle including range, range rate, and trajectory.

The GPS data are relayed back to a PC 104 computer in the target intersection by an 802.11a wireless communications device, while the sensor data from each vehicle are relayed to the PC104 computer via CAT V Ethernet cable. The computer processes the information into a database and then runs a "warning" algorithm and fusion of data from all four sources. This process estimates the POV's time to intersection and any possible conflicts with an approaching SV. If a conflict might occur, the computer sends a warning signal to the DII on the roadway infrastructure via hardwired CAT V Ethernet cables. Once the signal arrives, the DII activates and sends a signal to warn the SV driver against making a left turn, potentially avoiding a collision.

In addition to the infrastructure-based solution, we examined a vehicle-based solution with infrastructure that broadcasts State Map information from the roadside infrastructure to the vehicle. The purpose behind this research was to show the value of real-time data for drivers by using the 802.11a wireless communications device, which is the basis for the emerging generation of dedicated short-range communications (DSRC). The placement of the sensors and DII can be seen in Figure 5-3.

The main point behind the PATH LTAP/OD demonstration is that the system can broadcast a signal based on a synthesis of information from the four sources for a complete appraisal of the intersection traffic situation.

The system can function in either of two modes:

• Loop Only Mode – This mode uses only the existing infrastructure of loops within the pavement and 2070 NTCIP interactions.

• Remote Sensor Mode – This mode uses only the remote sensors (lidars, radars, and GPS) to detect the traffic conditions.

All hardware components for the PATH Demonstration plan were commercial offthe-shelf (COTS) equipment except for the DII, which was custom made.



Fig 5-4: Placement of Hardware at Infrastructure and Within Vehicles

## 5.2 Hardware

## 5.2.1 Sensing System Design

The sensors in the IDS system are used for detecting SVs and POVs. For the demonstration, the sensors need to serve three functions:

- Detecting the vehicles to trigger "on" warnings,
- Detecting the vehicles to trigger "off" warnings, and
- Building trajectories for State Map visualization.

Loops and similar presence detectors have been widely used in intersections as actuating sensors for advanced traffic controllers (e.g., 2070 controllers). Such sensors are useful in IDS because:

- Engineering experience in deployment of such sensors will help improve the design and deployment of future safety systems,
- The cost of future safety systems will be greatly reduced if sensors are already embedded In many intersections and can be reused, and
- It is easier to make future safety systems compatible with traffic controllers if they share the same sensors.

However, loop detectors are discrete sensors; i.e., they can only detect the presence of an object at specific locations and estimate its moving speed. Consequently, many loops are needed to detect the continuous trajectory of an object.

Radars and lidar are used as sensors for detecting objects in Adaptive Cruise Control (ACC) systems and in collision-warning and collision-avoidance systems. In contrast to inductive loops, radars and lidars can give almost continuous trajectories for objects. Also, radar and lidar can detect multiple objects simultaneously, and their range coverage can be more than 100 meters. Loop installation is usually a complex process that includes cutting the pavement, embedding loops and running wires to the processing units. Compared to loops, radars and lidar are easier to install, but they have their own shortcomings. They are mostly designed for two-dimensional plane detection (range and azimuth). Individually, they are not suitable for uneven (quickly sloping up and down) roads which expand to three dimensions, i.e., with superelevation. Radars can suffer from a multi-path transmission of microwaves which can cause the loss of a target vehicles or significant measuring errors. Other vehicles passing by or nearby buildings can all cause multi-path transmission of microwaves. This phenomenon can significantly degrade radar performance in safety-critical applications. Laser scanners are defective in certain weather conditions such as rain and fog, and laser beams can be harmful to human eyes in some circumstances. These factors limit radar and lidar utility in intersection applications.

For the demonstration, we used all three kinds of sensors (i.e., loops, radars and lidars) to increase the likelihood of success, and to illustrate a variety of potential sensors. Future research within the IDS project will identify the best sensors for real-world implementation.

The GPS supplements the sensing system by providing data on vehicle position and trajectories for the real-time State Map display. Table 5-1 lists the sensors and the functions they served in the demonstration.

Vehicle to	Sensors to	Sensors to trigger	State Map, sensors to
detect	trigger "ON" warnings	"OFF" warnings	build up trajectories
POV	Loops	Loops	GPS
	Radar + lidar		Radar+lidar
SV	Loops	Loops	GPS
	Radar + lidar		Radar+lidar

Table 5-1: Sensors and Functions for Detection

The "radar plus lidar" combinations (sensor sets) can serve both to trigger warnings and to build trajectories. For each SV or POV vehicle, we needed only one set of radar and lidar. The radars and lidars should be placed in the intersection facing the lanes under their surveillance.

To detect a SV that will trigger warnings, the loop should be placed at a distance away from the intersection such that at least one loop will detect the vehicle before it runs to the condition "warning point". The so-called "warning point" is the time when the DII is triggered "ON". The warning point is temporarily set as one second before the SV reaches the stop line, so at least one loop detector should be more than 1 second away from the stop line. Assuming that the maximum speed of the SV around the warning point is 15 mph, if a loop is about 1 to 2 seconds away, the location of this loop can be calculated as:

$$\frac{15}{2.2}(m/s)\times(1\sim 2)(s)\approx 7\sim 14(m).$$

To detect POVs that will trigger "ON" warnings, loops should be placed at a distance away from the intersection such that at least one loop will detect the vehicle before its time-to-intersection (T2I) reaches the warning threshold. The warning threshold at the temporary warning point is initially assumed to be in the range of about 1 to 7 seconds. Assuming that the maximum speed of the POV is 25 mph, the location of the loops can be calculated as:

$$\frac{25}{2.2}(m/s)\times(1\sim7)(s)\approx11\sim80(m).$$

The one-second warning point (the SV's time-to-stop line) has not yet been tested in a naturalistic environment with a large distribution of drivers. It may need to be adjusted, in which case multiple loops will be needed to cover a longer range. Moreover, the warning threshold is referenced to the warning point. Once the warning point is changed, the warning threshold is also changed; multiple loops should be placed along the POV track accordingly.

The standard loop layout for traffic control arranges multiple loops in each lane to detect queues. For the demonstration, loop detectors were embedded according to the standard practice, which is four in-pavement loop detectors. The first one was placed at the stop line, and the rest are spaced three meters apart edge-to-edge from the first loop detector along the lane. At conventional intersections, all four approaches as well as the left-turn pockets have loop detectors, but for the demonstration, only the loop detectors in the SV and POV tracks were required. Three more loop detectors on the northbound approach lane (POV track) were added to detect the POV and determine its speed earlier. The first loop was 16 meters from the beginning of the curve, the second one was at the beginning of the curve, and the third one was at the end of the curve since the POV will go from its starting point to the intersection.

The layout of the sensors in the intersection is illustrated in the following Figure 5-4.





To validate the sensing system design, a sensor set (one lidar plus one radar) was set up and installed at an intersection at the UC Berkeley Richmond Field Station facility. This sensor set was installed at a height of about 1.5 meters on a pole standing in a corner of the intersection. Both sensors were adjusted to face the same direction. During testing, a compact car was driven forward and backward in front of sensors four times. Then a car that was taller than the compact car was driven the same way twice. The output of the sensors was collected through a PC/104 computer and then analyzed to verify the validity of the sensing system design and to check the capabilities of the sensors. The data are plotted in Figure 5-





(Compact and Larger Car)

From this testing, we made several observations.

- The radar and the lidar both detected the vehicles. The slowly varying trajectories are those of the cars. Other trajectories are of some stationary objects.
- 2. Azimuth angle coverage is the principal limit of minimum detectable range. In the plots, at the dropout points of the trajectories, the azimuth angle values are approaching the limits ( $\pm 6$  degrees for the radar and  $\pm 20$  degrees for the lidar). This implies that the targets dropped out because they were out of the azimuth range. Comparing the lidar plots (1<sup>st</sup> row) with the radar ones (2<sup>nd</sup> row), it can be seen that lidar's short-range performance is better, most likely because of its wider field of view.
- 3. Detection probability of the taller car is better. Both the lidar and the radar detect the taller car with fewer "drop-outs." Radar and lidar were originally designed for detecting rear bumpers of vehicles, but in the testing (as in the IDS system), they are used to detect the front face of cars. The windshield is a tilted reflecting surface, which may reflect away light waves and cause loss of targets. This finding was verified by lowering the height of the sensors. Both radar and lidar detected the vehicles better at lower positions.

