ANALYSIS OF CROSSING PATH CRASH COUNTERMEASURE SYSTEMS

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ABSTRACT

This paper summarizes the results of an analysis of promising countermeasure systems for crossing path crashes, and thus provides a foundation for setting research priorities under the United States (U.S.) Department of Transportation's Intelligent Vehicle Initiative. Crossing path crashes involve one moving vehicle cutting across the path of another, which amounted to 1.72 million police-reported crashes in the U.S. based on the 1998 General Estimates System crash database. Three basic countermeasure concepts and their functional requirements were developed to warn drivers of imminent collision caused by stop sign violation, red light violation, or insufficient gaps between vehicles at intersections or driveways. A survey was conducted to assess the technical viability of current systems and enabling technologies that could implement these concepts using infrastructure-based, vehicle-based, or cooperative vehicle-infrastructure systems. This paper concludes with recommendations to pursue the development of complete performance specifications and objective test procedures for promising crossing path crash countermeasure concepts.

INTRODUCTION

This paper presents the results of an analysis of promising countermeasure concepts for crossing path crashes in support of the United States Department of Transportation's (U.S. DOT) Intelligent Vehicle Initiative (IVI). Crossing path crashes involve the type of traffic conflict where one moving vehicle cuts across the path of another, both initially traveling from either lateral or opposite directions, in such a way that they collide at or near junctions. The goal of the IVI is to facilitate the development and accelerate the deployment of crash avoidance systems that address seven problem areas including crossing path crashes [1]. The IVI emphasizes the significant and continuing role of the driver in solving traffic safety problems by means of vehicle-based and vehicle-infrastructure cooperative systems. Vehicle-based systems operate autonomously within the vehicle and will increasingly interact with an intelligent infrastructure, over time, to yield even greater gains in traffic safety. Intelligent infrastructure is the necessary network of technologies, a communication and information backbone, which supports and unites key user services of the U.S. DOT's Intelligent Transportation System (ITS) program. The IVI explores possible vehicle-infrastructure cooperative systems that employ communications between the vehicle and the infrastructure, or among vehicles, to enhance the performance of vehicle-based systems or to enable the operation of some critical crash avoidance system functions.

Listed below are the steps that were undertaken to analyze promising countermeasure concepts for crossing path crashes:

1. Identify common pre-crash scenarios and causes
2. Devise crash countermeasure concepts
3. Develop countermeasure functional requirements
4. List existing performance specifications
5. Survey system and enabling technologies
6. Assess system deployment
7. Project system effectiveness
8. Recommend future research

CROSSING PATH CRASHES

Crossing path crashes accounted for about 1.72 million crashes or 27.3% of all police-reported crashes in the U.S. based on the 1998 General Estimates System (GES) database [2]. About 1.343 millions of these crashes or 78.1% of all crossing path crashes occurred at intersections or were intersection-related. A total of 361,000 crashes or 21.0% of all crossing path crashes happened at driveway or alley access roadways. Intersection or intersection-related crashes and driveway or alley access crashes are designated respectively as "intersection" and "driveway" crashes for the remainder of this paper.

Pre-Crash Scenarios

Figure 1 illustrates five common pre-crash scenarios among all vehicles and indicates vehicle movements immediately prior to impact in crossing path crashes:

1. LTAP/OD: Left turn across path/opposite direction
2. LTAP/LD: Left turn across path/lateral direction

3. LTIP: Left turn into path
4. RTIP: Right turn into path
5. SCP: Straight crossing paths

Table 1 provides the frequency of the five scenarios based on the 1998 GES at intersections and driveways by three types of traffic control device: signal, stop sign, and no controls. The traffic control "signal" refers to a light signal that processes through the green, amber, and red times. A "stop sign" is coded in the GES if there is at least one stop sign present at an intersection or driveway. The GES does not contain any data that distinguish between 2-way and 4-way stop signs at intersections or driveways. "No Controls" is coded in the GES if at the time of the crash there was no intent to control vehicle traffic. The sum of frequencies in Table 1 amounts to 1.418 million crashes or 83% of all crossing path crashes at intersections and driveways.

