# Improving Driver Decisions and Performance in High-Speed, Multilane, Complex Conditions

*Requested by*
Wes Lum, Chief, Safety Innovation and Cooperative Research

December 15, 2009

*The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.*

## Executive Summary

### Background

In an effort to reduce fatalities resulting from traffic collisions, California's Strategic Highway Safety Plan identified 16 Challenge Areas under the State Highway Safety Plan. Improper driving decisions about the right of way and turning became the focus of Challenge Area 5 (CA-5). To better address the needs in this area, Caltrans staff proposed a research project that considers the following priorities outlined in the plan:

- 5.1 Develop and encourage implementation of a systematic approach to the identification and improvement of existing and potential "high-crash concentration locations" involving improper driver decisions about rights of way and turning.
- 5.4 Explore and implement approved technologies being used by other states and countries to reduce severe traffic collisions associated with turning and lane changing on high-speed, multilane facilities.
- 5.5 Expand the use of existing technology-based tools and strategies that have been demonstrated to correct or minimize the traffic operating conditions which are a primary cause of collisions related to abrupt lane changing in the vicinity of freeway merge and diverge points.
- 5.7 Support new and ongoing research and development projects associated with in-vehicle communication and information technologies to help detect and warn drivers of potential collision with other vehicles in the adjacent lane during lane change maneuvers.

In support of the proposed research project, this Preliminary Investigation focused on identifying strategies and technologies to reduce crashes and fatalities by improving the performance/decision making of drivers who are confronted with complex infrastructure and/or operating conditions. To carry out this investigation, we summarized completed domestic and international research and research in progress. We also surveyed transportation agencies to identify best practices for conducting crash investigations using a multidisciplinary team and contacted transportation agencies directly to learn more about the countermeasures used to improve safety on complex freeways.

### Summary of Findings

We gathered information in seven topic areas related to improper driver decisions in complex driving conditions:

- Multidisciplinary Crash Investigations.
- Driver Behavior.

- Factors Contributing to Crashes.
- Countermeasures.
- Tools and Strategies to Improve Traffic Operating Conditions.
- Collision Avoidance for Lane Changing.
- In-Vehicle Technologies.

Following is a summary of findings by topic area.

**Multidisciplinary Crash Investigations**

- A survey of members of the National Safety Engineers listserv to identify transportation agencies that employ the expertise of medical and behavioral specialists in crash investigations netted 12 responses. Only one respondent—the Virginia Multidisciplinary Crash Investigation Team affiliated with Virginia Commonwealth University—makes active use of this type of expertise.
- While the majority of transportation agencies responding to the survey are not employing the expertise of medical and behavioral specialists, some agencies make limited use of emergency medical personnel and other nontraditional participants such as members of advocacy groups, local residents and businesspeople.
- Virginia's Transportation Safety Training Center, which is home to the Virginia Multidisciplinary Crash Investigation Team, is offering a two-day training workshop on human factors in crash investigation in March and April 2010.
- A December 2006 study by the Indiana Department of Transportation describes the Road Safety Investigation Tool, a prototype software designed to reduce the required size of a crash investigation team and decrease the time spent at the investigated site. The tool uses a knowledge-based system that represents various specialties, including traffic engineering, human factors, roadway geometry, traffic control and others.
- Road Safety Audits (RSAs)—independent assessments of the safety performance of an existing or proposed roadway by a team of safety specialists—have been used in the United Kingdom and Australia since the 1980s and 1990s, respectively. The 2004 publication *NCHRP Synthesis of Highway Practice 336* provides some historical perspective and an assessment of current practices in North America. Like most of the domestic research we located related to RSAs, little is said about the use of medical and behavioral specialists on RSA teams.
- While RSAs in the United States appear to make limited use of medical and behavioral specialists, we found evidence of the use of these specialists abroad. The VALT 2003 Method is used in Finland to investigate all fatal crashes using a multidisciplinary team that includes a police officer, vehicle engineer, traffic engineer, physician and sometimes a psychologist.

**Driver Behavior**

- Papers presented at the 2009 TRB Annual Meeting examined information load rates to determine whether a relationship between driver information loads and crash rates could be found, and discussed the findings from focus groups that investigated drivers' intended actions along a freeway-ramp merging segment.
- Age-related factors are considered in a 2009 study of older drivers in Norway and Sweden, and a 2008 investigation of actual and perceived behavior of older drivers on freeways.
- Behavioral modeling is explored in studies that investigate driver behavior differences across freeway lanes, mandatory lane-change behavior and lane-changing behavior in the presence of exclusive lanes such as high-occupancy-vehicle (HOV) lanes.
- Other factors affecting driver behavior are addressed in studies that consider distraction and inattentive driving and the effects of eye height or movement.

**Factors Contributing to Crashes**

- Injury severity at freeway diverge areas and the effects on crashes of lane-change and car-following behavior were examined in two 2009 TRB Annual Meeting papers.

- The safety effects of weaving segments—where vehicles entering or exiting the freeway are required to execute one or more lane changes—are documented in publications from 2004 and 2008.
- Conference papers from 2006 and 2007 described models applied in Florida to examine crash severity using temporal, spatial and real-time traffic conditions and reveal the roadway geometrics and traffic characteristics on six-lane highways that influence crashes.
- Publications in 2007 and 2009 describe the use of California collision data to assess the safety performance of HOV lanes with two different types of access—continuous and limited—and the distribution of collisions on different lanes on the freeway.
- A 2007 conference paper presented the results of a safety analysis of the Virginia Department of Transportation's time-of-day freeway managed-lane system on Interstate 66.
- Vehicle-related factors such as mirror size and body-pillar vision obstructions are considered in studies conducted by the University of Michigan's Transportation Research Institute.

**Countermeasures**

- A 2009 publication looks at the performance of countermeasures for collisions related to ramp/freeway mainline junctions in California. Other reports consider countermeasures for high-risk locations in Virginia, the effects of in-roadway lights linked with a speed detection system on crashes, and the effects of signage on crashes and lane-change distance.
- Studies that span the period 2004 through 2008, and a Missouri Department of Transportation research project in progress that is expected to conclude in November 2010, examine the safety benefits of variable speed limits and offer suggestions for optimum speeds and intervention duration.
- We contacted five states—Arizona, Illinois, Massachusetts, Nevada and Texas—to inquire about countermeasures used in complex operating conditions. Among the practices noted by respondents are changes in the use of overhead guide signage, supplemental pavement markings and use of continuous flow lanes.

**Tools and Strategies to Improve Traffic Operating Conditions**

- A 2008 report outlines a crash likelihood estimation model for high-crash areas in Minnesota that uses a detection and surveillance infrastructure deployed on a section of freeway.
- Other studies examine the relationship between the number of lanes and safety on urban freeways and how urban freeway on-ramps act as invasive influences on mainline operations. Design aids for the length of acceleration and deceleration lanes for freeway speed-change lanes that are based on expected collision frequency are offered in a paper presented at the 2006 TRB Annual Meeting.

**Collision Avoidance for Lane Changing**

- Reports that span the period 2006 through 2009 present systems designed to help drivers avoid or reduce unsafe lane changes, including sensor-based collision avoidance systems and a communication system that provides for communication between the drivers of individual vehicles and between drivers and the infrastructure.

**In-Vehicle Technologies**

- A wide range of in-vehicle technologies are presented in articles and conference papers that describe an in-vehicle data recorder that provides driver feedback; a side blind zone alert system that provides information drivers fail to obtain with over-the-shoulder glances; an automatic detection system to recognize irregular lateral vehicle movements; use of vehicle positioning and wireless communication technologies to implement a collision warning system without using direct ranging sensors; vehicle-to-vehicle communication systems that extend coverage beyond areas where roadside equipment has been placed; and the use of verbal collision avoidance messages.

## Gaps in Findings

Relatively little research or experience derived from state practice is available to inform the development of multidisciplinary teams to conduct crash investigation. As the volume of research presented in this Preliminary Investigation indicates, much is being done to evaluate the effects of roadway design and driver behavior on safety. However, while researchers are clearly making progress, many studies indicate the need for continuing research to employ real-world scenarios or validate initial findings.

## Next Steps

As Caltrans pursues development of strategies and technologies that improve driver performance and decision making in complex driving environments, the department might consider:

- Following up with the Virginia Multidisciplinary Crash Investigation Team to learn more about using medical and behavioral specialists in crash investigation.
- Attending the spring 2010 class on human factors in crash investigation offered by Virginia's Transportation Safety Training Center.
- Identifying specific areas of interest to investigate that will expand on promising recent research.
- Carrying out field tests of one or more of the tools and strategies identified in this Preliminary Investigation.

# Contacts

During the course of this Preliminary Investigation, we spoke with the following individuals:

## State DOT contacts

**Mike Manthey**
State Traffic Engineer
Arizona Department of Transportation
(602) 712-8888, MManthey@azdot.gov

**Priscilla A. Tobias**
State Safety Engineer
Illinois Department of Transportation
(217) 782-3568, Priscilla.Tobias@illinois.gov

**Thomas Broderick**
Deputy Chief Engineer for Safety and Mobility
Massachusetts Highway Department
(617) 973-7847, thomas.broderick@mhd.state.ma.us

**Chuck Reider**
Principal Safety Engineer
Nevada Department of Transportation
(775) 888-7335, creider@dot.state.nv.us

**Jaime B. Tuddao**
Senior Road Safety Engineer
Nevada Department of Transportation
(775) 888-7467, jtuddao@dot.state.nv.us

**Margaret (Meg) A. Moore**
Director, Traffic Engineering Section
Texas Department of Transportation
(512) 416-3135, mmoore1@dot.state.tx.us

## University contacts

**Thomas J. McDonald**
Safety Circuit Rider
Institute for Transportation
Iowa State University
(515) 294-6384, tmcdonal@iastate.edu

**Lori G. Rice**
Team Leader and Psychologist
Virginia Multidisciplinary Crash Investigation Team
Transportation Safety Training Center
Virginia Commonwealth University
(804) 828-1031, lgrice@vcu.edu

# Multidisciplinary Crash Investigations

Multidisciplinary crash investigations employ the expertise of a range of specialists—highway design, maintenance and safety engineers, law enforcement and emergency medical personnel, psychologists and other medical professionals—to examine the safety performance on existing road or planned roadway expansion. Caltrans is particularly interested in the activities of team members from medical and behavioral specialties in examining issues such as road-user health and motives.

Below we provide information about the results of a survey to gather information about the use of multidisciplinary teams to investigate crashes. We also highlight related research and other resources that describe the use of road safety tools, RSAs and the use of multidisciplinary investigation teams here and abroad.

## Survey Results

We conducted a survey of the members of the National Safety Engineers listserv to identify transportation agencies that employ the expertise of nontraditional specialists in the investigation of crashes, with a particular interest in the participation of medical and behavioral specialists. Twelve agencies responded to the survey. Results of the survey appear in Appendix A of this Preliminary Investigation.

Most of the survey responses indicate little or no work with multidisciplinary teams. In some cases, use of medical-related specialists was sporadic and limited to emergency response personnel. We followed up with telephone contacts to three states—Iowa, Nevada and Virginia—to further explore their use of multidisciplinary teams.

With one exception—Virginia—results of the survey and follow-up contacts indicate that agencies using multidisciplinary crash investigation teams make limited or no use of medical and behavioral specialists. Other nontraditional participants, such as members of advocacy groups, local residents and businesspeople, are sometimes included on investigation teams.

**Institute for Transportation, Iowa State University**
http://www.intrans.iastate.edu/
Thomas J. McDonald, Safety Circuit Rider, (515) 294-6384, tmcdonal@iastate.edu

The composition of Iowa's safety teams varies. Teams include representatives from the agency responsible for the roadway under review and may include local residents, businesspeople, and emergency medical and law enforcement personnel. McDonald noted that medical professionals are more difficult to locate and include in a crash investigation. Safety teams conduct six to eight investigations each year. While the teams do not include psychologists or other medical-related specialists other than emergency medical staff, including participants outside traditional engineering disciplines has been helpful. The anecdotal information often shared by local residents brings to light different questions than those that may have been raised by reviewing only crash data.