Another test was conducted to ensure that when two sensor sets work together; they will not interfere with one another. The two lidar certainly would not interfere with each other because in the demonstration, they are mounted back-to-back, facing different directions. However, the two microwave radars might cause mutual interference because they are so close back-to-back that the side lobe energy of one emitter may enter the other receiver. Eaton Vorad claimed that the EVT radars have frequency-agility capability to avoid such same-frequency interference. To

substantiate this claim, a test was done with two radars mounted back-to-back on the same pole. As expected, findings suggested that two radars can work together without interference.

The topography of the vicinity of the demo intersection increased the difficulty of using radar and lidar since no single sensor can cover the whole SV lane or POV lanes. We carefully adjusted the orientation and elevation angles of the sensors so that each sensor would cover part of a whole lane, and two sensors together covered the whole. While problems we encountered may be beneficial to the future design of the sensor systems, these problems may be artifacts of the peculiar layout of the intersection at TFHRC, which is not typical of intersections, and these problems should not be encountered in the majority of intersections.

First, the POV lane consists of a sharp curve with two straight segments at each end. On the inner side of the curve is a small crest with a stand of trees. It is impossible for one sensor to cover the entire lane. We tried using the lidar to detect the distant segment beyond the curve. However, lidar can only report up to 8 targets, and when the lidar was facing the distant segment, trees on the small hill were detected – then the lidar apparently became saturated. Hence, a vehicle moving along the lane could not be reliably detected by the lidar.

We then tried using the Doppler radar (which can filter out stationary objects such as trees) to detect the distant segment. However, when a vehicle was on the distant segment, its moving direction was approximately along the tangential line (i.e., almost perpendicular to the radar's aiming direction), and the radial component of speed that the radar detected was very small. Hence, the radar could not detect the vehicle reliably.

We set up a second sensor pole on the opposite (Southwest) corner of the intersection and moved one sensor to the second pole to detect the vehicle beyond the curve. Since this strategy required too much time and re-wiring, it was

abandoned. The final sensor configuration of the POV lane included lidar facing the straight near segment (from the intersection to the curve), and the radar faced the curve and beyond. Along the curve, the radar still had problems because when the vehicle was turning along the curve toward the intersection, the radial speed component was variable along the body of the vehicle, from the fastest at the front end to the slowest at the rear. While radar usually splits the same vehicle into multiple targets because of speed segmentation in its target detection algorithm, the split targets all have significant moving-direction error.

Figure 5-6 illustrates how radar splits one target into multiple targets along a curve. There are three subplots in the figure. The top is the range plot; the second is the radial speed plot; and the last is the azimuth angle plot. A negative angle means the target is to the left side of the radar's boresight (aiming direction). A positive angle means that the target is to the right of boresight. While there was only one vehicle moving along the curve in our test, the radar reported three targets at the same distance with slightly different azimuth angles and different speeds. The target with negative angle (left side) appeared and disappeared earlier, while the one with positive angle (right side) appeared and disappeared later. This negative-to-positive angle transition implies that the real moving direction is from left to right. This is exactly the way the target vehicle was moving. But if we look at each individual split target, the azimuth angle is almost constant. None of the split targets can represent the true target in terms of moving direction. To deal with this problem, we needed to fuse the closely distributed targets together, using the average distance and azimuth as the true target position.



Fig 5-6: Radar Splits a Turning Vehicle into Multiple Targets

We have an even more difficult geometric field of regard with the SV lane. We need to detect the SV when it is making left turn in the intersection. Since radar did not appropriately cover this segment (because of the target-splitting along curves), we used lidar to cover the intersection and a short segment beyond the stop line. The radar was then adjusted to detect the distant segment. The SV lane was a straight road, but it was uneven (i.e., built on a slope). As a result, the sensor pole was on the highest point, and the SV stop line was much lower than the point of sensor pole. Beyond the stop line, the road gradually increased in elevation. Very close to the stop line at the end of the road was a building with a large tree with branches hanging over the road, with the building less than 100 meters away from the intersection. The lidar's elevation angle needed to be carefully adjusted so that it would not detect the pavement or the tree leaves. Although carefully adjusted, the lidar still occasionally detected the leaves when it was windy, which sometimes appeared as a false SV around the stop line. If a POV's timing were to match this otherwise spurious signal, it might cause a false alarm. Therefore, the radar had to be adjusted to cover as much of the whole lane as possible. This resulted in an unavoidable problem: that is, when the SV approaches the stop line, at a certain critical distance, a multi-path effect appears. From that point, the real target is lost and another false target, which is even more distant than the building, appears to be moving away from the sensor. In response, we carefully adjusted the orientation angle of the lidar to cover the radar's blind spot.

Figure 5-7 shows how a multi-path effect caused the loss of a target vehicle and introduced a false target. The target was moving towards the sensor in the SV lane. Just before time point 148 in the figure, the multi-path effect appeared. After a short transition, the original target disappeared, and another new and more distant target appeared to be moving away from the sensor. Because of this problem, radar is unlikely to be able to detect a target behind a building; rather, it detects the image of the real target reflected by the building.



Fig 5-7: Multiple Path Effect Induces Loss of Target Vehicle and Detection of a False Target

We detail the above because the lessons learned from the demo intersection are not unique to this intersection. Intersection approaches often include curved and/or sloping roads, with backgrounds that includes trees or poles, and nearby buildings. When used in intersections, radar and lidar need to be well located and posed to avoid these problems, which increases the complexity of deployment of safety systems that use such sensors.

### 5.2.2 PC/104 IDS Control Computer

Since we were already quite familiar with operation of the PC/104 computer, it was chosen to be the IDS control computer for sensor fusion, warning, and tracking algorithms. It is also used to trigger the DII warning signal. The PC/104 is rapidly becoming a standard for computers in factories and laboratories to provide programmable control of complex systems. The PC/104 is a standard for PC-compatible modules (circuit boards) that can be stacked together to create a complete computer system. PC/104 systems are very similar to standard desktop PCs, but they have a different form factor. The name "PC/104" is derived from this likeness and the special stackable bus connector having 104 pins (See Figure 5-8).



Fig 5-8: Typical PC/104 Stack

These systems can be programmed with the same development tools used with fullsize PCs, which reduces the need and cost of custom development efforts. Although only about 100 cm x 100 cm, PC/104 boards are very powerful for their size. PC/104 products are designed for minimal power consumption, small foot print, modularity, expandability, and durability.



The IDS project control computer consists of 3 stacked boards as shown in Fig 5-9.

# Fig 5-9:PC/104 Stack for the IDS Control Computer with Sensor InterfacePanels Located at EachEnd of the Computer Enclosure.

The port assignments for the sensors (radar, lidar, and loop detectors) are shown in Table 5-2. All ports/digital I/O channels use the Emerald-8232-XT board except ports COM1 and COM2, which are resident on the CPU.

Port/Channel	Sensor/Device	Baud Rate
Com 1	Not Used	N/A
Com 2	Not Used	N/A
Com 3	Eaton Vorad Radar (SV)	19200
Com 4	Denso Lidar (SV)	19200
Com 5	Eaton Vorad Radar (POV)	19200
Com 6	Denso Lidar (POV)	19200
Com 7	Not Used	N/A
Com 8	2070 Computer Access	38400
	(Loop Detectors)	
Dig. I/O A	DII ON/OFF Signal	N/A
Dig. I/O B	Not Used	N/A
Dig. I/O C	Not Used	N/A
Dig. I/O D	Not Used	N/A
Dig. I/O E	Not Used	N/A
Dig. I/O F	Not Used	N/A
Dig. I/O G	Not Used	N/A
Dig. I/O H	Not Used	N/A

### Table 5-2: Port Assignments for Sensors/Devices

### 5.2.3 IDS Hardware Configuration

This section discusses the hardware configuration for the IDS intersection at FHWA. It includes two main parts. The first part is the sensors. The sensor pole holds the radars (Eaton Vorad EVT-300), Lidars (Denso), and the DII. Other sensors are the inductive loops which are embedded in the roadway. The second part includes the control computer system, which is located diagonally across the

intersection in a control cabinet. A schematic of the sensor-pole configuration is shown in Figure 5-10.



Fig 5-10: Sensor Pole with DII.

The POV and SV sensors are rotated approximately 180 degrees apart to allow detection of the northbound (POV) and southbound (SV) vehicles. Figure 5-11 shows the overall hardware layout used for the IDS demonstration.



Fig 5-11: Schematic of IDS System Including Signal Type for all Sensors and Devices.

Communication between the control computer and the sensor pole is accomplished using two standard category 5 twisted-pair cables that are installed underneath the roadway. At each end, the cable wires are converted to standard RS-232 serial lines that connect to either the control computer or the sensors using a converter box shown in Figure 5-12.



Fig 5-12: Converter Box.