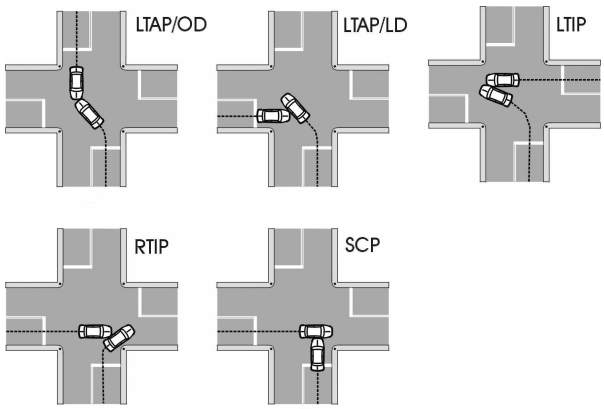

Figure 1. Crossing path pre-crash scenarios.

Table 1.
Frequency Distribution of Crossing Path Pre-Crash Scenarios by Traffic Control Device (1998 GES)

Traffic Control Device	Junction	Crossing Path Pre-Crash Scenarios				
		LTAP/OD	LTAP/LD	LTIP	RTIP	SCP
Signal	Intersection	229,000	53,000	15,000	20,000	182,000
	Driveway	7,000	5,000	1,000	3,000	1,000
Stop Sign	Intersection	16,000	128,000	34,000	29,000	236,000
	Driveway	1,000	12,000	4,000	3,000	3,000
No Controls	Intersection	94,000	26,000	10,000	11,000	35,000
	Driveway	86,000	101,000	29,000	28,000	16,000

Numbers in cells were rounded to the nearest 1,000.

Causal Factors

Tables 2 and 3 provide statistics on causal factors associated with crossing path crashes at intersections and driveways, respectively. These causal factors are arranged into two major categories: signal/sign violation and insufficient gap. Tables 2 and 3 exclude crashes caused by drivers under the influence (DUI) of alcohol or drugs, considered as non-specific to crossing path crash countermeasures and common across all crash types. There are virtually no crashes in the shaded cells of Tables 2 and 3 and thus respective countermeasures are not necessary.

The breakdown of crashes into signal/sign violation and insufficient gap causal factor categories was accomplished using 1998 GES statistics about violations charged to drivers for "Running a Traffic Signal or Stop Sign" and "Failure to Yield Right-of-Way", respectively. Traffic signal violation was charged to drivers who did not see the traffic signal or its status, tried to beat the amber light, or deliberately ran the red light. Drivers who committed sign violation either did not detect the presence or deliberately ran the stop sign. Tables 2 and 3 encompass a total of 1.395 million crashes or 82% of all crossing path crashes at intersections and driveways. These are target crashes for the crossing path crash countermeasure concepts described below.

Table 2.
Crossing Path Crash Causal Factors at Intersections Excluding DUI (1998 GES)

Traffic Cntrl Device	Causal Factor	Crossing Path Pre-Crash Scenarios				
		LTAP/OD	LTAP/LD	LTIP	RTIP	SCP
Signal	Insuf. Gap	193,000			13,000	
	Signal Viol.	31,000	52,000	15,000	6,000	178,000
Stop Sign	Insuf. Gap	15,000	113,000	26,000	25,000	173,000
	Sign Viol.	1,000	12,000	7,000	3,000	62,000
No Controls	Insuf. Gap	92,000	25,000	10,000	11,000	35,000

Table 3.
Crossing Path Crash Causal Factors at Driveways Excluding DUI (1998 GES)

Traffic Cntrl Device	Causal Factor	Crossing Path Pre-Crash Scenarios				
		LTAP/OD	LTAP/LD	LTIP	RTIP	SCP
Signal	Insuf. Gap	6,000			3,000	
	Signal Viol.	1,000	5,000	1,000		1,000
Stop Sign	Insuf. Gap	1,000	11,000	3,000	2,000	3,000
	Sign Viol.		1,000	*	*	
No Controls	Insuf. Gap	85,000	100,000	29,000	28,000	16,000

- The symbol * represents crash frequencies below 500.
- Empty cells refer to scenarios that had no crashes in the 1998 GES sample.