Recent RSA reports can be found at http://www.intrans.iastate.edu/research/detail.cfm?projectID=-1066222863. Reports often suggest low-cost improvements such as signing upgrades, improved pavement markings and additional lighting, though more costly countermeasures may be recommended.

When asked about challenges, McDonald commented that audits conducted in connection with a well-documented safety issue are more straightforward than audits arising from concerns raised by the public that may not be supported by crash data.

**Nevada Department of Transportation**
http://www.nevadadot.com/
Jaime B. Tuddao, Senior Road Safety Engineer, Safety/Traffic Engineering Division, (775) 888-7467, jtuddao@dot.state.nv.us

Nevada's independent, multidisciplinary teams range in size from three to as large as 10 participants, with the size of the team often based on the scale of the project. Differing perspectives are gathered through interviews with the community and business owners and observations from the public. A proactive approach is taken to evaluate safety issues at the beginning of the project-planning phase. Emergency medical personnel are included in RSA teams as often as possible. Twelve RSAs are conducted each year using procedures based on Federal Highway Administration (FHWA) guidelines and prompt lists. Tuddao noted that the greatest challenge in fielding an effective RSA team is the presence of an effective team leader. In some cases, a consultant has been used to fill this position to bring the necessary managerial expertise to a project. Communication has been critical to ensuring the success of the RSA program.

**Virginia Multidisciplinary Crash Investigation Team, Transportation Safety Training Center, Virginia Commonwealth University**
http://www.vcu.edu/cppweb/tstc/index.html
Lori G. Rice, Team Leader & Psychologist, (804) 828-1031, lgrice@vcu.edu

The Transportation Safety Training Center (TSTC) was formed in 1971 by the Highway Safety Division with the cooperation and support of the Virginia Departments of State Police and Transportation and Virginia Commonwealth University. The Virginia Multidisciplinary Crash Investigation Team (VMCIT) is a unit within TSTC. VMCIT team members include a Virginia state trooper, a highway engineer and a psychologist, with advisory assistance from medical, engineering or other personnel as necessary.

The team's state trooper, trained as an accident reconstructionist, is responsible for obtaining the driver's history and possible criminal record. The psychologist addresses human factors, consulting with experts from various disciplines when needed, and works closely with the medical examiner's (ME's) office. The team's highway engineer brings expertise in roadway design.

The VMCIT meets with the investigating officer at the crash scene before vehicles are destroyed to take measurements and videotape the area under the same conditions present at the time of the crash. (This is done at night if the crash occurred at night.) A review is conducted of the impact area and beyond to look for evidence of ejection and seat belt use, and information from the airbag control module that stores data for 20 seconds before the crash is downloaded. Data from the airbag control module can include speed, change in velocity, whether seat beats were belted, whether the gas or brake pedal was engaged and percent of throttle. Different vehicles provide different amounts of data, and a converter box is required to download and read data. The data are used to corroborate physical evidence at the site. Physical evidence is also matched to information from the ME's office.

Each member of the team independently completes his or her portion of the report, and the team works in concert to finalize a comprehensive draft. Team reports are made public, though it can take months for a report to appear online. Some online reports include animated crashes. Crash team reports are available at http://www.vcu.edu/cppweb/tstc/crashinvestigation/crash-report.html.

TSTC offers annual courses on incident analysis. A two-day training workshop on human factors in crash investigation focuses on the following motor vehicle crash investigation and reconstruction topics: multidisciplinary crash investigation techniques; general principles of human factors psychology; driver characteristics; perception-reaction times; effects of vehicle and roadway characteristics; occupant kinematics; restraint use; and interviews and witness statements. See http://www.vcu.edu/cppweb/tstc/training/investigation/human.html for information about classes scheduled for March and April 2010.

## Related Research and Other Resources

**"Road Safety Assessments for Community Traffic Safety Teams,"** Lawrence T. Hagen, *ITE 2008 Technical Conference and Exhibit*.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01109074.html
The author has taken the two-day FHWA RSA training class and compressed it into a one-day briefing targeted at Community Traffic Safety Teams (CTSTs) throughout Florida. The CTSTs are groups that typically meet monthly to try to address traffic safety issues. This paper focuses on success stories and benefits realized by the agencies and team members.

**Expert System to Support Site Investigation for Safety Improvement**, Andrew M. Kwasniak, Bogdan Chivoiu, Andrew P. Tarko, Indiana Department of Transportation, Report No. FHWA/IN/JTRP-2006/25, December 2006.
http://rebar.ecn.purdue.edu/JTRP_Completed_Project_Documents/SPR_2951/FinalReport/SPR_2951_Final/SPR_0625.pdf
Researchers developed the Road Safety Investigation Tool (RSIT), a prototype software, to reduce the required size of a crash investigation team and decrease the time spent at the investigated site. A smaller team size is required because knowledge is organized and developed into a knowledge-based system that represents various specialties: traffic engineering, human factors, roadway geometry, traffic control and others. The knowledge-based system uses information extracted from the crash database and collected during a site investigation and connects this information with relevant safety countermeasures. Researchers noted that human factors were studied in greater detail because drivers cause more than 80 percent of all crashes.

The knowledge base includes information from the following sources:

- Human factors.
- Safety facts (crash database).
- Road safety, including road safety guidance, checklists and methodology behind the RSA process.
- RSA final reports.
- Observations of the safety specialist team during real-time safety investigations.
- Road geometry studies.

The report cites the following benefits of the tool:

- The flexibility of the user-friendly tool increases the efficiency of site investigation and contributes to more effective findings.
- The tool allows investigators to obtain all possible adequate solutions based on factual data. It was shown that the RSIT prototype described more roadway deficiencies than a safety team.
- The investigation process can be conducted by a team or an individual.

**"Road Safety Audits: The North American Experience,"** Sany R. Zein, Margaret Gibbs, Frank Navin, *ITE 2005 Annual Meeting and Exhibit Compendium of Technical Papers*.
Abstract: http://ntlsearch.bts.gov/tris/ http://www.nevadadot.com/ record/tris/01006817.html
This paper describes how RSAs are used in North America. Pioneered in the United Kingdom and Australia, RSAs were first used in North America in 1997. The authors discuss the evolution of audits in North America, and how the RSA process and report is changing in response to factors such as severe time constraints, owners' and design teams' attitudes, liability concerns, and safety concerns associated with subclasses of road users such as cyclists and older drivers.

**Roadway Human Factors and Behavioral Safety in Europe,** Kevin Keith, Michael Trentacoste, Leanna Depue, Thomas Granda, Ernest Huckaby, Bruce Ibarguen, Barry Kantowitz, Wesley Lum, Terecia Wilson, Federal Highway Administration, American Association of State Highway and Transportation Officials, Report No. FHWA-PL-05-005, May 2005.
http://www.international.fhwa.dot.gov/humanfactors/pl05005.pdf
This scanning study of Denmark, Finland, France, the Netherlands, Norway and Sweden identified how these countries incorporate human factors issues in the research, design and operation of highways. Chapter 4 describes the VALT 2003 Method developed by the Finnish Motor Insurers' Centre, which provides a set of procedures for multidisciplinary traffic accident investigation teams.

From page 12 of the report (page 28 of the PDF):

> "…all fatal crashes in the country are investigated by a multidisciplinary team that includes a police officer, vehicle engineer, traffic engineer, physician, and sometimes a psychologist. The investigation results are documented in an original folder and database with more than 300 variables using a methodology from the Finnish Motor Insurers Centre. Results can vary, depending on the composition of the team. From the examples given, it appeared that the presence or absence of a psychologist on the team could critically alter conclusions and interpretation of data. Considering all perspectives provided by a multidisciplinary team improved the overall research program.

"No data were presented on the statistical reliability of this method. Since multidisciplinary crash investigation has been criticized in the United States for lacking such reliability, this caveat must be kept in mind when evaluating European results."

Continuing on page 13 (page 29 of the PDF), the report describes participation of the health-related specialists:

*Physician Member*

- Investigates the vehicle and, with the vehicle specialist, the possible sources of injury.
- Investigates, with the police and psychologist, the physical and psychological state of the drivers and pedestrians involved.
- Examines the risk factors related to driving ability.

*Psychologist Member*

- Investigates, with the road specialist, issues related to the traffic environment and traffic control, and evaluates the actions of the parties involved.
- Investigates, with the police and physician, the psychological state of the drivers and pedestrians, obtains historical information about the health of the parties involved, and evaluates the effect of these on the origin of the accident.
- Functions as a consultant in investigation queries within the team.
- Examines the risk factors related to driving ability and produces improvement proposals.

**Road Safety Audits**, *NCHRP Synthesis of Highway Practice 336*, 2004.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_336.pdf
While focusing on North American applications of RSAs and road safety audit reviews (RSARs), this document also discusses international practice and the history of RSA development. RSAs were first introduced in the United Kingdom more than 20 years ago, and RSAs have been extensively applied in New Zealand and Australia since the 1990s. The state of the practice described in this report was developed based on a 2003 survey, state and local agency practices, FHWA- and National Highway Institute-sponsored training for state departments of transportation, local agency training experiences, international practices, a literature review and personal contacts.

Page 12 of the PDF describes the audit team composition:

- Audit team composition—size of team (three to five members were recommended) and team skills—most states identified a core related to traffic operations, design, and safety, with additional skills related to construction, maintenance, law enforcement, planning emergency medical services, and human factors depending on the audit stage and scope of the project.

**"Methods of Multidisciplinary In-Depth Analyses of Road Traffic Accidents,"** Lotte Larsen, *Journal of Hazardous Materials,* Vol. 111, Nos. 1-3, 2004, pages 115-122.
Abstract: doi:10.1016/j.jhazmat.2004.02.019
This article offers a discussion of Denmark's multidisciplinary Road Accident Analysis Group. The multidisciplinary approach provides detailed knowledge of the contributing factors leading up to an accident. The method requires significant resources, which is a limiting factor for the number of accidents that can be analyzed in this manner. Researchers suggest use of the method for analysis of commonly occurring or very serious types of accidents.

**Road Safety Audits (RSA)**
http://safety.fhwa.dot.gov/rsa/
This FHWA web site provides information for agencies just beginning or seeking to advance an RSA program, including policies; information on FHWA's RSA peer-to-peer program; a library that contains reports, articles and other documents related to RSAs; and links to other RSA resources. The 2006 publication *FHWA Road Safety Audit Guidelines*, available at http://safety.fhwa.dot.gov/rsa/guidelines/documents/FHWA_SA_06_06.pdf, provides prompt lists that can be used by the RSA team to identify potential safety issues and by designers to proactively identify potential safety issues as roadways are being designed.

# Driver Behavior

Driver behavior can have a significant impact on crashes. Information load contributes to how effectively drivers operate their vehicles, and various other factors—age, distractions and inattention, eye height and movement, and human factors—play a role in the safety of our roadways. The citations below offer examples of recent research in driver behavior and the behavioral modeling that can help transportation safety engineers better understand how, when and why drivers make decisions.

**"Driver Responses at Different Information Loads on Urban Freeways,"** Alexei Rimmich Tsyganov, Randy B. Machemehl, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-1883.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01123242.html
In this paper, researchers classified incoming information into three categories: highway, traffic control and traffic. After identifying quantification criteria for these information sources, researchers compared more than 80,000 crashes on selected urban freeways in the major metropolitan areas of Texas to information load rates to determine whether relationships between driver information loads and crash rates could be found. Next, researchers conducted test driving of instrumented vehicles on the selected urban freeways representing typical combinations of information load. Based on an analysis of speed variations, frequency of intense braking, heart activity characteristics, eye-scanning processes and a crash statistics analysis, researchers identified freeway informational dimensions that cause abnormal driver responses.