### 5.2.4 Driver-Infrastructure Interface (DII)

The DII was designed with the specific intention to command attention of the driver, using a conditional sign. The visual warning signals were constrained to be built in approximately the form of a standard 24 in. x 24in. MUTCD R3-2 "no left turn" sign. Our active LED-based DII measures 26.5 in. x 26.5 in. x 5 in(1 x w x d). The endpoint of the experimentation, to design an optimal DII, has yet to be achieved, but the intermediate step is to elicit a faster reaction time response from the driver.

We chose a 'looming' signature designed to stimulate the faster visual pathway of the brain. To achieve this effect, the DII component that we designed has an expanding red circle with a slash that is sequenced so that at "turn-on," it appears to immediately enlarge and thus appear to move toward the observer. The intermediate step has a DII that has the following criteria for the looming aspect:

- Initially "OFF"
- 200 msec "ON" (meaning only the thinner red circle with a slash is lit).

• 300 msec "flash" (meaning the extra red LEDs are lit, making the red circle with a slash thicker).

The brightness,  $4505.9526 \text{ cd/m}^2$ , set in the prototype DII, can be seen in Figure 5-15 from the false color image of the DII.



Fig 5-15: False Color Image of the LED-based DII with Colorscale<sup>iii</sup>

Based upon this understanding of human physiology, it seemed prudent to design a warning signal that incorporated motion, and in particular the motion associated with 'looming,' which is known to engender an increased attention on the part of

<sup>&</sup>lt;sup>iii</sup> All DII video photometer images were taken at 24 feet using two x8 ND filters. The Eyeppearance software can only take whole percentages of transmission; therefore, only 2% was used. The shutter speed was 6.

the observer, and which might lead the observer to believe that the warning signal was getting closer more rapidly than a veridical percept would suggest. The DII with its three stages of "turn on" can be seen in Figure 5-16.



# Figure 5-16: DII "OFF" State, Followed by DII "ON" State, Followed by DII "Flash" State

While there are no references to "looming" in the MUTCD, there are references to and examples of flashing beacons which can be used to supplement a warning or regulatory sign.<sup>iv</sup> According to the MUTCD a flashing red beacon can be used to accentuate a stop sign, and a flashing yellow beacon can be used to accentuate a warning sign such as "curve ahead" or "stop ahead." Additionally, there are cases involving the use of a conditional flashing beacon, such as "road slippery when flashing" (to indicate the potential for ice on the roadway) or "intersection ahead, be prepared to stop when flashing." Given these examples, the looming effect of the DII is consistent with prior applications of flashing beacons, and hopefully (subject to experimental field test), it will not cause undo confusion to drivers.

<sup>&</sup>lt;sup>iv</sup> MUTCD Section 4K.01

The placement of the DII also affects the how well it commands the attention of drivers. To select the best location for the DII, we considered where the driver would most likely be looking when the sign illuminated. Although empirical evidence will be gathered in future stages of this project, we hypothesized that by the time drivers reached the intersection and were trying to decide whether the gap in oncoming traffic was large enough to allow a safe left turn, their vision (and attention) would be focused on the oncoming traffic or on the destination (or alternating between these) but not on the overhead traffic signal. Placing the DII on the far left corner of the intersection would place the sign much closer to the driver's center of attention than the overhead traffic signal, thus increasing the chances that the driver would detect the sign when it activated.

The field of view for the eye is roughly 180 degrees from left to right, but the detail that eyes can appreciate is greatly diminished within a few degrees of the direction that the eyes are looking. If the DII is located next to the corner traffic light, drivers can scan this area to see any opposing traffic and to view the destination for their imminent left turn.

Given that the DII was supposed to provide decision support to the driver, the goal of the timing algorithm was to activate the DII as the driver of the SV approached the intersection, shortly before a typical driver would make the decision whether to stop at the intersection to collect more information before turning left, or to proceed through the intersection and turn left without stopping. The literature reviewed in Section 4.2 of this report suggests that the decision point occurred about 1 second before the vehicle reached the intersection stop line. Findings also suggested that while waiting at an intersection, if the oncoming vehicle gap was less than 3 seconds, drivers always rejected the gap. If the oncoming vehicle gap was greater than 8 seconds, then the drivers always accepted the gap and turned before the vehicle reached the intersection. Based on this literature review, a timing algorithm was constructed to warn drivers of oncoming traffic.

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Although the timing algorithm was based on results in the literature, it had never been fully tested before the demonstration at TFHRC. During the test, there was speculation that the DII came on too early or too late. In the final implementation, the DII actuated as planned about 1 second before the SV reached the stop line, and the DII remained "ON" for about 3 seconds as the POV passed through the intersection. However, for most drivers, braking occurred up to several seconds before the DII activated. Given the low SV approach speeds of 10 to 20 mph, the braking behavior suggested that the drivers were deciding to stop before the DII was activated, since at such a low speed, the driver could easily complete the turn without slowing the vehicle. This observation suggests that the initial estimate of where the warning point should be was too late, and more extensive testing of the timing algorithm should be pursued in future stages of this project.



#### 5.3 Warning Algorithm

**Figure 5-17: Algorithm Architecture** 

Figure 5-17 diagrams the architecture of the algorithm. Inputs to the algorithm include sensor measurements for the SV and for any POVs. Output of the algorithm is a warning signal that triggers the DII. For SV and POV sensor measurements, sensor data processing is necessary to refine the measurements by means of filtering

and tracking, to form a system-level description of vehicle states by means of multiple sensor data fusion, and to derive vehicle-motion parameters such as range and speed by means of statistical parameter estimation. Vehicle motion parameters are further processed in a warning algorithm, based on a decision-making criterion to decide whether or not to "turn on" the DII. The criterion is that if the POV's time-to-intersection (T2I) falls in a critical time gap, which is a safe time gap required by the SV to make a left turn, the DII triggers a warning; otherwise, no warning should be given. T2I is defined as the time that SV or POV needs to get into the intersection. (More precisely, T2I is the time to reach the stop line of SV lane.)

The basic warning timing based on this criterion is illustrated in Figure 5-18. The warning initiation point (O) is the time at which the DII "turns on." This point can be selected during the time interval when the SV driver is gathering information from the environment, immediately before reaching the intersection. The SV driver's decision-making point is distributed in a time interval because of the diversity of situations and driver's capabilities. The required safe-time gap is bounded by points A and B. As shown in the timing diagram, if the POV's T2I at point O is shorter than OA or longer than OB, no warning should be given; otherwise a warning should be issued at O. Once the DII is triggered "ON", it stays on until the POV passes the intersection.



Figure 5-18: Basic Warning Timing

In the Figure 5-19, the SV lane is modeled as a straight road. The POV lane is modeled as two straight segments connected by a curve.



Fig 5-19: Road Geometry (Not to Scale)

The numbers in degrees are the moving direction of the route in GPS frames. The road width is 17meters. Locations of the loops are also calibrated using GPS. The locations of loops with respect to the sensor pole are as follows (in meters in the Virginia State Coordinate Plane or VSCP):

- SV loop1: (22-4.8\*0.866,2.4)
- SV loop2: (22,0)
- SV loop3: (22+4.8\*0.866,-2.4)
- SV loop4: (22+9.6\*0.866,-4.8)
- POV loop1: (-3.5\*0.866, 3.5/2+3)
- POV loop2: (-8.4\*0.866,8.4/2+3)
- POV loop3: (-13.1\*0.866,13.1/2+3)
- POV loop4: (-17.9\*0.866,17.9/2+3)
- POV loop5: (-24.87,18.31)
- POV loop6: (-44.65,10.66)

• POV loop7: (-47.69,-4.9)

Some values are not given as a number but an expression. This shows how the locations are derived.

Radar and lidar can detect multiple targets. However, the algorithm needs to recognize from multiple targets which is the SV, and which vehicle is the POV. If a target is being firmly tracked, and it falls "into the route" of the SV or tempo, it is declared as the SV or the POV. "Falling into the route" refers to the spatial position within the specific lane; i.e., when a vehicle's moving direction is close to the direction of the route (within  $\pm 30^{\circ}$ ). However, if the SV moves slowly approaching the stop line, the algorithm may not be able to correctly estimate moving direction. In such cases, the moving direction threshold would be loosened.

For each vehicle, we used three kinds of sensors (i.e., loops, radar and lidar). The logic to fuse the data from all the sensors to form a system-level target is:

- If two objects are detected (either by two sensors or the same sensor), choose the one that is newer (i.e., the one whose detection time is later).
- If two objects are detected (either by two sensors or the same sensor) at the same time, choose the one that is closer to the intersection.