CROSSING PATH CRASH COUNTERMEASURE CONCEPTS

Three potential countermeasure concepts are devised to address crossing path pre-crash scenarios and concomitant causes as listed in Tables 2 and 3 by warning the driver of imminent collision caused by signal violation, stop sign violation, or insufficient gap. There are three variations on the "insufficient gap warning" based on whether the system senses the forward gap (LTAP/OD), lateral left gap (LTAP/LD, RTIP, and SCP), and lateral right gap (LTIP and SCP).

The "stop sign violation warning" concept applies to 6% of target crashes by assisting drivers who fail to:

1. recognize the presence of the stop sign (did not see) or
2. stop at the stop sign (deliberately ran).

The "traffic signal violation warning" concept applies to 21% of target crashes by helping drivers who fail to:

1. recognize the presence and status of the traffic signal (did not see),
2. judge the adequate time to safely clear the intersection (tried to beat), or
3. stop at the red light (deliberately ran).

It is noteworthy that in-vehicle warning might not be effective with drivers who deliberately run the stop sign or the red light. In these cases, law enforcement means might be more effective in deterring stop sign or signal violation.

The "insufficient gap warning" concept addresses 73% of target crashes by aiding drivers who fail to:

1. recognize the presence of oncoming traffic from lateral or opposite directions, or
2. judge the adequate gap to oncoming traffic so as to safely clear the intersection.

Forward-looking and lateral-looking insufficient gap warning systems apply to 28% and 45% of target crashes, respectively.

Table 4 lists the functional requirements and performance specifications of the three crossing path crash countermeasure concepts, with emphasis on the sensory element of the concepts. The performance specifications of these concepts were obtained from a recent project that developed performance guidelines for intersection crash avoidance systems [3].

SURVEY OF CROSSING PATH CRASH COUNTERMEASURE SYSTEMS AND ENABLING TECHNOLOGIES

A literature survey was conducted to evaluate the technical readiness of system and subsystem technologies capable of implementing the three countermeasure concepts discussed in the previous section. Three system classes were considered: infrastructure-based systems, vehicle-based systems, and cooperative vehicle-infrastructure systems. The third class of systems includes cooperative infrastructure-to-vehicle systems and cooperative vehicle-to-vehicle systems. The inclusion of infrastructure-based systems in this survey helps to identify cooperative systems that would transmit remote sensor data from these infrastructure systems to vehicles via communications link. Such a link would enhance the performance of vehicle-based systems or enable the operation of additional critical countermeasure system functions.

Table 4.
Functional Requirements and Performance Specifications of the Sensing Element for Crossing Path Crash Countermeasure Concepts

Functions	1	2	3	Performance
Determine host vehicle's:				
a. Heading	•	•	•	NA
b. Position	•	•	•	accur. ≤ 3 m
c. Velocity	•	•	•	accur. ≤ 0.5 Km/h
d. Acceleration	•	•	•	NA
Identify nearby intersection:				
a. Presence	•	•	•	accur. ≥ 99.99%
b. Location	•	•	•	accur. ≤ 1 m
c. Geometrical configur.	•	•	•	accur. > 98%
Identify control device:				
a. Stop sign/signal	•	•		accur. ≥ 99.99%
b. Signal status		•		NA
c. Time to next phase		•		NA
Predict driver intent to go straight or turn right or left			•	
Determine for oncoming vehicles from opposite/right/ left direction:				
a. Heading			•	NA
b. Position relative to road			•	accur. ≤ 3 m
c. Range from host vehicle				
i. Maximum range			•	≥ 150 m
ii. Minimum range			•	9 m
d. Range rate from host veh.			•	accur. ≤ 0.5 Km/h
e. Relative acceleration			•	NA

1: Stop Sign Violation Warning
2: Traffic Signal Violation Warning
3: Insufficient Gap Warning
NA: Not available from [3]

Infrastructure-Based Countermeasure Systems

Three infrastructure-based systems using advanced technology were considered as potential countermeasures to crossing path crashes at intersections.

Red Light Running Photo Enforcement: This system is designed to curb signal violation and deter drivers from deliberately running the red light at signalized intersections. It is currently deployed in the infrastructure using video detection technology in conjunction with loop detectors.