Results include:

- Increased sign frequency on urban freeways with two, three and four lanes seemed to be related to an increase in accident frequency, with a simultaneous increase in multivehicle collisions. This is in contrast to freeways with five and six traffic lanes, where smaller sign frequencies were characterized by more accidents.
- Data indicated a U-shaped relationship between internal driver responses and information load, with the most ideal driver reactions associated with the middle-range information classes on freeways with four or fewer traffic lanes.
- Intensive driver responses, including rapid heart rates and intensive braking on freeway sections with infrequent signs, may indicate insufficient information load, while very frequent signs may lead to driver information overload.
- For five- and six-lane freeways, the most desirable driver responses were measured at the highest information loads.

**"Driver Behavior at Freeway-Ramp Merging Areas: Focus Group Findings,"** Alexandra Kondyli, Lily Elefteriadou, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-2035.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01126586.html
This study conducted three focus groups to investigate drivers' intended actions along a freeway-ramp merging segment. The study considered both noncongested and congested traffic conditions and correlated drivers' responses to their individual characteristics. Conclusions drawn from the study include:

- Participants' responses were uniform with regard to the steps involved in merging, both for noncongested and congested conditions.
- Ramp design appears to affect drivers' merging process. Most of the participants indicated they would speed up and be more aggressive on taper ramps as compared to ramps of parallel design.
- If participants are on the freeway, their preference is to change lanes and avoid decelerating. If this cannot be accomplished, they will cooperate, depending on the speed/acceleration of the ramp vehicle and its size/type.
- The ramp vehicle's decision to initiate a forced merge depends mostly on traffic-related factors such as freeway speed, congestion and gap availability.
- In congested conditions, driver behavior displays less variability and may be more predictable.

## Age-Related Issues

**Older Car Drivers in Norway and Sweden: Studies of Accident Involvement, Visual Search Behavior, Attention and Hazard Perception**, Tania Dukic, Per Henriksson, Lena Levin, Selina Mårdh, Fridulv Sagberg, VTI Rapport 656A, 2009.
http://www.vti.se/EPiBrowser/Publikationer%20-%20English/R656A.pdf
This study identified hazardous situations for older drivers and analyzed older drivers' accident involvement and visual behavior in complex traffic situations. Results of the study recommend further research and refinement of methods for identifying hazardous behavior in complex situations, including:

- Testing of drivers in complex situations.
- Behavior due to temporary illness or tiredness.
- In-depth studies of drivers' perspectives, experiences and strategies to avoid road accidents.
- Research on Intelligent Transportation Systems and other adaptive systems in vehicles that support older car drivers.

**"Investigation of Actual and Perceived Behavior of Older Drivers on Freeways,"** Sophia Vardaki, *Transportation Research Record,* Vol. 2078, 2008, pages 41-48.
Abstract: http://dx.doi.org/10.3141/2078-06
Actual performance of older drivers was investigated on tasks such as freeway driving, exit finding, lane changing, and freeway entering and exiting and correlated with driver performance self-assessment. Results indicate that older drivers are aware of their performance inadequacies on the freeway. Researchers note that "some of the exhibited inadequacies might be correctable because they are probably the results of lack of knowledge of the appropriate performance, traffic rules (especially signs, signals and markings) and compensatory behavioral adjustments necessary for successful task execution. Training on safe driving practices such as freeway maneuvering, visual search techniques, hazard recognition (noticing the clues to possible dangers in time) and avoidance, and compensatory tactics helping drivers respond to their potential difficulties in less unfavorable ways could contribute to the improvement of older drivers' performance … ."

## Behavioral Modeling

**"Life in the Fast Lane: Duration-Based Investigation of Driver Behavior Differences Across Freeway Lanes,"** Samer Hani Hamdar, Hani S. Mahmassani, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-3647.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01126646.html
The objective of this research was to explore driver behavior in separate lane groups from a duration perspective using hazard-based models. Using Next Generation Simulation trajectory data, researchers analyzed time durations until lane-changing maneuvers are executed. Results indicate:

- In the left-most lane, drivers are traveling at higher speeds with an increasing hazard-probability to make a lane-change maneuver as times passes.
- In the middle lanes, approaching an on-ramp, a driver tries to avoid the merging traffic from the on-ramp to the right, resulting in an increasing hazard function or a snowballing effect. Once past the merging point, a decreasing hazard function reflects an inertia effect.
- In the right-most lane adjacent to the on-ramp, episode duration plays little role in influencing a driver's decision.
- In the on-ramp lane, a driver attempts to change lanes at the beginning of an episode (increasing hazard) before arriving at the end of the lane and waiting for an acceptable gap (decreasing hazard).

Researchers noted that the analysis is limited by the geometry of the study area. Additional study areas, including off-ramps or lanes downstream and upstream of signalized intersections, would provide considerable additional insight.

**Analyzing Microscopic Behavior: Driver Mandatory Lane Change Behavior on a Multilane Freeway,** Ghulam Hussain Bham, Research and Innovative Technology Administration, August 2008.
http://utc.mst.edu/documents/R157_CR.pdf
This report analyzes driver gap acceptance and rejection behavior during mandatory lane changes on a multilane freeway. A driver can reject a gap for several reasons—to avoid collision, failure to reach the intended location of a lane change, misperception of a gap, significant difference in relative speed, and other reasons. A critical gap lies between the rejected gap and the accepted gap.

Results obtained from the distribution of accepted time gaps and estimated critical time gaps can be used in traffic simulation models to generate values of accepted gaps and critical gaps for mandatory lane changes. This procedure can also be used in existing lane change models that use the collision avoidance check for allowing a lane change. Leading and trailing accepted and rejected gap values from the field data may also be used for calibrating traffic simulation models, while critical gap values may be used to identify the point where drivers start to make a lane change and traffic signs can be provided on the freeway.

**"Modeling Lane-Changing Behavior in Presence of Exclusive Lanes,"** Charisma Farheen Choudhury, Tomer Toledo, Moshe E. Ben-Akiva, *11th World Conference on Transport Research*, 2007.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/011175296.html
Lane-changing behavior is significantly affected by the presence of exclusive lanes such as high-occupancy-vehicle (HOV) lanes, value-priced lanes and heavy-vehicle lanes. This paper extends the authors' previous research on developing a generalized lane-changing model and enhances it by introducing an exclusive lane-specific component in the model. The model uses data collected from Interstate 395 in Virginia, which does not have any exclusive lanes, and Interstate 80 in California, which has an HOV lane. The model is validated and compared with the existing lane-changing model using a microscopic traffic simulator. Statistical comparisons of measures of performance indicate that the new model outperforms the previous model.

## Distractions

**Driver Distraction: A Review of the Current State-of-Knowledge,** Thomas A. Ranney, National Highway Traffic Safety Administration, Report No. HS-810 787, April 2008.
http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2008/DOT-HS-810-704.pdf
*From the abstract*: "Although existing data is inadequate and not representative of the driving population, it is estimated that drivers engage in potentially distracting secondary tasks approximately 30 percent of the time their vehicles are in motion. Conversation with passengers is the most frequent secondary task followed by eating, smoking, manipulating controls, reaching inside the vehicle, and cell phone use. Driver attention status is unknown for a large percentage of crash-involved drivers in the Crashworthiness Data System (CDS). However for the period between 1995 and 2003 it is estimated that 10.5 percent of crash-involved drivers were distracted at the time of their crash involvement. Approximately 70 percent of distracted drivers' crashes were either noncollision (single-vehicle) or rear-end collisions."

Page 22 of the report (page 26 of the PDF) offers recommendations for future research, including:

- Better reporting of driver attention status for crash-involved drivers to provide better estimates of the incidence of distraction in crashes.
- Development of an inventory of existing and emerging technologies and services accessible to drivers. From this, research is needed to define a taxonomy of driver distractions and specific sources.
- Development of objective, standardized measures of distraction. Emphasis should be given to improving the reliability and validity of eye-glance measures.
- Evaluation of the effectiveness of state distraction-related laws.

**"Effects of Visual and Cognitive Distraction on Lane Change Test Performance,"** Johan Engstrom, Gustav Markkula, *Driving Assessment 2007: 4th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, pages 199-205.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01055561.html

*From the abstract*: "Driver errors related to visual and cognitive distraction were studied in the context of the Lane Change Test (LCT). New performance metrics were developed in order to capture the specific effects of visual and cognitive distraction. In line with previous research, it was found that the two types of distraction impaired driving in different ways. Visual, but not cognitive, distraction led to reduced path control. By contrast, only cognitive distraction affected detection and recognition/response selection. Theoretical and practical implications of these results are discussed."

**A Guide for Reducing Crashes Involving Drowsy and Distracted Drivers**, Jane Stutts, Ronald R. Knipling, Ronald Pfefer, Timothy R. Neuman, Kevin L. Slack, Kelly K. Hardy, *NCHRP Report No. 500, Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, Vol. 14, 2005.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_500v14.pdf
The introduction to this report describes the distracted driver problem in this way:

> The National Highway Traffic Safety Administration (NHTSA) has identified driver inattention as a causative factor in 25–30 percent of crashes. Inattentive drivers may be temporarily distracted by something inside or outside the vehicle, may be drowsy or fatigued, or may simply have their mind on something other than the task of driving.
>
> The primary source of national data on the role of driver inattention in traffic crashes is the Crashworthiness Data System (CDS), which is based on a national sample of police-reported traffic crashes involving at least one passenger vehicle that has been towed from the crash scene. An analysis of 2000-2003 CDS crash data shows that:
>
> - 11.6 percent of crashes involve one or more distracted drivers,
> - 3.9 percent involve one or more drivers who were sleepy or had fallen asleep at the wheel, and
> - 10.2 percent involve one or more drivers who "looked but didn't see."

A table beginning on page 29 of the PDF classifies strategies to address distracted driving according to the expected time frame and relative cost. Most strategies are short-term, low-cost undertakings.

## Eye Height or Movement

**"Visual Inspections Made by Young and Elderly Drivers Before Lane Changing,"** M. Lavallière, N. Teasdale, M. Tremblay, N. Ngân, M. Simoneau, D. Laurendeau, *Advances in Transportation Studies,* Special Issue, 2007, pages 17-24.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01111046.html
This study evaluated eye glances of young and older active drivers during lane change maneuvers. Young (21 to 31 years) and older (65 to 75 years) active drivers drove through a continuous simulated environment. During the simulation's 16 events, researchers expected drivers to glance at three regions of interest to make a safe lane change: the left blind spot, left-side mirror and rear-view mirror. Lane-change maneuvers were necessary to avoid a static object blocking the lane partially or completely, or for overtaking a slower-moving vehicle. A reduced left-side mirror and blind-spot glance frequency was shown by older drivers when compared to younger drivers. A higher glance frequency, which increased when overtaking a slower vehicle, was generally shown by younger drivers, while a constant glance frequency across the two driving maneuver types was shown by older drivers.

**"Eye Glance Behavior of Van and Passenger Car Drivers During Lane Change Decision Phase,"** Louis Tijerina, W. Riley Garrott, Duane Stoltzfus, Edwin Parmer, *Transportation Research Record*, Vol. 1937, 2005, pages 37-43.
Abstract: http://dx.doi.org/10.3141/1937-06
In this paper, data are presented on the eye-glance behavior of passenger car and van drivers before the start of discretionary lane changes. Results indicate differences in the eye-glance behavior of van and passenger car drivers that suggest these drivers should be considered separately in further studies of lane-change warning systems. The impacts of road type are also noticeable, suggesting that varied driving conditions should be made a part of future on-road studies of lane-change warning systems. Results also suggest that center mirror displays should be considered for blind spot or lane-change warning systems in addition to the side mirrors more commonly used.