Therefore, to estimated SV T2I,

$$T2I_{SV} = \frac{D}{v} - d;$$

and for the POV,

$$T2I_{POV} = \frac{D+w}{v} - d;$$

where *D* is distance to stop line, *w* is width of intersection, *v* is speed, d is sampling delay. (D+w) is the POV's distance to SV's stop line.

To implement our algorithm, for each detection cycle, we tested the following conditions:

- DII is on;
- SV's T2I is within 0~2sec;
- One of the four SV loops detects SV;
- SV is detected falling into the loop area (by remote sensors).

If one of the four conditions is satisfied, then we check the POV's T2I. If the POV's T2I is within 1~7sec, flag (identify) the cycle as a critical situation.

If the DII is "OFF," and in the past five detection cycles we have three criticalsituation flags, trigger "ON" the DII, and store the current time and the POV's T2I.

If the DII is "ON," and the last cycle is flagged as critical, update the stored current time and POV's T2I.

If DII is "ON," and none of the past five detection cycles were flagged as a critical situation, check the time elapsed since the last flag. If time elapsed is longer than the stored POV's T2I, turn off the DII.

While this algorithm worked well for the demonstration, we point out that the warning point and warning threshold are not yet carefully tuned. In addition, driver reactions to the warning are untested. The timing parameters in the demo algorithm are temporarily set.

Furthermore, for the demonstration the following conditions were preset:

- Traffic signal cycle is green;
- There is only one SV and one POV;
- SV slows down before reaching the stop line;
- SV always makes left turn;
- POV always runs through the intersection.

While these assumptions greatly simplified the demonstration algorithm, they may not be valid in real applications. Research during the remainder of the IDS project will be aimed at determining valid conditions for real applications.

### 5.4 State Map Visualizer

The State Map Visualizer showed to the demonstration attendees real-time visualization for the demo scenario by using the vehicle and infrastructure states visually and graphically on the computer screen based on data from sensors, GPS, and the infrastructure. The implication behind the success of State Map Visualizer is to show the range and availability of the dataset on the actual system for the researchers and engineers to analyze the scenarios.

For the demo, we developed two state map visualizers for in-vehicle display and playback purposes. Both visualizers used infrastructure and GPS data to show the vehicle, traffic signal, and DII states during the demo. The only difference between these two visualizers was the level of detail in the graphics rendered. The in-vehicle display used simple image mapping technique to show the real-time visualization. The playback visualizer used complex photo-realistic 3D graphics to show the demo scenario with recorded data.

To duplicate the demo scenarios on our visualizer, the 3D model of the demo

intersection and roadways had to be built accurately. The 3D intersection and roadway models were based upon the geometries database provided by Minnesota's geospatial database. The geometries are defined in the VSCP.<sup>v</sup> The geospatial database covers the lanes and the intersection, and is shown in Figure 5-20.

To validate the geospatial database, we calibrated the geometries in our first trip to TFHRC. We picked a number of reference points at the intersection, measured the actual distances between the points and the loop locations with measuring tape, and double-checked the numbers with the design CAD drawing provided by FHWA. The result showed that the maximum error on Minnesota geometry database was +/- 0.1m., an error range that falls within the requirements of the visualization.



Fig 5-20: Demo Roads and Intersection Created in SWEditor Based Upon the Minnesota Geospatial Database

Based on the Minnesota geospatial database, the 3D model of the demo scene was created within SWEditor (Simulated World Editor), a network editor and visualizer developed by PATH researchers.<sup>vi</sup> To create the intersection, SWEditor first read in the geometries and drew the lines. Then the intersection and roadways were created manually based on these initial lines. The 3D models were created carefully to minimize the human errors. Notice that the SV leg indicated in Figure 5-20 is

<sup>&</sup>lt;sup>v</sup> Please refer to http://www.remotesensing.org/proj/ for details.

<sup>&</sup>lt;sup>vi</sup> Please visit <u>http://path.berkeley.edu/MEG/</u> for more details regarding this tool.

actually a parking lot. But it is treated as a normal roadway so that the demo scenario in the visualization looks more like a normal four way intersection. The green boxes shown in Figure 5-20 are trees, and they are not the actual locations of the trees located at the intersection. The trees were created randomly.

The next step in developing the visualization was to select the source for locating the vehicles during the demo. Technically, there were two sources for locating the vehicle. One was the infrastructure-based sensors, and the other was the GPS system. We compared the two sources of vehicle data based on the following criteria.

- *Range*. Since sensors have limited range to provide vehicle information, and they do not cover the entire SV and POV lanes, the visualizer cannot locate the vehicles if they are out of the sensor range. This limitation shrinks down the scale of the visualization to show the demo scenarios. The GPS system, on the other hand, provided the information of vehicle location for the entire demo scenario. However, the signal of the GPS system could be easily blocked by trees and other objects, so some areas may not have been captured. On-site testing will be required to determine the actual coverage of the GPS system.
- 2. *Update Frequency*. The radar and lidar are updating at 65 milliseconds and 100 milliseconds, respectively. In addition, the internal filtering process, the sensors have maximum delay of 500 milliseconds on processing the raw vehicle data based on our empirical data. While the highest update frequency for the GPS system is 5Hz, the updated GPS reading may not be the most current vehicle location.
- Target Sensing. Sensors have the potential problems with multiple targets, so they might provide multiple datasets the visualizer, some erroneous. The GPS system always sends one set of data.

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4. Quality. The range for sensor errors is basically the length of the demo vehicle since the radar and lidar may detect either the head or the tail end of the vehicle. While GPS system claimed great accuracy under ideal conditions, the quality of data was strongly affected by environmental and weather conditions. Some on-site testing will be required to find out the actual error range.

Based on this comparison, the GPS system was selected as the source for vehicle location for the demo visualizer because it provides more complete vehicle information for the demo scenario. Nevertheless, testing will still be needed to validate the quality of the GPS system data. If needed, a filter will be employed to process the GPS data to improve quality.

During the demo, the SV and POV in-vehicle laptops ran a broadcasting routine to send out its GPS readings. In addition, the SV laptop also needed to run the in-vehicle visualization to show the demo scenarios to the demonstration attendees in the back seat. In addition to the in-vehicle visualizer, a playback visualizer was also developed to playback the demo runs with the recorded vehicle and infrastructure data. This was shown to attendees at an exhibition area, where they could be briefed by PATH personnel.

Raw GPS data was not accurate, and vehicles would potentially be placed on the wrong lane on the visualizer. As a result, the GPS data had to be filtered to improve its quality. To develop the filter we first conducted runs on the SV and POV lanes with different driving speeds to validate the GPS coverage and to determine the effect of different driving speeds on the GPS data. Figure 5-21 illustrates that the areas where GPS data had poor coverage at the SV and POV lanes. Due to the design of the GPS system, there was the problem on updating the accurate vehicle position on time while the vehicles made quick turns. This is the main reason for Red Area 1 (SV lane), shown in the figure. In addition, the trees around the intersection caused additional degradation of the GPS coverage and data quality. Similarly, Red Areas 2
and 3 had difficulty updating the GPS data because the GPS signal was blocked by the trees. In fact, data for Red Area 3 were affected by both problems, so the update of the GPS data in this area was severely affected.



Fig 5-21: Red Area on GPS Coverage

In addition, the GPS system had trouble updating the vehicle locations on time when the vehicles started to move. (The delay was around 1~2 seconds.)

In order to have a smooth image for the visualizer, we required a consistent flow of data with a refresh rate of 10 Hz from the GPS system. Unfortunately, due to these three problems in the GPS system, a smooth real-time 3D visualization was not possible to produce. As a result, we decided to use the top view-image of the intersection (from the 3D database) and to map the current locations of SV and POV vehicles onto the intersection for in-vehicle visualization.

Since the intersection and roadway in SWEditor were built based upon VSCP, the GPS data had to be converted to the same coordinate frame to keep the consistency in the visualizations. To do so, two known locations (where we knew the VSCP) were selected at the intersection, and its GPS readings were collected for an hour. The mean GPS readings were calculated, and the means of these two points were then converted to our local coordinate frame. One point was chosen as the reference point (as the origin of our local coordinate frame), and another point was chosen as a testing point to test the accuracy of the transformation between our local coordinate frame and the VSCP. The transformation between VSCP and our local coordinate was only a linear translation, with the translation factor simply the VSCP coordinate of the reference point. In addition to the transformation, the other difference was the definition of the axis, easily resolved by multiplying by -1.

In the end, we used a quick and simple filter to avoid heavy computation load to the processor. This simple filter would make sure that the vehicles always stayed at the center of the lanes. First, since the demo scenario was predefined, we constructed a database for the SV and POV trajectories in VSCP. The resolution of the trajectories was 0.1 meters.