Red Light Hold: This system prevents crashes caused by signal violation by holding the red light in all directions to allow violators to clear the intersection. Still in the conceptual stage, this system would use sophisticated multilane radar capable of tracking and calculating the direction, distance, and speed of each approaching vehicle and employ a special algorithm to identify a potential red light violator. The feasibility of such a concept depends on the availability of sensors that continually track multiple vehicles as they approach the intersection from long distances (> 75 m

[3]). Video and multi-zone radar traffic detectors could be potential sensors for this application. The performance of radar sensors is better than video sensors in adverse weather, at night, and in other special lighting conditions. Leading radar traffic detectors sense whether traffic is standing still or moving in either direction, and measures the count and speed of vehicles. Each radar detects moving or stationary targets in a maximum of 8 zones (2×7 m). This concept would require separate radars to cover each lane in the longitudinal direction along the approach to the intersection. These radars should also be designed to minimize interference with automotive radars operating at 76-77 GHz.

Intersection Collision Warning: This system addresses crossing path crashes caused by insufficient lateral gap or sign violation (did not see sign) at intersections controlled by 2-way stop signs. This experimental system was recently tested at one U.S. location using two types of traffic-actuated warning signs linked to loop detectors and a signal controller [4]. The system displays a warning to vehicles approaching the intersection from the major road when a loop detector detects the presence of a vehicle waiting to cross the intersection from either direction on the minor approach. The system also provides a crossing traffic alert to vehicles waiting at the stop signs on the minor approach, using data from two loop detectors that measure the presence and speed of vehicles approaching the intersection from either direction on the major road. This system can be readily implemented with commercially available technology.

Vehicle-Based Countermeasure Systems

Three types of vehicle-based systems may provide the crossing path crash countermeasures for both intersections and driveways.

Stop Sign Violation Warning: This system applies to crossing path crashes caused by drivers unaware of the presence of a stop sign ahead. Two different technologies might be used on-board a vehicle to implement this autonomous system. The first would utilize the global positioning system (GPS) matched with a geographical information system (GIS). The second would rely on vision-based technology using two forward-looking cameras: one down-looking black and white (B&W) camera to identify intersections from road markings and another up-looking color camera to recognize posted signs.

An experimental system was built using GPS/GIS technology, which incorporated differential GPS to obtain better measures for vehicle position, speed, and heading [3]. The GIS was based on special maps that provided information on the presence of a stop sign, intersection configuration, intersection center, and angles of adjoining roadways. This application requires enhanced digital maps that must be regularly updated to keep accurate information on roadway geometry and signage. Such a system might be added on to vehicle navigation systems that incorporate GPS/GIS technology as a core component, or to vehicle telematics that deliver several services such as roadside assistance using in-vehicle GPS devices.

An experimental system was developed in 1980's using vision-based technology, which conveyed to the driver road sign information based on definable patterns of standard traffic signs [5]. A major feature of the system was the color processing system adopted to eliminate the effects of brightness and shadow due to weather, sun angle, and other conditions encountered during driving. This system read stop signs but did not measure distance to the sign or intersection. Another experimental system using active vision with two forward-looking color cameras is currently being pursued to recognize signs and signal colors, detect the presence of the intersection from road markings, and determine the distance to the intersection [6]. Vision-based detection strongly depends on the road, lighting, and weather conditions. For instance, difficulties arise due to road damage, water on the road, or strong shadows. A new camera chip is needed for this application to meet the required dynamic range of at least 100 dB's necessary for high-contrast scenes with brightness changes of 100,000:1 from frame to frame and to avoid severe saturation caused by reflections of bright sources such as the sun. Research is currently underway to develop a color CMOS imager with a dynamic range of 120 dB's and local on-chip brightness adaptation.