## Human Factors

**"An Approach to Identify Areas with Traffic Safety Issues Due to Driver Behavioral Factors—Arizona Experience,"** Kohinoor Kar, Tapan K. Datta, *TRB 87th Annual Meeting Compendium of Papers DVD,* Paper #08-2340.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01100664.html
The authors developed the Safety Performance Index, which can be calculated for a county, region or city from historical crash and exposure data. The tool is expected to help decision makers prioritize areas for safety improvement measures that address driver behavior. The current study uses the same approach and methodology developed as a part of a Michigan study. The Arizona project is aimed at identifying the utility and applicability of the methodology.

**Commercial Driver Human Factors**, William C. Rogers, Ronald R. Knipling, *Transportation Research E-Circular No. E-C117*, May 2007, pages 92-112.
http://onlinepubs.trb.org/onlinepubs/circulars/ec117.pdf
This section of circular E-C117 addresses several major human factors topics that contribute to traffic crashes. Included in the discussion are driver functional capabilities, driver age and demographic trends, commercial driver training, driver fatigue and drowsiness, and macroergonomics and safety motivation. Concluding comments concern the need for research and development relating to commercial driver human factors.

## Inattention

**The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data,** S. G. Klauer, T. A. Dingus, V. L. Neale, J. D. Sudweeks, D. J. Ramsey, Virginia Tech Transportation Institute, National Highway Traffic Safety Administration, Report No. HS-810 594, April 2006.
http://www.nhtsa.dot.gov/portal/nhtsa_static_file_downloader.jsp?file=/staticfiles/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2006/DriverInattention.pdf
The purpose of this report was to conduct in-depth analyses of driver inattention using the driving data collected in the 100-Car Naturalistic Driving Study. Results include:

- Any eye glance away from the forward roadway greater than 2 seconds greatly increases near-crash/crash risk.
- If collision avoidance warning systems can incorporate driver eye-glance location prior to a crash, the false alarm rate of these warning systems could be greatly reduced.
- More visually cluttered, lower sight-distance or demanding traffic environments (intersections, entrance/exit ramps, curved roadways), poor weather or roadway conditions (rainy weather, icy or wet road surfaces) are not optimal locations to engage in secondary tasks.
- Near-crash/crash risk due to drowsiness increased when drivers were on straight/level roadways and less visually demanding environments (low traffic densities).

# Factors Contributing to Crashes

Below we highlight research that analyzes factors that contribute to crashes, with special attention given to freeway diverge areas, lane changing, weaving sections, and temporal and spatial conditions. Also highlighted are the safety performance of managed lanes and safety implications of vehicle design.

## Crash Analysis

**"Exploring Impacts of Factors Contributing to Injury Severity at Freeway Diverge Areas**," Zhenyu Wang, Hongyun Chen, Jian Lu, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-3383.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01123086.html
This study identified various factors contributing to the injury severity at freeway diverge areas and evaluated the impacts of the factors. Crash data and roadway geometric deign information were collected at 231 selected freeway exit segments in the state of Florida. Study results include:

- Exit ramp types (single-lane exit ramps, single-lane exit ramps with a taper, two-lane exit ramps with an optional lane, and two-lane exit ramps without optional lane) have no significant effects on injury severity at freeway diverge areas.
- Factors that significantly influence injury severity at freeway diverge areas include length of deceleration/ramp lanes, curve and grade at diverge areas, light and weather conditions, alcohol/drug involvement, heavy vehicle involvement, number of lanes on mainlines, average daily traffic on mainlines, surface conditions, land type and crash type.

**"Effects of Lane-Change and Car-Following-Related Traffic Flow Parameters on Crash Occurrence by Lane,"** Chris Lee, Peter Young-Jin Park, Mohamed A. Abdel-Aty, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-1909.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01123224.html
This study investigates the effects of the traffic flow parameters related to individual drivers' lane-changing and car-following behavior on the occurrence of sideswipe and rear-end crashes on freeways. Researchers used 184 sideswipe and 605 rear-end crashes on the Interstate 4 freeway in Orlando and the associated loop detector data for the analysis.

Findings include:

- Higher ratio of the flow in the center lane to the flow in the adjacent lanes and higher overall average flow ratio increase the likelihood of sideswipe crashes in the center lane.
- Sideswipe crashes are more likely to occur in the center lane than the right lane downstream of an on-ramp. The likelihood of sideswipe crashes in the left or center lane was not significantly different downstream of an on-ramp.
- Lower ratio of the speed in the center lane to the speed in the adjacent lanes and lower overall average speed ratio increases the likelihood of rear-end crashes in the center lane.
- Rear-end crashes are more likely to occur in the center lane than the right lane upstream of an off-ramp.
- While the flow-related variables were significant in sideswipe crashes, the speed-related variables were significant in rear-end crashes.

Although development of specific traffic control techniques was beyond the scope of this study, researchers provide the following suggestions:

- Balancing the flows across lanes and discouraging the abrupt merging into the inner lanes downstream of an on-ramp may reduce sideswipe crashes.
- Reducing the speed difference across lanes through temporary differential speed limits across lanes and discouraging the abrupt speed reduction upstream of an off-ramp may reduce rear-end crashes.

**"Evaluation of Weaving Sections Through Safety Assessments,"** Srinivas S. Pulugurtha, Jaimin Bhatt, *ITE 2008 Technical Conference and Exhibit*.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01109066.html
Anecdotal evidence shows that the likelihood of being involved in a crash on a freeway is greater along weaving sections than on other freeway sections. This paper focuses on an evaluation of weaving sections through safety assessments. Data collected for 25 weaving sections in the Las Vegas metropolitan area were used to study the relationship between crashes and characteristics of weaving sections such as weaving configuration, length and percent of weaving volume.

**"Crash Severity Along an Urban Freeway: Modeling Temporal, Spatial, and Real-Time Traffic Conditions**," Mohamed A. Abdel-Aty, Vikash V. Gayah, *11th World Conference on Transport Research*, 2007.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01117327.html
Models used in this study to examine the crash severity along Interstate 4 in Orlando, FL, found that the day of the week, time of the day and location along the freeway all contribute to the severity of crashes that occur. High speeds and a sudden real-time increase in lane occupancy along the freeway caused by fast-moving backward queue shock waves increase the likelihood of severe crashes.

**"Analysis of Crashes Occurring on Florida Six-Lane Roadways,"** Renatus Mussa, *2006 ITE Annual Meeting and Exhibit Compendium of Technical Papers*.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01036818.html
The safety characteristics of roadways with six or more travel lanes in the state of Florida have raised concerns because the annual crash rates are higher than those on four-lane roadways. This study was designed to build a crash prediction model to assist researchers in revealing roadway geometrics and traffic characteristics on six-lane highways that influence crashes. The model showed that:

- Section average annual daily traffic (AADT), number of access points, percentage of trucks in the traffic stream and the width of the sidewalk had positive correlation with the crash frequency.
- Median width, shoulder width, surface width, roadway curvature and posted speed limit were negatively correlated with the crash frequency.

Results also showed that section AADT was the most positively correlated variable with crash frequency, while the posted speed limit was the most negatively correlated based on the variable levels analyzed.

**"Safety Aspects of Freeway Weaving Sections,"** T. F. Golob, W. W. Recker, V. M. Alvarez, *Transportation Research. Part A: Policy and Practice,* Vol. 38, No. 1, 2004, pages 35-51.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/00968014.html
This study investigates the safety of various types of weaving sections on urban freeways, where vehicles entering or exiting the freeway are required to execute one or more lane changes. Accident data for a portion of Southern California was used to examine accidents occurring on three types of weaving sections, including:

**Type A weaving section**

- **Description:** Every merging or diverging vehicle must execute one lane change. The most common configuration is a pair of on- and off-ramps connected by an auxiliary lane.
- Vehicle conflicts occur within the interior lanes. These conflicts are more prevalent at off-peak periods, especially at night and on wet roads.
- These accidents are the least severe among the three types of weaving sections.
- Traffic engineering improvements might include improved signage, improved lighting, and/or pavement resurfacing in the form of scoring or wet-friction materials.
- Signage in advance of all Type A weaving sections should be reviewed to determine if drivers are given sufficient warning of the need to change lanes to exit or enter the freeway, especially at night and during inclement weather, and when traveling at posted speeds under free-flow conditions.

**Type B weaving section**

- **Description:** One of the merging or diverging movements can be done without changing lanes, while one lane change is required for the opposite movement. A common configuration has a lane added at an on-ramp; merging traffic does not need to change lanes, but traffic diverging downstream must change onto this added lane to exit at the off-ramp.
- Vehicle conflicts involve vehicle lane changing, predominantly in either the right or left lanes. These accidents are likely to be more severe than accidents in either Type A or Type C weaving sections.
- Accidents may stem from the disparity between the speed of the movement requiring the lane change and that of the through and nonlane-change merge.
- Special speed restrictions or more effective enforcement of posted speeds may be warranted.
- Signage and driver education should be reviewed as means of alerting drivers to potential problems in this type of weaving section.

**Type C weaving section**

- **Description:** One weaving movement can be made without making any lane change, while the other weaving movement requires at least two lane changes.
- Vehicle conflicts tend to occur in the left lane during weekday rush hours.

- There may be no simple safety mediation for accidents involving complex, successive lane changing other than restriction of the merge during periods of peak traffic, which may not be practical.
- Changeable message signs warning of potential hazards at these locations might be effective in alerting drivers to potential hazards during periods of heavy traffic flow.

## Managed Lanes

**"Safety Performance of High-Occupancy-Vehicle Facilities: Evaluation of HOV Lane Configurations in California,"** Kitae Jang, Koohong Chung, David Ragland, Ching-Yao Chan, *Transportation Research Record*, Vol. 2099, 2009, pages 132-140.
Abstract: http://dx.doi.org/10.3141/2099-15
Collision data from high-occupancy-vehicle (HOV) facilities with two different types of access—continuous and limited—are examined in this paper. Findings include:

- HOV facilities with limited access offer no safety advantages over those with continuous access.
- Compared with continuous access HOV lanes, a higher percentage of collisions were concentrated on limited-access HOV lanes. Limited-access HOV lanes also had higher collision rates.
- HOV facilities with shoulder width greater than 8 feet had significantly lower collision rates regardless of access type.
- Corridors that used the continuous HOV access had lower HOV-lane collision rates compared with a comparably sized limited-access HOV lane.
- Limited-access HOV facilities with a combination of short ingress/egress length and proximity to the nearest on- or off-ramp can result in markedly higher collision rates than other limited-access freeway segments, although these factors need more systematic investigation.

Researchers recommend studying more sites to further evaluate the relationship between the length of ingress/egress areas and their proximity to neighboring on- or off-ramps as well as the effect of a buffer.

**"HOV Lane Configurations and Collision Distribution on Freeway Lanes: Investigation of Historical Collision Data in California,"** Koohong Chung, Ching-Yao Chan, Kitae Jang, David Ragland, Yong-Hee Kim, *TRB 86th Annual Meeting Compendium of Papers DVD,* Paper #07-3276.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01049582.html
In this paper, historical data over a 10-year period from a number of freeway corridors were used to illustrate the distribution of collisions on different lanes on the freeway. Peak hours' data, when compared to those in nonpeak hours, from all corridors support the hypothesis that more interactions due to traffic weaving near the HOV lanes led to a greater concentration on the inside lanes of the corridors. A comparison of corridors with continual access with those with dedicated ingress/egress sections indicates that the restricted entrance and exit into HOV lanes likely caused more intense and challenging lane-changing actions and subsequently a greater proportion of collisions near the HOV lanes.