When the visualizer receives the updated GPS readings in VSCP format, the filter uses the readings to find the best match point from the trajectory database to locate the vehicles onto the intersection. To determine the trajectory point that best matches the current vehicle position, we searched the trajectory database (starting at the previous location in the database until the end of trajectory database) to see which point had the minimum distance from the current GPS data. The point with the minimum distance was chosen to be the vehicle location at the current time step.

## In-vehicle Visualization

One challenge to developing the in-vehicle visualization is to keep the visualization running in real time. As the estimated delay was 200 milliseconds from the

infrastructure to visualizer through wireless communication, 200 milliseconds on GPS system, and then 100 milliseconds for rendering time for the demo scene on the visualizer, the minimum delay for each update frame was 500 milliseconds, which is half a second. As a consequence, the system did not support a smooth 3D visualization.

Because we wanted to run the in-vehicle visualization in as close to real-time as possible, we decided to eliminate the rendering load on the processor to save the 100 milliseconds delay. Finally, the in-vehicle visualization used a top-view image obtained from the 3D models as a background image created in SWEditor. Vehicles and DII were represented by boxes with different colors in the visualizer. As shown in Figure 5-22, the red box represents the SV, the blue box represents the POV and the yellow box is the DII at its "OFF" state. When the DII is on, the color of the DII will change to red. The visual aspect of this visualizer is satisfactory because it shows all the vehicle and DII states.

After setting up the in-vehicle visualization, the last step was to map the VSCP onto the image at pixel level. To get and fine tune the correct numbers for mapping parameters, we took a number of trial runs through all four legs of the intersection. In addition to visualization, this visualizer also shows the status of the wireless communication, which allows the observers to keep track of the network status for analysis purposes.



Fig 5-22: In-vehicle Visualizer

To find the scale factors (X<sub>f</sub>, Y<sub>f</sub>) for this mapping,

- Let  $A = (X_A, Y_A)$  at VSCP coordinate,  $(X_{Ap}, Y_{Ap})$  at Pixel coordinate
- $B = (X_B, Y_B)$  at VSCP coordinate,  $(X_{Bp}, Y_{Bp})$  at Pixel coordinate
- $C = (X_C, Y_C)$  at VSCP coordinate,  $(X_{Cp}, Y_{Cp})$  at Pixel coordinate
- Point C is the reference point
- Y<sub>max</sub> is the distance along Y axis between Point A and Point C ) at VSCP coordinate
- X<sub>max</sub> is the distance along X axis between Point A and Point B ) at VSCP coordinate
- Y<sub>pmax</sub> is the number of pixels on vertical axis between Point A and Point C
- $X_{pmax}$  is the number of pixels on horizontal axis between Point A and Point B

- $X_f = (X_{Ap} X_{Cp})/X_{max}$
- $Y_f = (Y_{Ap} Y_{Cp})/Y_{max}$

To map the vehicle on the visualizer

- $(X_v, Y_v)$  is the VSCP coordinate of the vehicle,  $P_v$
- $(D_{xv}, D_{yv})$  is the distance between  $P_v$  and Point C.
- $(X_{vp}, Y_{vp})$  is the P<sub>v</sub> at Pixel coordinate in the visualizer, which is
- $X_{vp} = X_{Cp} + D_{xv} * X_f$
- $Y_{vp} = Y_{Cp} + D_{yv} * Y_f$

## **Playback Visualization**

The main purpose of this playback visualization is to replay the demo in-vehicle visualization offline with photo-realistic 3D computer graphics. This means that the demo scenarios can be replayed over and over again. Moreover, the recorded vehicle trajectories were filtered so that the vehicles were located at the center of the lanes all the time. The playback visualization also provided a better view for DII's activity. Traffic signal phases were shown in this visualization as well.

To replay the visualization correctly, the simulation time, vehicle position, velocity, and yaw rate were recorded from the actual demo to reproduce the offline visualization with correct timing. While the playback visualization was running, the update time stamp between the previous frame and the current frame was compared with the computer system time to make sure that the visualization was running at the right timing.

In addition to replaying the demo scenario, SWEditor has the capability of recording the demo runs to video files. The created media file also allows the public to download and view the demo scenarios online. The video file is located at <<u>http://path.berkeley.edu/~swekuang/IDS\_Demo/movie/IDS-Demo-playback.avi</u>.>.

Divx 5.0 is required in order to play the movie file in your media player.

Figure 5-23 is a screenshot of the video playback available to the consortium on the above website.



Fig 5-23: Playback Visualization

## 5.5 Software Configuration

This section describes the overall software architecture used as part of the midterm demonstration, and gives a description of the software interface to the 2070 Advanced Traffic Controller. The overall architecture was based on reusable software components (many of which were developed during previous projects at PATH), and on the use of a full-featured real-time operating system, QNX Neutrino, for the rapid prototyping of innovative roadside infrastructure technology. Other application software – for sensor operation, warning algorithm and visualizaer – are described in previous sections.

## 5.5.1 Real Time Software Architecture

The rapid deployment of PATH's demonstration depended on pre-existing software standards, components and methodology developed as part of many previous government funded transportation projects at PATH and elsewhere. These included:

- The National Transportation Communications for ITS Protocol (NTCIP) standard Management Information Base for communication with Actuated Signal Controllers, developed under the auspices of the FHWA<sup>47</sup>;
- Radar and lidar device drivers developed at PATH as part of previous work under FTA contracts for Smart Bus Rapid Transit and Frontal Collision Warning System research and under FHWA contracts for research on Vehicle-Follower Longitudinal Control;
- Software utilities developed on the QNX4 Real-time Operating System<sup>48</sup> to support vehicle automation work at PATH funded under the National Automated Highway System Consortium;
- A methodology for application development that uses an in-memory *publish-subscribe* database for communication between processes that has been developed over the course of many previous projects at PATH and described by Tripakis<sup>49</sup> (2002).

Using this pre-existing technology base allowed us to integrate innovative elements into an operational system for operating the DII very quickly. The ability to use standard networking IP protocols and COTS 802.11 wireless components on a real-time system also made it possible to:

• Integrate our demonstration with that of Minnesota and share the use of the DII for two different scenarios: i.e., LTAP/OD in an urban setting and LTAP/LD in a rural setting.

• Couple both of these scenarios with a demonstration of the ability of an infrastructure computer to broadcast information gathered from roadside sensors and from surrounding vehicles to an in-vehicle display or warning system.

The software architecture is illustrated in Figure 5-24.



Fig 5-24: Software Architecture for a Left-turn Warning System

The following processes were running under QNX6 on a PC/104 computer in the infrastructure cabinet as part of the demonstration:

- The Cogent Cascade queue server and name server, and an instance of the Cascade Datahub private to the IDS DII application<sup>50</sup>. This in-memory database provides a flexible, shared memory interface between processes, allowing easy reconfiguration and incremental development, while protecting the shared data from race conditions and update inconsistencies.
- A process to turn off and turn on the output of the digital I/O board that connected to the DII sign, depending on a value read from the database.
- Two processes to communicate with each of the two serial ports connected to the Denso Lidars.
- Two processes to communicate with each of the two serial ports connected to the EVT300 radars.
- A process to read and write the serial port connected to the SEPAC 2070 Actuated Signal Controller (ASC). This process queried the ASC for loop detector information, and also switched the signal between actuation patterns for the different demo scenarios, using NTCIP standard messages.
- Two processes for communication, one to receive GPS information from the vehicles, using 802.11a wireless communication, as well as information over Ethernet from the Minnesota system, and one to broadcast the state map information indicating vehicle locations known to the infrastructure over 802.11a wireless. The visualization process that received the state map information ran on a laptop computer in the vehicles, and is described earlier.
- A process to fuse the sensor information from the radars, lidars, and loop detectors and implement the warning algorithm. This process is described in section 4 of the report.

• A process to save sensor, ASC and state map data for later analysis.

The software architecture can be easily reconfigured to run with the full complement of radar and lidar sensors as well as loop-detector data, with loop detectors alone, or with only radar and lidar sensors, depending on the characteristics of the intersection.

Researchers at PATH over the past nine years have used a database available as source under QNX4. For the IDS Project's development under QNX6, we wished to be able to use the tested methodology and re-use source code previously developed, but the changes in interprocess communication in the new version of the operating system made porting the previously used database to QNX6 difficult.

We found that a commercial product, the Cogent Cascade Datahub, free for noncommercial use, provided the communications and data-trigger functions that we needed. However, it provided only simple integer, float and character string data types, so as a first step for this project we implemented an API for structured data types compatible with the QNX4 database.