Red Light Violation Warning: This system would assist drivers who failed to recognize the presence and status of a traffic signal ahead or misjudged the adequate time to safely clear signalized intersections in crossing path crashes. This countermeasure type might be implemented on-board the vehicle using vision technology that employs a down-looking B&W camera to identify the presence and distance to an intersection and up-looking color camera to identify the presence and color of the signal. GPS/GIS might be used as an alternative to the down-looking camera. This system type is still in the experimental stage using vision technology as discussed earlier. An autonomous system can be built to recognize signal colors but unfortunately cannot acquire any information about signal timing. The infrastructure would have to transmit such information to the vehicle.

Insufficient Gap Warning: This system would enhance the situational awareness and/or warn the driver of imminent collision with an approaching vehicle either from the forward, lateral left, or lateral right direction at an intersection or driveway. This

vehicle-based system might be realized by a radar system integrated with either GPS/GIS or vision-based system using a down-looking B&W camera. An alternative implementation would be a vision-based technology using multiple cameras.

An experimental system was assembled to warn drivers of inadequate gaps when crossing intersections, by incorporating GPS/GIS with 3 similar radar systems: one pointing left, one pointing straight ahead, and one pointing right [3]. The system utilized 24.7 GHz commercially available radar with an antenna beamwidth of 4° that limited the resolution of target heading. An antenna beamwidth of 1° was recommended for better resolution. Road tests showed that this experimental system had difficulty detecting approaching vehicles blocked by other vehicles, roadway geometry, and roadside appurtenances. Moreover, it was difficult to predict drivers' intent to pass straight through or turn either right or left at intersections without using turn signals. The technology of automotive radar systems has improved considerably, driven by the recent deployment of adaptive cruise control (ACC) systems on luxury cars in Europe. Most automotive forward-looking radar systems operate at 76-77 GHz and rely on mechanical or electronic scanning of a single beam antenna. This radar type might be used as the sensing element for insufficient forward gap warning (LTAP/OD) applications. The challenge for such radar is the ability to:

- cover all traffic lanes ahead for both directions of travel,
- detect and track all approaching (moving) vehicles including obstructed ones, and
- switch between rear-end crash warning and LTAP/OD crash warning.

Forward-looking automotive radars might also be used as the sensing element for insufficient lateral left or lateral right gap warning applications, but they must:

- be mounted physically on the front side of the vehicle, pointing in a lateral direction, and
- co-exist with other sensors that monitor the blind side and the rear adjacent side of the vehicle for lane change warning applications.

Vision-based experimental systems were built to aid drivers in judging lateral gaps to other vehicles approaching intersections. Test results of one system showed that approaching vehicles were difficult to detect at a range over 25 m using optical flow image processing techniques [7]. Another system employed rotating 2-camera set to track up to 5 objects in parallel for up to about 100 m distance in the forward direction using stereo vision techniques. Such a system only measured the range to targets. Vision-based systems face difficulty in detecting and tracking multiple targets approaching from a lateral direction. Moreover, such systems cannot detect obstructed vehicles. In addition, their performance is degraded in reduced visibility conditions such as in adverse weather or nighttime conditions. Particularly at night, the headlights of oncoming vehicles or the lack of side (lateral) lighting by the host vehicle might hinder the observation capability of vision-based systems.

Cooperative Vehicle-Infrastructure Countermeasure Systems

Four cooperative systems are discussed which would improve the performance and accelerate the introduction of crossing path crash countermeasure concepts.

Cooperative Red Light Violation Warning: This system would include an infrastructure component to transmit to a vehicle-based system dynamic information about the traffic control device (type, status, and time to next phase) as well as static information about the presence of a red light running photo enforcement. One-way, directional, dynamic-message communication link from the infrastructure to a moving vehicle would be required. The U.S. has allocated a range of 5,850 – 5,925 MHz (75 MHz bandwidth) for dedicated short-range communication (DRSC) links between vehicles and roadside electronic systems for ITS applications such as intersection collision avoidance. An industry consortium is currently defining a North American DSRC standard that supports an active synchronous transponder and data rate of 2 Mbit/sec with a long 300 m range downlink and a medium 90 m range uplink. This consortium does not include any member from U.S. automakers or first tier suppliers. DSRC link requirements for cooperative red light violation warning applications have not yet been specified.