**"Case Study of Safety Analysis on Interstate 66 Freeway Managed Lane Operations,"** Jung-Taek Lee, Randy Dittberner, Hari Sripathi, *Managing Congestion—Can We Do Better? ITE 2007 Technical Conference and Exhibit*.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01076805.html
The Virginia Department of Transportation operates a time-of-day freeway managed-lane system on Interstate 66 that restricts the inner-left lanes to HOV only and opens the right shoulders for general traffic operations during peak hours on weekdays. The typical conventional crash rate analysis shows that crash rates are about four to seven times greater during managed-lane operations than during other times. This paper describes a comprehensive safety analysis, including conventional crash rate analysis and predictive model development, conducted for the study area that used three years of recent crash data. Results include:

- A lane type-specific analysis identified congestion and driver behavior in merging and diverging areas during adverse light conditions as contributing factors to crash occurrence rather than the effect of the managed-lane system.
- The variable AADT volumes appear to be significant, resulting in about a 2 percent increase in weekday crashes for each increase of 1,000 vehicles per day.

- Motorist behavior in lane changing at the merge and diverge influence areas during adverse light conditions appears to be significant, resulting in about a 38 percent increase in crashes in these areas.

## Vehicle-Related Factors

**Mirror Size and Lane-Change Crashes**, Michael Sivak, Joel Devonshire, Michael J. Flannagan, Matthew P. Reed, University of Michigan Transportation Research Institute, May 2008.
http://deepblue.lib.umich.edu/bitstream/2027.42/58738/1/100958.pdf
This study examined the relationship between the size of the driver-side outside mirror and the frequency of lane-change crashes. Results indicate that the relative likelihood of lane-change crashes was not related to the width, height or area of the driver-side mirror. The most likely reason for this finding is that the effective field of view was not related to mirror size.

**Body-Pillar Vision Obstructions and Lane-Change Crashes,** Michael Sivak, Brandon Schoettle, Matthew P. Reed, Michael J. Flannagan, The University of Michigan Transportation Research Institute, September 2006.
http://deepblue.lib.umich.edu/bitstream/2027.42/58719/1/99778.pdf
This exploratory study investigated the relationship between vision obstructions from body pillars and lane-change crashes. Results indicate that the relative frequency of lane-change crashes tended to increase with both wider A-pillars and A-pillars located farther away from straight ahead. This finding supports the hypothesis that visibility obstructions due to A-pillars have safety implications.

# Countermeasures

Below we highlight research relating to countermeasures intended to improve safety on freeways. There is a wealth of information on this topic, and the studies below that focus on high-risk locations, lighting, signage and variable speed limits represent only a sampling of the available research on countermeasures.

Additional information about countermeasures—from a broad perspective and with a focus on recommended treatments—can be found in the Preliminary Investigation *Crash Reduction Factor (CRF) Update* at http://www.dot.ca.gov/research/researchreports/preliminary_investigations/docs/final_crf_update_pi_02-17-09.pdf. FHWA's September 2008 publication *Desktop Reference for Crash Reduction Factors* describes a CRF as "the percentage crash reduction that might be expected after implementing a given countermeasure." We also contacted selected state DOTs to inquire about their application of countermeasures on complex freeways.

**Crash Causal Factors and Countermeasures for High-Risk Locations on Multilane Primary Highways in Virginia,** Chase R. Buchanan, Nicholas J. Garber, Young-Jun Kweon, Virginia Department of Transportation, VRTC Report No. 09-r15, 2009.
http://www.virginiadot.org/vtrc/main/online_reports/pdf/09-r15.pdf
The purpose of this study was to identify causal factors and appropriate countermeasures for crashes occurring at high-risk locations on multilane primary highways in Virginia from 2001 through 2006. The 365 study sites, 1 to 2 miles in length, were located on rural and urban highways with divided, undivided and traversable medians. Models were developed for rear-end crashes, total crashes, injury crashes, property damage only (PDO) crashes, and injury + PDO crashes. Potential countermeasures were identified based on the significant causal factors identified in the models. Results indicate:

- Rear-end crashes were the predominant type of crash, representing 56 percent of all PDO crashes on urban divided highways and 37 percent of all PDO crashes on rural divided highways.
- Implementing the recommended countermeasures for total, rear-end and angle crashes is expected to result in a crash reduction of up to about 40 percent depending on the site and level of rehabilitation undertaken.
- A benefit/cost analysis showed that the benefit/cost ratios were higher than 1 for all levels of countermeasure implementation.

**Quantifying the Performance of Countermeasures for Collision Concentration Related to Ramp/Freeway Mainline Junctions**, Joon ho Lee, Ching-Yao Chan, David R. Ragland, California PATH Research Report UCB-ITS-PRR-2009-4, January 2009.
http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2009/PRR-2009-04.pdf
This report describes a study that used before-and-after analyses of the collision rate at nine study sites in California to compare collisions before and after the construction of auxiliary lanes. The objective of the study was to quantify the effectiveness of different types of countermeasures installed near freeway ramps by estimating the freeway CRF for auxiliary lanes. The study also developed design guidelines for constructing auxiliary lanes.

Findings include:

- The construction of auxiliary lanes was found to reduce the collision rate at six out of nine study sites. On average, the collision rate decreased by 31 percent.
- For two sites, outside factors resulted in increases in collision rates after construction.
- Construction of auxiliary lanes may not be appropriate if:
    - The potential site has high ramp flows with congestion.
    - Construction is likely to form a lane-drop bottleneck.

**"Crash Risk Assessment Using Intelligent Transportation Systems Data and Real-Time Intervention Strategies to Improve Safety on Freeways,"** Mohamed Abdel-Aty, Anurag Pande, Chris Lee, Vikash Gayah, Cristina Dos Santos, *Journal of Intelligent Transportation Systems,* Vol. 11, No. 3, 2007, pages 107-120.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01055217.html
Using historical data, this study sought to identify conditions under which drivers are more likely to make mistakes that lead to crashes, and propose proactive real-time countermeasures that can lead to a reduction in crashes. Researchers identified crash-prone conditions on the freeway mainline and ramps using loop detector data. Two models were used to assess crash risk occurring under two speed regimes: high-to-moderate and low speed. Findings include:

- Higher speed upstream of a ramp and lower speed downstream of a ramp increase the probability of crashes on off-ramps. In contrast, lower speed upstream of a ramp and higher speed downstream of a ramp increase the probability of crashes on on-ramps.
- Lower ramp volume contributes more to crash occurrence on off-ramps, whereas higher ramp volume contributes more to crash occurrence on on-ramps.
- Abrupt reduction in speed limit by 15 mph two miles directly upstream and raising the speed limit by 15 mph two miles directly downstream of the station of interest reduced the crash potential most efficiently for moderate- to high-speed situations. More modest changes in speed also produced positive results.
- For low-speed situations, allowing vehicles to enter the mainline using smaller amounts of green time during shorter cycle lengths for seven consecutive on-ramps in the network provided the best results.
- Speed management on off-ramps (such as in-road lights) and the warning of an impending queue using variable message systems on on-ramps are potential countermeasures that can be suggested based on the findings.

## Lighting

**Evaluation of Innovative Safety Treatments, Volume 6: A Study of the Effectiveness of In-roadway Lights,** Vivek Reddy, Tapan Datta, Satya Pinapaka, Florida Department of Transportation, Report No. 40502-PL-004-001, January 2008.
http://www.dot.state.fl.us/research-Center/Completed_Proj/Summary_SF/BD500/BD500_v6_rpt.pdf
In November 2004, the Florida Department of Transportation installed a series of in-roadway lights along the off-ramp from southbound I-95 to westbound State Road 84 in an effort to reduce travel speeds and improve motorist safety. The in-roadway lights were linked with a speed detection system, which would illuminate the lights when the approaching vehicle's speed was detected to be greater than the preset speed of 50 mph. A before-and-after evaluation plan was used to determine the effectiveness of in-roadway lights on travel speeds and crashes. Results indicate that use of in-roadway lights reduced vehicular speeds by 2 mph to 7 mph but did not have a substantial impact on crashes at the study intersection.

## Signage

**"Analysis of Crashes on Freeway Ramps by Location of Crash and Presence of Advisory Speed Signs,"** Chris Lee, Mohamed Abdel-Aty, *Journal of Transportation Safety & Security,* Vol. 1, No. 2, 2009, pages 121-134.
Abstract: http://www.informaworld.com/10.1080/19439960902735329
In this study, records of crashes that occurred on 98 ramps of a 25-mile section of the Interstate 4 freeway in the Orlando, FL, metro area were used in models to identify the relationship among the frequency of ramp crashes, ramp geometry and ramp traffic volume. Models were also developed to observe the frequency of a specific type of ramp crash in terms of ramp curvature, number of vehicles involved in crashes and collision type.

Model results indicate:

- Crash characteristics differed for ramp-related and ramp intersection-related crashes.
- The presence of advisory speed signs potentially reduces the likelihood of crashes on off-ramps and rear-end crashes on ramps.
- Female drivers, single-vehicle crashes and shorter ramp length are correlated with higher probability of fatal and severe crashes on ramps.

**"Modeling Lane Change Distance for Sign Placement,"** Fengxiang Qiao, Xiaoyue Liu, Lei Yu, *TRB 87th Annual Meeting Compendium of Papers DVD,* Paper #08-1940.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01099208.html
This paper proposes a model that uses lane-change distance to derive sign placement. Instead of statically determining sign placement, the proposed methodology takes various factors into consideration, including traffic flow characteristics, highway geometries and vehicle interactions. Using reasonable assumptions based on drivers' vision, the methodology estimates advance distance of guide sign placement under prevailing traffic conditions and can be used as a supplemental reference to MUTCD for more efficient placement of guide signs.

## Variable Speed Limits

**"Testing Effects of Warning Messages and Variable Speed Limits on Driver Behavior Using Driving Simulator,"** Chris Lee, Mohamed Abdel-Aty, *Transportation Research Record,* Vol. 2069, 2008, pages 55-64.
Abstract: http://dx.doi.org/10.3141/2069-08
This study examines the effect of warning messages and variable speed limits (VSLs) on driver speed. Using a driving simulator, the study observed the behavior of 86 participants who drove a five-mile section of a freeway. Three types of warning messages were displayed in variable message signs to warn of an impending speed change. Drivers were typically required to reduce speed first and then increase speed according to VSLs. Findings include:

- Participants generally followed warning messages and VSLs under congested conditions or when speed limits were gradually reduced, which led to significant reductions in the variations in speed that can lead to high crash risk.
- Drivers tended to increase speed immediately after the speed limit increased and they departed from a congested area.
- A drivers' response to a message or VSL at one sign is closely related to their response to messages or VSLs at subsequent signs.
- A message that warns drivers of impending dangerous traffic conditions rather than strict law enforcement significantly increases drivers' acceptance of speed limits.

Suggestions/recommendations arising from this study include:

- Warning messages and reduced VSLs should be displayed upstream of congested areas only when congestion occurs.
- Speed limits should be gradually reduced over longer distances, rather than abruptly.
- Speed limits downstream of congested areas should be increased to meet drivers' need of travel time compensation and also facilitate drivers' departure from congested areas to prevent the growth of congestion.

- Field experiments should be performed to observe whether drivers display similar behavior on real freeways.

**"Dynamic Variable Speed Limit Strategies for Real-Time Crash Risk Reduction on Freeways,"** Mohamed A. Abdel-Aty, Ryan John Cunningham, Vikash V. Gayah, Liang Hsia, *Transportation Research Record*, Vol. 2078, 2008, pages 108-116.
Abstract: http://dx.doi.org/10.3141/2078-15
Recent research involving crashes on Interstate 4 in Orlando, FL, led to the creation of new statistical models capable of determining freeway crash risk in real time. VSL strategies were used in a networkwide attempt to reduce rear-end and lane-change crash risks where speed differences between upstream and downstream vehicles were high. Findings include:

- Implementation of VSLs successfully reduced rear-end and lane-change crash risks at low-volume traffic conditions (60 percent and 80 percent loading conditions).
- The most successful treatments involved lowering upstream speed limits by 5 mph and raising downstream speed limits by 5 mph.
- Lowering upstream and raising downstream speed limits was found to be resistant to the effects of crash migration in free-flow conditions.
- Treatments implementing speed limit changes upstream and downstream over half the length of the speed zones, although unable to effectively reduce rear-end and lane-change crash risks, were more resistant against the effects of crash migration than other treatments.
- No treatment was found to successfully reduce the rear-end and lane-change crash risks in the congested traffic condition (90 percent loading).