Developing software in California for a demonstration at the Turner Fairbank test intersection in Virginia required modular development and an ability to test software components using both hardware-in-the-loop (with the traffic signal controller) and trace-driven simulations of software components. Radar and lidar drivers had previously been tested with an earlier version of the QNX operating system, but had to be ported to the newer version.

QNX is self-hosting, that is, programs can be written and built with a user-friendly graphic interface on the same computer system that will be placed in the field, and then easily launched on power-up with no video terminal in the final tested system. These features facilitated incremental modular and integration testing of software components.

Radar and lidar drivers were tested separately in installations at California PATH, while concurrently the wireless communication processes were also being tested. Then radar and lidar trace data were gathered during our initial visit to Turner Fairbank. These data were then used to debug the warning algorithm code in a tracedriven simulation. In this simulation the warning algorithm could run in real-time as another process read the trace data and placed it in the database using timestamps to keep the timing of data arrival the same as the timing when the data was gathered.

#### 5.5.2 Interface with 2070 Actuated Signal Controller (ASC)

The software that interfaced with the 2070 ASC had two functions in our demo:

- To acquire loop detector data and signal phase information from the traffic signal controller. This was a necessary function for inexpensive implementation of the warning sign in intersections already equipped with loop detectors.
- To change the programming of the traffic signal from actuated to yellow flash when switching from the California demo to the Minnesota demo. This was an artifact of the particular conditions of the IDS demonstration, but was an interesting demonstration of the ability to change the programming of the signal from an infrastructure computer using NTCIP.

We used the Eagle Traffic Systems 2070A controller with SEPAC software. This software currently supports NTCIP standard on a serial port. This limits the bandwidth of information that can be provided, but we hope that in the future we will be able to obtain software for the 2070 that supports NTCIP on Ethernet.

We developed and debugged our QNX ASC interface software using a 2070 on a desktop with a test system to set inputs and read outputs on the standard connector. Baud rate is set from the 2070 front panel and on the PC104 serial port to match. The NTCIP Exerciser, an open-source Windows application developed by others under

funding from FHWA and available from ntcip.org, was a great help for testing the initial set-up of the 2070 and as a reference for correct message formatting.

Our code was written in C, and it is portable to any system with the standard serial port interface. We obtained the Management Information Base (MIB) for Actuated Signal Controllers, as described in NTCIP standard 1202, and installed it with the NTCIP Exerciser. SEPAC documentation from Eagle Traffic Systems indicated which of the optional capabilities of the ASC are actually supported on their implementation of NTCIP.

NTCIP messages can be used both to get loop detector information and phase information and to set traffic signal parameters. A query must be sent; the 2070 (ASC?) operates in slave mode and will not send a message unless requested. For continuous data acquisition, a program was written in C, running on QNX, to send query messages and read responses. The program consists of libraries for sending and receiving messages according to the NTCIP protocol, and a main program where message lists for sending and receiving can be installed. The system call select is used to cause the program to wait until a message is received before sending a new message, with a time out if the message is not received within a valid time period.

The NTCIP standard and the Exerciser tool made it possible for us to write code in a relatively short period of time to obtain the loop detector information we needed. Higher bandwidth Ethernet implementation of NTCIP on the part of ASC manufacturers will make many more infrastructure applications that interact with the traffic signal possible.

## 5.6 Wireless Communications

Wireless communication for the IDS demo at FHWA in June 2003 was not meant to assist drivers to prevent collisions at the intersection, but rather to illustrate how data

could be communicated to in-vehicle devices in the future. The current 802.11a products are not meant for time critical safety application, and there is no commercial off the shelf products that can satisfy the requirements. A list of limitations is what follows:

- Each wireless node can take up to several seconds to join the network and without joining the network; each vehicle will not be able to receive information from the infrastructure. Depending on the size and the geometry of the intersection, vehicles might not be able to communicate with the infrastructure until they are very close to the intersection.
- The current 802.11 Medium Access Control (MAC) protocol doesn't have message priority, and it treats all messages with equal priority. If two or more messages are transmitted at the same time and collide, each of the senders will pick a random back-off timer to retransmit again. In the IDS system, we would like to give different priorities to different safety messages. For example, we would like to give collision warning message higher priority than periodic traffic signal messages.
- The current protocol does not guarantee each transmitted message to have high probability of reception. Applications have to implement this feature on their own.
- A better addressing scheme is needed. Vehicles need to find a way to determine whether messages are intended for them. For example, for collision warning messages, we would like the conflict parties to be aware of their situation and not vehicles a couple of hundreds meters away from the intersection. In the current protocol, the infrastructure would have to learn every vehicle's IP address, and associate them with each vehicle's trajectory. It is not feasible to assign each vehicle a unique IP address.

All these issues are currently under investigation, and at the end of the program, we will have solutions to deal with them. Nevertheless, in the IDS demo, we have demonstrated the type of information that can be delivered from infrastructure to

vehicles and from vehicles to the infrastructure. In the current system, GPS-equipped cars broadcast their positions to the infrastructure every 100ms, which could be fused with other sensor measurements (e.g. loops, radar, lidar, etc.) to produce more accurate vehicle position estimates. On the other hand, the infrastructure can broadcast the State Map to every vehicle, which could be used by an in-vehicle warning system to assist drivers according to their driving behavior. Another application illustrated at the demo was the DemoSwitcher. Users can switch the Advanced Traffic Controller (ATC) state/configuration wirelessly through a graphical user interface (GUI). DemoSwitcher talks to the Infrastructure computer to trigger a change on the ATC over the National Transportation Communication for ITS Protocol (NTCIP). The similar idea can be extended to accommodate signal priority and signal preemption for bus and law-enforcement.

## Equipment:

- Infrastructure: 802.11a Access Point (SMC 2755W) Infrastructure computer
- In-vehicle:
   DGPS Receiver (CSI-Wireless DGPS-Max)
   Atheros 802.11a MiniPCI wireless card
   Atheros 802.11a Antenna
   Laptop computer

All the in-vehicle equipment are the same as the Vehicle Safety Communication Consortium (VSCC) test kit. They have detailed instructions on equipment installation. Figure 5-25 below shows how the equipment is connected.

# IDS Communication System Hardware Setup



Fig 5-25: Wireless Communication Hardware Setup

Before operating the system, it is important to determine the maximum communication range and reception probability at different locations around the intersection. We used the VSC test kit to evaluate the FHWA test intersection. The tests were done with the following setup:

- Each station equipped with VSC test kit (e.g. GPS receiver, 802.11 wireless, and the laptop)
- One station was installed at the traffic controller cabinet with wireless antenna and GPS antenna placed on the top of the cabinet.(Base station)
- One station was installed inside of the car with GPS and wireless antenna placed on top of the vehicle roof. (Mobile station)
- Base station periodically sends out test packets with 500 bytes packet size at every 100 ms. Each packet contains a sequence number, and sequence number is incremented after a packet is transmitted.

• The Mobile station was moving at 15 to 20 mph along the north to south leg, and 20 to 25 mph along the west to east leg.

Figure 5-26 shows the test result for a mobile station moving from the North to the South leg. The blue line indicates the relative distances between the base station and the mobile station. The black color line indicates the cumulative packets received. If there were significant packets lost for a long duration, you would see the line holding the same value for this period. For the line with red and green spots, red spots indicate which packets were lost, and green spots indicate which packets were received. As shown in the figure, there is good wireless coverage along the north to south leg, with only few packet drops of short duration along the way.



Figure 5-26: VSC Test Kit Result for North and South Legs.

Figure 5-27 shows the result for the mobile node moving from the West to East leg. Some interesting phenomena can be observed. At the bottom of the blue curve, we see the smooth GPS curve disrupted for a period of time. This is due to the fact that the large trees at the Southwest corner of the intersection covered the sky. We can also observe that there are significant packets drop at ~200m East of the intersection. This could be caused by the elevation increases at the East legs that causes mobile station antenna height to exceed the base station antenna height which causes the transmit signal to attenuate.



#### Fig 5-27: VSC Test Kit Result for West and East Legs.

The software architecture for our wireless communications is described:

#### Infrastructure:

In the current system, there are two communication processes running on the QNX 6 real-time Operating System (OS). Please refer to Figure 5-28 below. One is called Broadcast Sender, whose job is broadcasting information out from the StateMap Database. A list of possible information stored in the StateMap Database is: vehicle position and speed, road condition, signal state and timing, road topology, warning messages and so on. For the demo, only vehicle positions and speed, signal state and timing, and collision warning messages are sent at a rate of 100 ms. Since the information is broadcast, all vehicles within the communication range will receive the same set of data, which preserves the consistency of the system. On the other hand, Broadcast Receiver listens to the network and filters out data that are not meant for it. A list of possible information that could be received includes vehicle position information from GPS, signal preemption, coordinated traffic signal messages and so on. In the demo system, it will only process vehicle positions from GPS, vehicle

positions detected by University of Minnesota (UM)'s system, collision warning message generated by UM's system, and demo switch signal. This process checks the network buffers every 50ms for incoming messages, and stores them into the StateMap database and shares them among multiple applications.