An alternative to 5.9 GHz DSRC link is the infrared-based link based on 850 nm wavelength, which is widely used by the Vehicle Information and Communication Systems project in Japan [8]. There are currently a number of products in the U.S. that provide communications between the roadside and low-power in-vehicle transponders. Used mainly for electronic toll collection, these products operate in the 902 – 928 MHz frequency range (915 MHz operating frequency), exchange data at a maximum range between 5 m and 30 m, and accommodate maximum vehicle speed between 97 and 129 Km/h.

The Radio Broadcast Data System (RBDS) in the U.S. (RDS in Europe) provides one-way communications medium, point-to-multipoint transmission of real-time data from one transmitter location to many receivers simultaneously over relatively large geographic areas. The RDBS transmits digital information encoded in a sideband of a carrier frequency for a normal FM

broadcast channel between 87.5 through 108.0 MHz. An Emergency Radio Data System (ERDS) was built to transmit warnings to vehicles in a local area over short distances at less than 1,200 m from a small, low power transmitter [9]. A second tuner is required on RBDS-equipped receivers to scan the FM band for a program identification code indicating that an ERDS transmitter is broadcasting.

Cooperative Stop Sign Violation Warning: This system would assist drivers who don't have GPS/GIS or vision-based system on-board their vehicles. The infrastructure component of this system would transmit to the vehicle static information about the nearby intersection and the presence of a stop sign ahead. One-way, directional, static-message communication link would be needed from the infrastructure to a moving vehicle. A current system in the U.S. operates a transmitter-receiver system on the 24.05 - 24.25 GHz band, which alerts motorists to potential road hazards within a 1.6 Km radius of the transmitter depending on terrain. The system broadcasts coded signals triggering one of 64 pre-programmed seven-bit code messages in special vehicle-mounted receivers. This particular system might not be suited for stop sign violation warning application due to the limited number of bits per message and the wide coverage zone. Such application requires the infrastructure transmitter to direct its broadcast to the right lane of travel and send codes identifying both the distance to the intersection and the presence of the stop sign.

A prototype transponder device is currently available to support short-range communications at 77 GHz by using small tags encoded with road sign information such as a stop sign. Automotive forward-looking radar can illuminate a tag placed on the back of any road sign and receive the coded sign information up to a maximum range of 200 m. The radar can measure the distance to the sign based on the time elapsed of the transmitted radar signal.

Cooperative Insufficient Gap Warning: The infrastructure component of this system would transmit to a vehicle-based receiver dynamic information about the kinematics of vehicles approaching the intersection from lateral or forward directions. This system might be implemented by transmitting data from infrastructure-based red light hold and intersection collision warning systems that might possess the capability to detect and track vehicles approaching intersections. Thus, the performance of this system would depend on the detection and tracking abilities of infrastructure-based systems and the capability of the infrastructure-to-vehicle communication link.

Vehicle-to-Vehicle Communications: A cooperative crossing path crash countermeasure concept can be devised to incorporate vehicle-to-vehicle communications as the sensing element for the location, direction, and kinematics of vehicles in the vicinity of the host vehicle. Each vehicle would have to be equipped with 2-way communication link and GPS/GIS. This conceptual system might implement the insufficient gap warning as well as the concepts that warn the host vehicle of imminent collision with another vehicle if either one is about to run the red light or stop sign. The capability of a vehicle-to-vehicle communication-based system highly depends on the 2-way communication link among multiple vehicles as they approach each other from different directions.

An experimental inter-vehicle communication system was developed in Europe to allow data transmission at 63 – 64 GHz between a cluster of up to 100 vehicles for ITS applications [10]. This system was designed to accommodate vehicles without any need for central management or synchronization based upon the concept of a dynamic communications network. Tests were carried out on a test track and on a highway with real traffic. Test track results showed that message-lost ratios were less than 0.1% and 0.3% when two stopped vehicles were in line of sight at respectively 250 m and 400 m apart. At 250 m, the ratio increased to 0.2% when another vehicle was inserted between the two stationary vehicles. In dynamic tests, the overall message-lost ratio was 9% mainly from driving around curves. Further tests showed that the communication range was about 20 m between parallel vehicles and 50 m between perpendicular vehicles. Highway tests resulted in a mean message-lost ratio of less than 2% with two equipped vehicles driving between 50 m and 300 m apart with different vehicles including trucks cutting in between them. The performance of this experimental system relies on the equipped vehicles being in line-of-sight, given the high operating frequency at 63 GHz. This millimeter-wave frequency is not available for vehicle applications in the U.S. Moreover, this system did not address applications dealing with vehicles approaching an intersection from perpendicular directions. The automated highway system program in the U.S. investigated vehicle-to-vehicle communications with vehicles moving within line-of-sight at short separation distances.