**"Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications,"** Peter Allaby, Bruce Hellinga, Mara Bullock, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 8, No. 4, 2007, pages 671-680.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01087693.html
This paper presents the results of an evaluation of a candidate VSL system (VSLS) for an urban freeway in Toronto, Ontario, Canada. The original VSL control algorithm achieved safety improvements for heavily congested (peak period) and moderately congested (near-peak period) traffic conditions, but a new reduction in safety resulted for uncongested conditions (off-peak period). The use of VSLSs also increased travel times for all traffic scenarios considered. While modifications to the original VSL control algorithm were successful in achieving significant additional safety improvements and reductions in the increase of travel times, a strategy could not be identified that provided consistent and positive impacts for both safety and travel time under all degrees of congestion.

**"Assessing Safety Benefits of Variable Speed Limits,"** Chris Lee, Bruce Hellinga, Frank Saccomanno, *Transportation Research Record*, Vol. 1897, 2004, pages 183-190.
Abstract: http://dx.doi.org/10.3141/1897-24
In this study, a real-time crash prediction model that was developed in earlier studies was integrated with a microscopic traffic simulation model to estimate crash potential for different control strategies of VSLs. The study found that VSLs can reduce average total crash potential by temporarily reducing speed limits during risky traffic conditions. Findings include:

- Short-duration intervention of 2 minutes results in increased crash potential because of the more frequent speed limit changes. An intervention duration of 5 to 10 minutes was found to maximize safety benefits.
- Reductions in speed limits—whether fixed or variable—appear to provide safety benefits through reduced crash potential. However, reductions in speed limits also increase system travel time.
- The greatest reduction in crash potential occurs at the location of high traffic turbulence, such as downstream of merging locations.
- This study verified that as speed limits are reduced, the speed deviation of individual vehicles from the mean speed decreases.
- Researchers recommend that the model be calibrated and validated by using real traffic data to ensure that the simulation reflects real-world traffic conditions.

**“Evaluation of Variable Speed Limits in the St. Louis, Missouri, Metropolitan Area,”** Missouri University of Science and Technology, expected completion date November 30, 2010.
http://rip.trb.org/browse/dproject.asp?n=21962
Sponsored by the Missouri Department of Transportation, this project in process will investigate the effectiveness of the VSL systems installed on Interstate 270 and Interstate 255 that combine changeable message sign technology with speed limit signs by comparing traffic flow performance measurements before and after VSL implementation. Performance measures will include speeds, volume, travel time, crash rates and incident delays.

## Informal Survey of State Practice

We contacted state DOTs to inquire about their experience with countermeasures to improve safety on high-speed, multilane, urban highways with frequent or unconventional access. We limited our contacts to those states most likely to maintain complex roadways like those described above. Our informal survey involved five states: Arizona, Illinois, Massachusetts, Nevada and Texas.

### Arizona

Contact: Mike Manthey, State Traffic Engineer, Arizona Department of Transportation, (602) 712-8888, MManthey@azdot.gov.

Projects, programs or initiatives include:

- Some time ago Arizona implemented lane markings on freeway ramps. Supplemental pavement markings are used to aid drivers when two lanes go off to a ramp that leads to another freeway. Six-inch-wide striping is most commonly used; 12-inch-wide striping is used to provide emphasis with dashed lines.
- Route shields or numbers are included as pavement markings to clearly identify lanes.
- Shared lanes have been restriped as dedicated lanes. Auxiliary lanes are used as a dedicated lane that becomes an off-lane for the next ramp.
- Cameras typically used in photo enforcement are deployed in nonpeak times to gather information at interchanges with high crash concentrations. Three cameras, placed two miles apart, are deployed at each interchange; signs are placed a half-mile and 300 feet before each camera. A research study that will use data gathered by the camera deployment is just getting under way.
- Overhead guide signage is being refined by considering possible locations for placement of down arrows and lane assignment signage. Guide signs at the two-mile, one-mile and half-mile markers are used rather than signage only at the half-mile marker.
- There is interest in early imposition of the provisions for larger signs that are proposed for the 2009 update to the Manual on Uniform Traffic Control Devices.

A February 10, 2009, PowerPoint presentation, “Traffic Engineering Countermeasures to Improve Safety,” is included as Appendix B. Appendix C contains images that provide examples of Arizona’s pavement markings and signage.

### Illinois

Contact: Priscilla A. Tobias, State Safety Engineer, Illinois Department of Transportation, (217) 782-3568, Priscilla.Tobias@illinois.gov.

Illinois has used offset right- and left-turn lanes, continuous flow lanes, signal timing and ramp metering to address high-crash locations on its freeways. More detailed information about countermeasures employed in the Chicago area is available from Steve Travia, Bureau Chief of Traffic, District 1, (847) 705-4141, Steve.Travia@illinois.gov.

### Massachusetts

Contact: Thomas Broderick, Deputy Chief Engineer for Safety and Mobility, Massachusetts Highway Department, (617) 973-7847, thomas.broderick@mhd.state.ma.us.

Countermeasures emphasize addressing lane departure with rumble strips and cable guardrail; rollover crashes caused by outdated roadway geometry are addressed with signage. Countermeasures are often employed to address congestion rather than crashes. Electronic message boards are frequently used in connection with HOV lanes, and black-on-yellow or black-on-white signs are used to identify the beginning and ending points of five locations where shoulders are used for roadway traffic during peak times. The state is installing overhead message boards on major roadways and starting to deploy variable-length solar-powered arms to protect lanes and move traffic when maintenance employees are using lanes.

**Nevada**

Contact: Chuck Reider, Principal Safety Engineer, Nevada Department of Transportation, (775) 888-7335, creider@dot.state.nv.us.

Las Vegas is the only location that meets the criteria under consideration, and a pattern has not been identified for crashes in this corridor. The safety implications for complex interchanges are considered during the design phase. Express lanes have been used as one option to separate lanes, and signage is reviewed for its effectiveness in identifying lanes and exits for drivers. Reider noted that Nevada's RSA program has reviewed complex interchanges; likely recommendations to improve safety include adding an express lane.

**Texas**

Contact: Margaret (Meg) A. Moore, Director, Traffic Engineering Section, Texas Department of Transportation, (512) 416-3135, mmoore1@dot.state.tx.us.

Countermeasures used in Texas include merge lanes as a continuous-access lane that drops off as an exit lane, restriping of roads to provide an additional lane and take away the shoulder, pavement markings that provide the route shield in lanes to help drivers better identify lanes, high-mast lighting at interchanges, and establishment of dual exits on ramps. Additional information about modeling and reconstruction scenarios that are conducted by district offices is available from:

Dallas area: Kelly Selman, (214) 320-6189
Houston District: Stuart Corder, (713) 802-5171
San Antonio District: Rick Castaneda, (210) 615-6134

## Tools and Strategies to Improve Traffic Operating Conditions

The reports and articles highlighted below present a variety of strategies to improve traffic operating conditions, including the development of a crash likelihood estimation model in Minnesota; an analysis of the relationship between the number of lanes and safety; as assessment of the effects of on-ramps on mainline operations; and the design of freeway speed-change lanes.

**Accident Prevention Based on Automatic Detection of Accident Prone Traffic Conditions: Phase I**, John Hourdos, Vishnu Garg, Panos G. Michalopoulos, Intelligent Transportation Systems Institute, University of Minnesota, CTS Report No. 08-12, September 2008.
http://www.cts.umn.edu/Publications/ResearchReports/pdfdownload.pl?id=984
This report describes a crash likelihood estimation model for high-crash areas based on a detection and surveillance infrastructure deployed on the freeway section experiencing the highest crash rate in the state of Minnesota. This state-of-the-art infrastructure allowed video recording of 110 live crashes, crash-related traffic events as well as contributing factors while simultaneously measuring traffic variables such as individual vehicle speeds and headways over each lane in several places inside the study area.

**"Exploratory Analysis of Relationship Between the Number of Lanes and Safety on Urban Freeways,"** Jake Kononov, Barbara A. Bailey, Bryan K. Allery, *TRB 87th Annual Meeting Compendium of Papers DVD,* Paper #08-0621.
http://diexsys.com/PDF/08-0621.pdf
In this paper, researchers describe an exploratory analysis of the safety performance functions (SPF) for multilane freeways in Colorado, California and Texas that suggests adding lanes may initially result in a temporary safety improvement that disappears as congestion increases. As AADT increases, the slope of SPF becomes steeper, indicating that accidents are increasing at a faster rate than would be expected from a freeway with fewer lanes. Researchers offer this possible explanation: "… as the number of lanes increases, the opportunities for lane-change-related conflicts also go up. As the number of lanes increases from two to five in one direction, the number of

potential lane-change-related conflict opportunities increases from two to 29. Additionally, increased maneuverability associated with availability of more lanes tends to increase average speed of traffic and speed differential."

**"Urban Freeway On-Ramps: Invasive Influences on Main-Line Operations,"** Hanwen Yi, Thomas E. Mulinazzi, *Transportation Research Record*, Vol. 2023, 2007, pages 112-119.
Abstract: http://dx.doi.org/10.3141/2023-12
The project described in this article sought to better understand the invasive influences of the freeway entry process to help promote efficient and safe operations of the mainline facility and identify more straightforward indicators of level of service for freeway on-ramp segments. Field observations conducted at three on-ramp sites along Interstate 35 within the greater Kansas City, KS and MO, metropolitan area, identified ramp merging behavior of vehicles in platoons as the direct cause of invasive influences on the freeway flow. Researchers evaluated the significance of the invasive influences in connection with the evasive events performed by freeway drivers, which include slowdown and lane-change maneuvers.

**"Design of Freeway Speed Change Lanes: Safety-Explicit Approach,"** Yasser Hassan, Abd El Halim Omar Abd El Halim, Mohamed Sarhan, *TRB 85th Annual Meeting Compendium of Papers DVD,* Paper #06-1937.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01024979.html
Freeway entrances and exits, whether located in a weaving or a nonweaving section, are among the areas that present the potential for errors in driver decision making that result in collisions. This paper presents modeling efforts to develop safety-explicit relationships for use in designing freeway speed-change lanes. The models are presented as design aids for the length of acceleration and deceleration lanes based on expected collision frequency.

# Collision Avoidance for Lane Changing

In the studies cited below, researchers examine sensor-based collision avoidance and communication systems that provide for communication between the drivers of individual vehicles and between drivers and the infrastructure—all in the interest of avoiding or reducing unsafe lane changes.

**"IMM-Based Lane-Change Prediction in Highways with Low-Cost GPS/INS,"** Rafael Toledo-Moreo, Miguel A. Zamora-Izquierdo, *IEEE Transactions on Intelligent Transportation Systems,* Vol. 10, No. 1, 2009, pages 180-185.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01142673.html
The authors propose an interactive multiple model (IMM)-based method for predicting lane changes on highways. The lane-prediction system is based on Global Positioning Systems and Inertial Navigation System sensors. Two models describing different dynamics are used to define the maneuver states "change lane" and "keep lane." Results from trials in highway scenarios show the capability of the system to predict lane changes in straight and curved road stretches with very short latency times.

**"Vehicle Infrastructure Integration-Based Highway Lane Change Warning System for Collision Prevention,"** Yi Qi, Bin Wang, Xin Chen, Lei Yu, *TRB 88th Annual Meeting Compendium of Papers DVD,* Paper #09-2400.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01123057.html
The vehicle infrastructure integration (VII) program involves enhancing the communication between drivers of individual vehicles and between drivers and the infrastructure by using a widely deployed communication system known as dedicated short-range communications. This paper describes the design and testing of a VII-based highway lane change warning system in a driving simulator experiment using an urban highway scenario. Tested drivers found the system easy to use and helpful in making safe lane changes. Test results show that the system helps drivers avoid unsafe lane changes and has the potential to reduce collisions.