# IDS Communication System Software Architecture - Infrastructure



#### Fig 5-28: Communication System Software Architecture for Infrastructure PC

#### In-Vehicle Communication System Software

In the in-vehicle computer, two applications are running on the Microsoft Windows Operating System. The reason behind the Windows OS usage is because this is the only OS that supports the Atheros 802.11a radio. (See Figure 5-29 below.) One of the applications is called GPS Broadcaster. As its name implies, its job is to broadcast the GPS measurements received from the GPS receiver to everyone. As soon as the GPS receiver generates a new reading, GPS Broadcaster will broadcast the measurement to everyone. Current update frequency of our GPS receiver is 5Hz, but users can configure the program to send the same measurement multiple times to increase the reception probability of the receivers. Since it is broadcasting, vehicles within the communication range could build their neighboring map by gathering all their neighbors' GPS messages even if the infrastructure fails to operate. In-vehicle safety applications could be based on this information to produce warning messages to drivers. More work is needed for neighboring mapping bases on GPS and other invehicle sensors. StateMap Visualizer, on the other hand, updates the GUI every time it receives new StateMap information from the Infrastructure computer.

## IDS Communication System Software Architecture – In-Vehicle



Fig 5-29: Communication System Software Architecture for Vehicles

## Packet Format

In our system, data packets transmitted across the IDS system should conform to the following format: IDS Header + Packet Payload. IDS Header contains two members, one is called mode, and the other is called data\_type. Mode indicates the type of operation (e.g. 0 for Infrastructure to Infrastructure, 1 for Infrastructure to Vehicles, 2 for Vehicles to Infrastructure...). Data\_type indicates the type of data (e.g. 0 for StateMap Packet, 1 for GPS Packet). Combination of mode and data\_type give the system flexibility to support large varieties of applications, and also allows the system to efficiently filter out messages, which are meant for it.

Vehicles transmit their GPS positions following the GPS Packet format. The GPS Packet includes positions, speed, and headings. (See GPS Packet format below.) All

of these fields should be available on GPS receivers that follow the National Marine Electronics Association (NMEA) data messages standard. In the future, when we are fusing the GPS, lidar, radars, and other sensor data, more fields might be added in this Packet for the GPS filter to work correctly.

#### **GPS Packet:**

char mode (1byte) char data\_type (1byte) short int veh\_id (2 bytes) float utc\_time (4bytes) double latitude (8 bytes) double longitude (8 bytes) double altitude (8 bytes) char num\_satellites (1 byte) char mode (1 byte) float heading (4 bytes) float speed (4 bytes)

←== Packet Header

The following format is the StateMap Packet. The current StateMap packet contains vehicle information, a collision-warning signal, and the signal state and timing. Because of the time constraint of the demo, vehicle information was broken down into measurements of different sensor type, and each type only supported a fixed number of vehicles. In the future, we would fuse all the sensor measurements from different types of sensors to produce one set of refined vehicle information. The StateMap packet will support a dynamic number of vehicles at the intersection. Information in this packet is likely to be broken down into different packets because some information is required to send more often than others. For example, collision-warning signals are generated only when there are potential conflicts. Likewise, signal phase and timing can be delivered every second versus every 100ms for vehicle information.

#### StateMap Packet

char mode (1byte)
char data\_type (1byte)
timestamp\_t timestamp
veh\_state sensor\_targets\_CA [2]
veh\_state gps\_targets\_CA [2]
veh\_state sensor\_targets\_MN [3]
infra\_dii\_state dii
asc\_2070\_typ signal\_state

#### 5.7 Simulation

The demo simulation shows some situations that could not be shown in the real-world demo at TFHRC. The demo simulation is actually a special case of much more general vehicle and traffic simulation software being developed at PATH. However, for simplicity, the full generality is not available in the demo software, and many settings are hard-coded for the specific range of scenarios considered for the demo.

## 5.7.1 Models

This section discusses simulation models as opposed to models in the sense of graphical constructs, which are discussed in the visualization section.

#### **Roadways and Intersections**

The underlying geometrical models are very general and can probably be used to approximate all but the most unusual systems of roadways and intersections. One temporary limitation is that the system must be planar.

#### Paths through intersections

Vehicles travel relative to fixed paths determined by their points of entry and exit from the intersection. Each path consists of segments that are either straight lines or

arcs of circles and may cross other paths. The points of entry and exit may be placed with arbitrary positions and orientations within the intersection, so the intersection does not have to be rectangular. These points of entry and exit are where the legs of the intersection connect to the intersection.

#### Roadways

Each leg of the intersection (and, more generally, any non-intersection roadway) is composed of one or more road sections. Each section has a constant number of lanes, but may have varying curvature. This variation is achieved by way of a further subdivision. A section decomposes into segments, each with the same number of lanes. Each segment can be a straight line or a circular arc, which determines the geometry of the lanes passing within the segment.

Sections can be connected to one or more other sections at their upstream and downstream ends, and the connection can allow lane splits, lane drops, merges, and so on. This characterization of roadway sections (but not intersections) follows the SmartAHS highway design library for SHIFT<sup>51</sup>.

The effect of these geometrical constructs is to provide local coordinate systems for each vehicle as it moves from one segment to another. The vehicle is not required to stay in the center of its lane or even to stay within its lane. The purpose of the local coordinate system is not to restrict vehicle motion but to make it easier to express vehicle dynamics and control. (For instance, a lateral controller can take lateral deviation as an input instead of global x and y.)

The difference between intersection and roadway sections is that in intersections, vehicles entering in adjacent lanes need not follow parallel paths, whereas vehicles entering a section in parallel lanes follow parallel paths through the section (unless, of course, they choose to deviate).

#### Vehicle

The vehicle models used in the demo simulation are very simple. Longitudinal position within the lane is computed by doubly integrating the requested acceleration. Route choice at lane splits and within intersections is specified in advance based on vehicle type and origin, but in the future, route choice will be computed dynamically by a driver decision-making model and pre-selected destination.

In the demo simulations, lateral motion is excluded for all but the SV. POVs do not deviate laterally from the center of their lane. With a trapezoidal lateral velocity profile, the SV changes lane only once as it enters the left turn lane. This motion is hard coded but will eventually be based on driver models and their assigned destinations.

Vehicle size is 5 meters by 2 meters.

## Vehicle Generation

Vehicles are generated by a vehicle source, or (as in the case of the SV) placed explicitly. There is one source at the end of each lane farthest from the intersection. Vehicles are generated at a sequence of arrival times, which in the demo simulations is fixed in advance, but in general could be a random variable. For the demo, all vehicles generated by a particular source have the same characteristics. This is because the current preliminary version of the warning algorithm requires constant speeds in each lane (variable speeds would lead to overtaking and difficulties calculating time-to-intersection).

### DII

The warning algorithm is simple, at least in concept: warn the SV driver when a POV will be on or near the SV's projected path as it makes the left turn.

The inputs to the algorithm are the speed and position of the SV and of each POV approaching from the opposing direction relative to the intersection. For each vehicle,

we consider the T2I (or time-to-intersection) that is defined as the ratio of distance to speed. For the SV, distance is measured from the front bumper to the stop line. For the POVs, distance is measured from the front (or back) bumper to the center of the intersection.

The algorithm is as follows:

If the SV has already initiated the turn, do not warn.

If the SV has not yet reached the intersection, do not warn. (More precisely, do not warn when the SV distance is more than 5 meters AND the T2I is more than 1 second.)

Finally, consider each potential conflict POV in turn. For each such POV, issue a warning if the front bumper has a T2I greater than 0 seconds AND the back bumper has a T2I less than 7 seconds.

Only the SV reacts to the warning.

#### Driver

In the demo scenarios, the SV changes from the left lane into the left-turn lane. The driver uses a trapezoidal lateral velocity profile, which results in a realistic and smooth lane change. The driver uses constant deceleration to approach the stop line, beginning deceleration as it enters the turn lane. The driver reacts to the withdrawal of the DII warning by waiting 1 second (nominal reaction time) and then accelerating through the intersection.

#### Sensors, Controllers, and Communication

For the demo simulations, we assume perfect sensing, control, and communication. That is, there is no error or delay. Future work will focus on integrating imperfect mechanisms into a working system, possibly using realistic models (or even hardware in the loop) to represent the intersection controller.