A review of the recent literature on vehicle-to-vehicle communications revealed a number of theoretical papers dealing with research being conducted at the academic level. Finally, the question arises to whether the DSRC standard in the U.S. would support vehicle-to-vehicle communications at the 5,850 – 5,925 MHz frequency band for crossing path crash countermeasure applications. A considerable 75-MHz bandwidth is available and proposed transponders would support about 91m range. However, research is needed to explore the feasibility of using such technology to successfully mitigate crossing path crashes including, but not limited to, communication architecture among

multiple vehicles, handling of large amount of transmitted data, message transmission through obstructions at intersections, and overcoming the problem of traffic mixed with equipped and non-equipped vehicles.

DISCUSSION

This analysis attempted to project the deployment potential and safety benefits for various realistic technology implementations of the three fundamental crossing path crash countermeasure concepts by assuming an evolving environment of infrastructure- and vehicle-based systems on two parallel tracks of development. First, the analysis considered infrastructure-based systems that are actually being or have the highest real likelihood of being widely deployed in the U.S. This first step was critical to determine the remaining size of crossing path crashes that the IVI would need to address. Second, the potential deployment and safety benefits of IVI vehicle-based systems were evaluated using results from the first step. The results of the first two steps were then analyzed to identify opportunities for accelerating the deployment and increasing the safety benefits through IVI cooperative vehicle-infrastructure systems.

The introduction of a new safety system depends on many factors such as system capability and maturity (mass production); liability and invasion of privacy concerns; and consumer acceptance, willingness to pay, and perceived benefits of the system [11]. Introductions of these new systems could be constrained by the capability of the underlying technology and algorithms to meet desired performance objectives given vehicle size and operating characteristics, and to perform in a range of operating environments or conditions. If a new automotive product is ready for commercialization, its rollout will frequently be staged over 2 to 5 year period and will also be limited to certain platforms or models and geographical markets. The cost ratio – the retail cost of the technology to the vehicle's base price – strongly influences the platforms and models on which these technologies are introduced. Given the high cost of many of these new emerging IVI systems, the tendency is to first offer them as options on the most expensive platforms and models. Although they might have already moved through the development and the testing stages, the commercialization of IVI systems would not occur until suppliers have succeeded in the creation of a centralized information control package for cost reasons. A limited consumer interest or the result of an ill-fated introduction of one IVI system would also delay the debut of these systems. Reliable estimates of IVI system safety benefits highly depend on the availability of data that describe driver performance with and without the assistance of an IVI system in real-world driving environment.

The assessment of deployment potential and safety benefits for IVI crossing path crash countermeasure systems proved to be difficult at this time due to the lack of essential data from actual systems. For instance, results from early deployment of red light running photo enforcement in few U.S. locations demonstrated a reduction in the number of red light violations but did not correlate the impact of this reduction on the number of crossing path crashes. Other infrastructure-based systems such as the red light hold and intersection collision warning systems remain in the conceptual and early experimental stages with non-existent or insufficient data on their effects on driver performance. Similarly, vehicle-based systems linger in the preliminary stages of development. The safety benefits were derived for two experimental systems that implement stop sign violation and insufficient gap warning functions. However, their effectiveness estimates were too high based on data obtained from limited experiments with very few subject drivers. Data on vehicle-based or cooperative red light signal violation warning systems don't exist at the present time.