**Towards Evolution of Collective Sensory Systems for Intelligent Vehicles,** Yizhen Zhang, Karl Grote, METRANS Transportation Center, California State University, Long Beach, California Department of Transportation, Project Number USC PO 100821, June 2006.
http://www.metrans.org/research/final/04-03%20Final.pdf
This report covers research conducted on sensor-based collision avoidance during freeway lane-changing maneuvers. The first part of the report discusses theoretical work on the modeling of collision avoidance systems

(CAS). Models are compared and modifications suggested, and potential scenarios for CAS are outlined. The second part of the report presents a validation of the theory using a test vehicle outfitted with sensors. Researchers offer an analysis of possible sensor alternatives, discuss criteria for sensor selection and make sensor recommendations.

## In-Vehicle Technologies

The articles and reports below highlight in-vehicle communication and information technologies that alert drivers about driving conditions that can lead to collisions during lane changes and other driving maneuvers.

**"In-Vehicle Data Recorders for Monitoring and Feedback on Drivers' Behavior,"** Tomer Toledo, Oren Musicant, Tsippy Lotan, *Transportation Research Part C: Emerging Technologies*, Vol. 16, No. 3, 2008, pages 320-331.
Abstract: doi:10.1016/j.trc.2008.01.001
In this paper, researchers describe the potential of in-vehicle data recorder (IVDR) systems to be used in various commercial and research applications as tools to monitor and provide feedback to drivers on their on-road behavior. The system described in this paper records the movement of the vehicle and uses this information to identify and classify various maneuvers the vehicle performs. These maneuvers are then used to calculate various driving risk indices. Drivers receive feedback through various summary reports, real-time text messages or an in-vehicle display unit. A study of crash rates in the period before system installation and after drivers were exposed to IVDR feedback shows large and statistically significant reductions in crash rates.

**"Lane Change Behavior with a Side Blind Zone Alert System,"** Raymond J. Kiefer, Jonathan M. Hankey, *Accident Analysis & Prevention,* Vol. 40, No. 2, 2008, pages 683-690.
Abstract: doi:10.1016/j.aap.2007.09.018
This in-traffic study explored the effect of a side blind zone alert (SBZA) system on driver lane-change behavior. Drivers failed to execute over-the-shoulder—or blind zone—glances for 68 percent and 85 percent of the left and right lane changes, respectively. These results suggest that the SBZA display provides information that the driver often fails to obtain with over-the-shoulder glances. When the SBZA system was enabled, there was a 31 percent reduction in left lane changes attempted without the driver checking the left mirror, and a 23 percent reduction in right lane changes attempted without the driver checking the inside mirror.

**"A Methodology on the Automatic Recognition of Poor Lane Keeping,"** Banihan Gunay, *Journal of Advanced Transportation*, Vol. 42, No. 2, 2008, pages 129-149.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01087700.html
This paper provides a theoretical description of an automatic detection system to recognize irregular lateral vehicle movements resulting from various forms of dangerous driving. The system is based on establishing certain threshold values for normal driving patterns and checking given traffic instances against these criteria.

**"Analysis of Vehicle Positioning Accuracy Requirements for Communication-Based Cooperative Collision Warning,"** Steven E. Shladover, Swe-Kuang Tan, *Journal of Intelligent Transportation Systems,* Vol. 10, No. 3, 2006, pages 131-140.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01036015.html
This article describes an analysis of the use of vehicle positioning and wireless communication technologies to implement a collision warning system without using direct ranging sensors. Analyses are reported for forward collision warnings, lane-change warnings and several intersection conflict scenarios. The most demanding accuracy requirements are associated with identifying whether a target vehicle is in the path of the subject vehicle.

**"Efficiency of Simulated Vehicle-to-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor,"** Hao Wu, Jaesup Lee, Michael Hunter, Richard Fujimoto, Randall L. Guensler, Joonho Ko, *Transportation Research Record,* Vol. 1910, 2005, pages 82-89.
Abstract: http://dx.doi.org/10.3141/1910-10
Vehicle-to-vehicle communication may be considered for applications such as incident detection, crash reporting, traveler information dissemination and network operations. These systems allow coverage to extend beyond areas where roadside equipment has been placed. Using a study area along the Interstate 75 freeway in the Atlanta, GA, area during peak or high-density traffic periods, researchers found that message propagation delay is highly variable

except when vehicle density becomes saturated. For applications requiring highly reliable, minimal message propagation times, it may be necessary to design networks that provide extra support to avoid such variations.

**"Verbal Collision Avoidance Messages of Varying Perceived Urgency Reduce Crashes in High Risk Scenarios,"** Carryl L. Baldwin, Jennifer F. May, *Driving Assessment 2005: 3rd International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.
Abstract: http://ntlsearch.bts.gov/tris/record/tris/01006747.html
This driving simulation investigation examined crash avoidance behaviors in high-risk driving situations and crash rate reduction as a function of exposure to different types of verbal CAS messages. CAS messages varied in presentation level (PL) and signal word. Post-drive ratings of perceived urgency (PU), alerting effectiveness and annoyance were also examined. The type of CAS warning resulted in significant differences in appropriate crash avoidance behaviors and crash rates. The most effective CAS warnings were those of moderate PU, specifically the low PU signal word "notice" presented at high PL, and the high PU signal word "danger" presented at low PL.

**APPENDIX A: National Safety Engineers Listserv Survey Results**

**Hawaii**
Contact: Sean Hiraoka, Traffic Safety Engineer, Hawaii Department of Transportation, (808) 692-7684, Sean.Hiraoka@hawaii.gov.

Hawaii does not have Multidisciplinary Accident Investigation Teams (MAIT). Accident investigations are conducted by the County Police Departments. There was a bill in a recent Hawaii Legislative session that pushed for MAITs, but it died.

**Illinois**
Contact: Priscilla A. Tobias, State Safety Engineer, Illinois Department of Transportation, (217) 782-3568, Priscilla.Tobias@illinois.gov.

Illinois has trained all crash reconstruction officers with the Illinois State Police (ISP) in Road Safety Assessments. ISP has been revising their crash reconstruction policy manual to incorporate RSAs into their processes. A law enforcement representative is included in all RSAs. We have trained several local law enforcement representatives also.

**Iowa**
Contact: Tom McDonald, Safety Circuit Rider, Institute for Transportation, Iowa State University, (515) 294-6384, tmcdonal@iastate.edu.

In response to an inquiry from Caltrans Safety Engineer Jesse Bhullar, I would advise that we have conducted a series of crash reviews on selected roadways in Iowa as part of our road safety audit process. While these activities may not be as detailed as what you might have in mind, these audits are multidisciplinary in nature, always including law enforcement officers and sometimes other disciplines as well. In-depth crash data is available for review and field conditions are examined in detail by the audit team. Contributing factors are considered in determining feasible mitigation for identified crash characteristics.

If you are interested and desire more information about the Iowa program for safety audits, please contact me at your convenience and I can provide more details and reports from past audits.

**Minnesota**
Contact: David B. Engstrom, State Traffic Safety Engineer, Minnesota Department of Transportation, (651) 234-7016, David.Engstrom@dot.state.mn.us.

There isn't an easy answer to your question, but I will attempt to describe what Minnesota does in general. If you have some follow-up questions, you could give me a call.

1. Road Safety Audits. We have done a number of audits utilizing a variety of differing expertise, but primarily it's engineering and enforcement who are prominently represented. We do these by request (haven't done one for over six months), and they usually are driven by a political need. A report is generated with recommendations that the responsible jurisdiction must respond to.

2. Road Safety Plans. We have just started developing detailed safety plans for all of our 87 counties and eight Mn/DOT districts. These plans will generate a prioritized list of low-cost systematic safety improvement projects for each jurisdiction. These will be driven by data and countermeasures that work and are acceptable to each jurisdiction. A workshop will be conducted for each jurisdiction. Expertise from the 4 Es [engineering, enforcement, education and emergency services] and beyond will be invited to participate and provide their expertise in developing priorities for each plan.

3. Local Fatal Review Committees/Teams. A number of counties/districts have created these teams which meet on a regular basis to discuss fatal crashes and potential solutions for them. My office (Central Office Traffic) has not been involved in these meetings. The extent to which they generate safety projects is unknown.

**Mississippi**

Contact: Jim Willis, Safety Engineer, Mississippi Department of Transportation, jcwillis@mdot.state.ms.us.

MS has not used this approach.

**Missouri**

Contact: John P. Miller, Traffic Safety Engineer, Missouri Department of Transportation, (573) 526-1759, John.P.Miller@MoDOT.mo.gov.

In Missouri, we are beginning to use Road Safety Assessments to evaluate safety issues at both segments and intersections where we have had severe crashes. The team often consists of District safety representatives, a Central Office safety representative and local law enforcement and other safety representatives that can help identify the real issues. We believe this is a reactive strategy, but something that can still help us bring down fatalities and disabling injuries on our roadways.

Another strategy we have been using relates to systemwide safety solutions. We feel we can be proactive in bringing down the fatalities and disabling injuries by trying to eliminate certain problem crash types. We know that our problems are run-off-road crashes, curve-related crashes, impaired driving, seat belt usage and aggressive driving. While we do continue to work on the behavioral issues, we have put a heavy emphasis on keeping the vehicles in their lane. We have installed well over a thousand miles of rumble strips (both edgeline and centerline) on our most traveled roadways. We have also improved the visibility of the roadway with better stripes (we paint the rumble) and other delineation. Additionally, we have installed over 600 miles of median guard cable in order to eliminate the cross-median crash problem (it has worked).

So while we are not necessarily using multidisciplinary crash investigation teams, we are using some other key strategies to drive down our severe crashes.

**Nevada**

Contact: Chuck Reider, Principal Safety Engineer, Nevada Department of Transportation, creider@dot.state.nv.us; Jaime Tuddao, Senior Road Safety Engineer, Nevada Department of Transportation, jtuddao@dot.state.nv.us.

NDOT does not have a multidisciplinary crash investigation process, but we do have a Road Safety Audit multidisciplinary program that performs audits on NDOT road improvement projects as well as "ad hoc." The latter audit typically comes as a request from our administration, district office, or even the public to investigate high-crash locations (or sometimes perceived high-crash locations). If you are interested in more information please contact NDOT's RSA Coordinator Jaime Tuddao.

**New York**

Contact: Donald Terry, Safety and Security Planning & Development Bureau, New York State Department of Transportation, (518) 457-1926, dterry@dot.state.ny.us.

New York State Department of Transportation has very little experience in the use of multidisciplinary teams in conducting crash investigations. Just about all of our investigations are limited to interdepartmental disciplines with design, maintenance and operational expertise. There has only been only one instance that I am aware of where an investigation was conducted concerning an older pedestrian crash location where advocates for the elderly (AARP and the Health Department) had limited involvement.

**Oklahoma**
Contact: David Glabas, Traffic Safety Engineer, Oklahoma Department of Transportation, (405) 521-2861, dglabas@odot.org.

Oklahoma is just starting with Road Safety Audit teams. We are putting together a standard program which will include multidisciplinary teams, and for now will only consist of ODOT, FHWA, local law enforcement, OK Highway Safety Office and OK Highway Patrol. We should have more experience in another year.

**Pennsylvania**
Contact: Girish N. Modi, Division Chief, Bureau of Highway Safety & Traffic Engineering, Pennsylvania Department of Transportation, (717) 783-1190, gmodi@state.pa.us.

We do not have multidisciplinary crash investigation teams in Pennsylvania.

**Texas**
Contact: Meg Moore, Texas Department of Transportation, MMOORE1@dot.state.tx.us.

Does your agency conduct multidisciplinary crash investigations? No.