## 5.7.2 Simulation Application

The application contains an implementation the models, as well as visualization, configuration, control, and output functionality.

## Simulation Language

The simulation proper is written in RedShift (to be released eventually at <u>http://redshift.sourceforge.net</u>). RedShift is a derivative of the hybrid system simulation language SHIFT (<u>http://path.berkeley.edu/SHIFT</u>).

The demo simulations were run at a timestep of 100 ms (10 Hz). The step size can be smaller, but we chose this step size because we are currently saving all simulation data for playback and needed to keep the files small.

## Simulation Visualization

The Figure 5-30 shown below shows a screenshot of the simulation visualization.



Fig 5-30: Simulator Playback Function

## 5.7.3 Graphics Language

The underlying graphics language is OpenGL. Also, the vehicle size is 5 meters by 2 meters, drawn to scale. The graphical models used for vehicles are 3DS models, which are widely available. Figure 5-31 represents the vehicle image within the simulator.



Fig 5-31: Sample Vehicle Image with Simulator

The roadway and grassy background are simply patches of solid colors. Future versions will use OpenGL textures to give a realistic look to the road and off-road surfaces.

## **GUI Toolkit**

The visualization uses the Fox GUI toolkit<sup>52</sup>, with the FXRuby bindings to the Ruby language<sup>53</sup>. Fox is a cross-platform toolkit with an emphasis on OpenGL. The Fox GL Viewer allows multiple views of the same scene from varying angles and zoom levels. Initially, the visualization shows a top-view and an oblique view that has been zoomed in towards the intersection.

New views can be added and view characteristics can easily be adjusted by the user using mouse operations within the view window or using the control panel on the right of the window. Lighting and fog effects can also be controlled in this way.

## **Connection with Simulation**

The simulation generates "scripts" which are saved to be replayed. The scripts record all relevant data from the simulation, such as vehicle movements, that cannot be easily recomputed by the visualization.

Storing scripts in this way is not necessary but is advantageous for several reasons. The clock of the simulation can be moved forward or backward arbitrarily. The GUI provides several ways to do this, including a scroll bar, Play/Stop/Reset buttons, forward and backward 100ms arrows, and a clock-value field. In addition, keeping all simulation data around allows the use of interpolation to display the simulation with arbitrary time granularity. This is useful because it is not predicable (from machine to machine or even from moment to moment) how long it will take for the OpenGL software and the video hardware to display the scene. By dynamically assessing the delay, successive frames of the animation can display simulation data that corresponds precisely to the time it takes to display the data. The animation therefore occurs in real-time with no time drift, although a slow graphics adaptor may result in a low frame rate.

## Visualization of Non-physical Properties

The visualization in Fig 5-32 shows which vehicles generate a warning using four small red boxes positioned around the vehicle. In the future, we plan to visualize sensor cones, sight lines, and other features.

The DII is visualized in a separate window, showing the state of the warning (one of four possible states: "OFF", warming up, and two "throbbing" states). Pulsing occurs with a frequency of 10 Hz (this is configurable), which, as with the animation, is as close to real time as the graphics hardware allows.



Fig 5-32: Picture Sequence for DII Actuation

#### 5.7.4 Demo Configuration

The site represented in the simulation is not related to the TFHRC site. It was chosen to show more general and typical situations that cannot be shown at the somewhat confined TFHRC site.

The simulated intersection represents a busy four-lane arterial roadway crossing a smaller two-lane side road at right angles. The intersection is unsignalized (or, equivalently, we may think of the simulation as occurring during the green phase for arterial traffic). The northbound direction of the arterial has a left turn lane to reach the west leg of the side road.

The leg length of the intersection is 130m. (The radar range is supposed to be 120m, though we are not explicitly modeling sensors in the demo simulation.) The turn lane is 40 meters long. Each lane has a width of 4 meters.

There are four scenarios in the demo software. We describe first what they have in common.

## Initial Conditions

SV starts at 20 m/s in the left lane of the northbound south leg, 90 meters from the intersection.

POVs heading southbound towards the intersection (i.e., potential conflict vehicles) start 130 meters from the intersection with initial speeds of 15-20 m/s. In one of the scenarios, there are also POVs heading northbound towards the intersection, but these are not potential conflicts, so there is no need to discuss them further.

## Driver Behavior

All POVs continue at their initial speed without turning or changing lanes. This simplification is necessary because the warning algorithm is still in its early stages and cannot yet deal with unpredictable motions.

The SV driver decelerates to a stop after the vehicle enters the left-turn lane. It remains stopped as long as the DII is lit. When the DII is unlit, the driver reacts 1.0 seconds later by accelerating into a turn through the intersection. If the DII turns on again after the driver enters the intersection, the driver does not react. The SV accelerates at 2.0 m/s/s.

## Four Scenarios

The demo software includes four scenarios using the same demo configuration described above. The scenarios vary in the number and initial conditions of the POVs.

- Heavy traffic in both directions along the arterial. The SV eventually finds a gap. This example shows that the warning algorithm is robust enough to handle a stream of POVs.
- 2. Two POVs, with just barely enough gap between them. The SV driver is able to turn through the gap.
- Two POVs, as in #2, except that there is not quite enough gap. The driver has to wait until both POVs have passed to turn.
- 4. Three POVs. Like #2, but the third POV is moving faster than the others (in the left lane) and is fast enough to prevent the gap between the first two POVs from being usable. The driver has to wait until all three POVs have passed to turn.

#### 5.7.5 Software Platform Requirements

RedShift currently runs only on Unix/Linux systems, but a Windows adaptation is in progress. The rest of the simulation application runs on windows using recorded data from simulation runs performed under Linux.

#### **6.0 Observations and Future Work**

In our IDS research to date, we have begun to assess lessons for a deployment of an IDS system that has an essential element cooperating among vehicle and infrastructure elements at intersections.

We start with a fundamental understanding of the intersection problem, summarized as:

- Junctions are High-Risk Sites for Crashes, Particularly Crossing Path Crashes. IDS countermeasures designed to prevent crashes at intersections could efficiently address a significant share of all traffic crashes.
- 2. *Most Intersection Crashes Occur at Controlled Intersections*. IDS approaches should be compatible with existing traffic control devices.
- Types of Crashes at Intersections Vary by Type of Traffic Control. IDS approaches will need to address the different patterns of crash types occurring with different traffic control configurations.
- Driver Errors are Primary Causal Factors in Intersection Crashes. IDS should be designed to increase the salience and relevance of information available to drivers about potential risks as they navigate the intersection.
- Older Drivers are Somewhat Over-Represented in Crossing Path Crashes at Intersections. IDS countermeasures must be designed with potential functional limitations of older drivers in mind.

- 6. *Many <u>Non-Crossing Path Crashes Occur at Intersections</u>. We note the possible impacts of IDS countermeasures on other types of crashes and plan to design them with the intent of not increasing the frequency or severity of those other crashes.*
- 7. *IDS May Reduce Risk Without Reducing Intersection Capacity*. IDS countermeasures may be able to reduce risk for crossing path crashes at intersections by providing salient and relevant information to drivers, while maintaining intersection capacity.

We have made very significant accomplishments in understanding human factors issues and how to instantiate an IDS prototype (with our TFHRC demo). To fulfill the remaining years of our effort, we must conduct:

- Roadside Observations. We have shown in the demo that while kinematic calculations will work well in a scripted scenario, we must be conscious of real drivers at real intersections – behaving in real ways. We plan to gain understanding about drivers' vehicle movements and interactions at intersection, and we should use this information to develop alert timing and ultimately, intersection collision warning systems.
- 2. *Observations Using an Instrumented Vehicle at Actual Intersections.* We must further observe driver behavior at intersections and understand to high fidelity speed, braking, eye movement and driver decisions at intersections, as a function of location, presence of other vehicles, and characteristics of the driver. This will help us further in designing an alert system.
- 3. Observations Using an Instrumented Vehicle at the Test Intersection at RFS. We plan on investigating driver behavior (e.g., gap acceptance) by measuring driver turning responses with regard to approaching vehicles.
- Design for Collision Warning Systems. Putting together items 1 3, we must design a detailed algorithm and protocol for alerting drivers of potential crossing path collisions.

- DII Design. We plan on receiving feedback on MUTCD compliance of our DII or options thereof, e.g., California Traffic Control Devices Committee inputs.
- 6. *Test Implementation with Controller and COTS Sensors.* We must understand fully implementation issues with the 2070 advanced traffic controller and also how COTS sensors will work with IDS (since these are the devices and sensors familiar to the IDS user community, traffic engineers).

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