The development and installation of IVI systems into new vehicles would evolve in an integrated fashion similar to vehicle control enhancement technologies such as antilock braking systems (ABS), traction control systems (TCS), and automatic stability systems. By making use of wheel speed sensors available for ABS, automakers introduced TCS that act on a vehicle's drive wheels to prevent unwanted wheel spin under acceleration. While this helps in low-traction situations such as snow or rain, the ability of TCS to assist in more extreme emergency situations is limited. As a result, automakers built on and integrated key features of ABS and TCS technologies to develop automatic stability systems that actually detect when a driver has lost some degree of control and then automatically stabilize the vehicle to help the driver regain control. The addition and integration of various vehicle subsystems that can share electronics, sensors, and software will increase system functionality and improve performance while minimizing complexity and cost.

Currently installed on new vehicles using 76 - 77 GHz forward-looking radar, the ACC system would play the role of ABS following the trend of vehicle control enhancement technologies. Rear-end collision avoidance systems might be built on and integrated with ACC, using additional devices such as a down-looking B&W camera-based lane tracker to obtain information about the road geometry ahead and GPS/GIS to identify vehicle location and its

surroundings. Other collision avoidance systems might then be developed to perform run-off-road collision avoidance, insufficient forward gap warning, and stop sign violation warning functionalities. The addition of beacons to infrastructure-based systems and transponders to vehicles would enable the exchange of data between the infrastructure and vehicles. As a result, DSRC 5.9 GHz transponders or modified RBDS radios would allow vehicles to receive information from the infrastructure, enabling vehicles to execute red light violation and insufficient lateral gap warning functionalities. The use of 2-way communication devices such as DSRC 5.9 GHz or other transponders might later evolve to provide vehicles with the ability to realize vehicle-to-vehicle communications-based crossing path crash countermeasure systems.

System synthesis and tradeoff analysis to choose between vehicle-based and cooperative components for crossing path crash countermeasure concepts will not be credible until more reliable numbers for component effectiveness and deployment can be created than exist today. Infrastructure deployment models are not done today in a way that is comparable to current vehicle deployment models. Creating an infrastructure deployment model and matching it with a vehicle deployment model poses what may be an intractable and pointless problem apart from input and buy-in from all the stakeholders. Hidden in this is the issue of standards and interoperability, which looms as a limiting factor for a cooperative vehicle-infrastructure deployment given the fragmented approach the individual States in the U.S. are now using for deployment. Hopefully, this issue will be settled in conjunction with all the stakeholders (e.g., U.S. DOT, State DOT's, automakers, and infrastructure providers).

CONCLUDING REMARKS

A systems analysis was conducted to identify most promising countermeasures to crossing path crashes. This analysis was based on a detailed definition of crossing path crashes at intersections and driveways using 1998 GES. Crash statistics were broken down by pre-crash scenario, traffic control device, and primary causal factor. Three basic countermeasure concepts were devised to address target crossing path crashes. Three classes of countermeasure systems were considered for implementing these concepts, including infrastructure-based, vehicle-based, and cooperative vehicle-infrastructure systems. The last class was separated between infrastructure-to-vehicle communications and vehicle-to-vehicle communications. For each proposed countermeasure system, this paper presented a summary of a literature survey about the technical readiness of available systems, sensors, and enabling technologies.

Based on the results of this analysis, the IVI is encouraged to focus on the development of tools such as performance specifications, objective test procedures, and safety benefits estimation methods for crossing path crash countermeasures. These tools are technology independent and do not imply any particular implementation, either for sensors or for cooperative versus autonomous components. The technology implementation will be a deployment decision made by deployers based on trade-offs in law enforcement, revenue and market issues, cost-benefit, and many other factors.

The following steps are recommended for future research into IVI crossing path crash avoidance:

1. Complete the performance specifications in Table 4 for the sensor, warning algorithm, and driver-vehicle interface elements of each concept. More naturalistic driving data will be needed to sufficiently understand the pre-crash kinematics problem and help to accurately fill in this table. This will also create baseline data to estimate safety benefits in a later step.
2. Begin to develop objective test procedures where the performance specifications are now adequate to solve a part of the crash problem (e.g., host vehicle stop sign violation).
3. Complete objective tests for the performance specifications.
4. Develop safety benefits methods to evaluate crossing path countermeasures.
5. The next step would be a field operational test of those implementations that the deployers feel are ready for deployment, as a final pre-deployment decision gate.

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