**Virginia**
Contact: Lori G. Rice, Team Leader & Psychologist, Virginia Multi-disciplinary Crash Investigation Team, Transportation Safety Training Center, Virginia Commonwealth University, (804) 828-1031, lgrice@vcu.edu.

Your address was referred to me by a Virginia Department of Transportation engineer who saw a request regarding multidisciplinary teams on a listserv. Please let me know what information you need for your survey. The VMCIT has been researching crashes in Virginia for about 35 years. Some recent reports can be found at the website linked below (http://www.vcu.edu/cppweb/tstc).

# Traffic Engineering Countermeasures to Improve Safety

Every One Counts Safety Summit
February 10, 2009

**Mike Manthey, P.E.**
State Traffic Engineer
Arizona Department of Transportation

# Roadway Departure

- Wider, durable pavement markings
- Reflective pavement markers
- Rumble strips
- Cable barrier
- Guardrail end treatments
- Roadside/guardrail delineators

# Intersections

- Signal heads
- Pedestrian countdown signals
- Access management
- Transverse rumble strips
- Street name signs
- Speed feedback signs
- Roundabouts

# Freeways

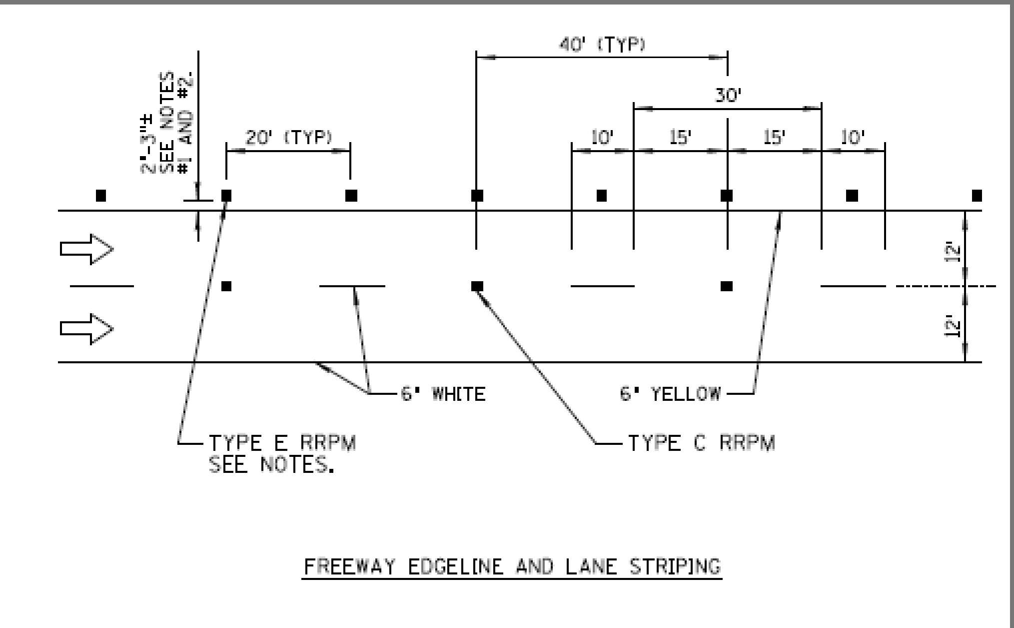
- Directional signing
- Route decals
- Lighting
- Raised pavement markers

# Pavement Markings

- 6-inch wide lane and edge lines
- Durable
- 3% CRF (from 4 to 6 inch)

# Reflective Pavement Markers (RPMs)

- 16% nighttime crashes
- Freeways: left edge line (20-foot spacing) and lane lines (40-foot)




# RPMs

- Recessed in groove for snowplow areas


# Rumble Strips

- 25% CRF head-on/sideswipe (centerline)
- 18 to 35% road departure (shoulder)


SPEED
LIMIT
45

# Cable Barrier

- 90% CRF for freeway cross-median crashes

# Guardrail End Treatments

- System-wide replacement of BCTs

# Roadside/Guardrail Delineators

- 25% CRF
- Initiating statewide roadside delineator project
  - Texas Transportation Institute spacing
  - Maintainable system

# Signal Heads

- Larger (42% CRF for angle crashes going from 8 to 12 inch LED lens)
- Backplates and visors (20% to 50% CRF)
- Optic (15% CRF)


PUSH
BUTTON
FOR


PUSH
BUTTON
FOR

# Pedestrian Countdown Signals

- 25% CRF for pedestrian crashes

# Access Management

- Statewide Access Management Plan being developed
- Raised medians 40 to 60% CRF

# Transverse Rumble Strips

- 28% CRF for stop condition

# Street Name Signs

- Easier to read
  - Clearview font
  - Capital and lower case letters
- Advance Street Name signs


Grand Ave


99th Ave

# Speed Feedback Signs

- Speed reductions of 5 mph
- Each 1 mph reduction in speed may reduce injury crashes by 5%

# Roundabouts

- 76% CRF for injury crashes
- 89% CRF for fatal/incapacitating injury crashes

# Directional Signing

- Lane assignments from 2 miles in advance


EXIT 176A
101 South
1 1/2 MILE
EXIT 176B
101 North
1/2 MILE
EXIT ONLY
EXIT 177
Dobson Rd
1/4 MILE

10 East
Tucson
EXIT ONLY
60 West 10
Phoenix

# Route Decals


# Lighting

- 20% CRF for nighttime crashes
- Replaced Type H and I breakaway light poles on interstates (high weight caused excessive vehicle damage)


# Other

# Other

# Other

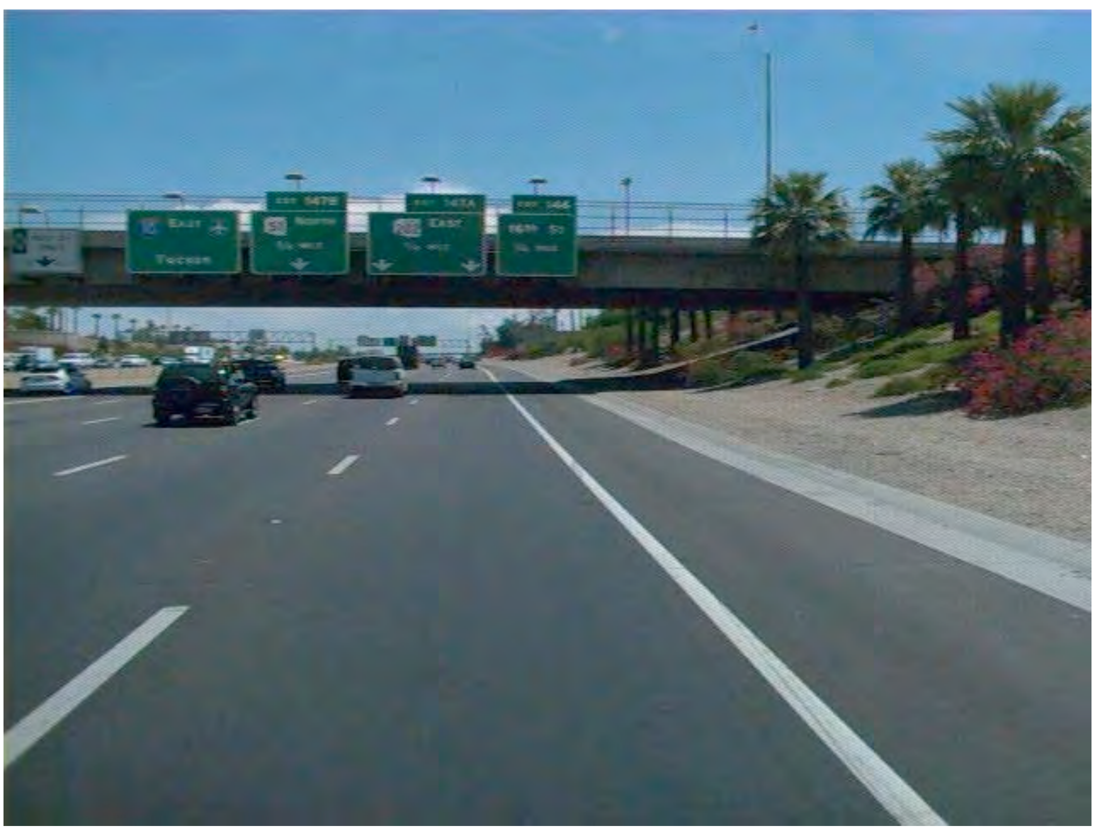
- Wrong-way movements

# Thank You!

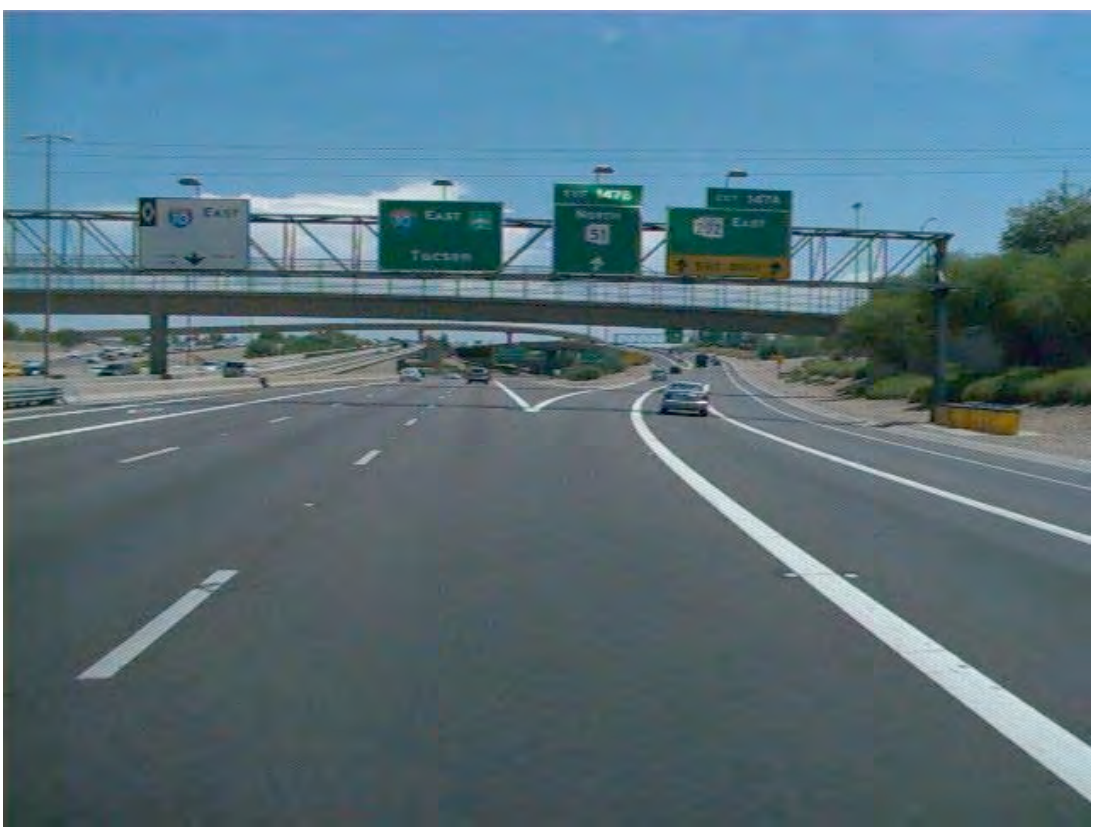
# Questions?

Contact for any additional information:
mmanthey@azdot.gov

**APPENDIX C: Images of Arizona Pavement Markings and Signage**



The sign in yellow is “Exit Only.” Auxiliary-lane striping begins at the point of this sign.



Note the auxiliary lane striping that confirms the "Exit Only" portion of the sign.

**APPENDIX C: Images of Arizona Pavement Markings and Signage**


This a sign with the larger route shields and legends as proposed in the new MUTCD.

## APPENDIX C: Images of Arizona Pavement Markings and Signage


I-10 West showing larger route shields for Interchange routes.