DEVELOPMENT OF OBJECTIVE TESTS FOR EVALUATING LANE-KEEPING/ROAD DEPARTURE DRIVER ASSISTANCE SYSTEMS

August Burgett
URC Enterprises Inc.,
United States
Raja Ranganathan
Gowrishankar Srinivasan
Rainbow Technologies Inc.,
United States
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ABSTRACT

This paper describes a step-by step process for the development of test procedures for pre-production driver assistance systems. The process begins with a detailed engineering description of system performance and utilizes a universal description of the causal factors and resulting crash types as the foundation for a detailed analysis of crash data. The process ends with a set of objectives test procedures that can be applied to pre-production driver assistance systems that address lane-keeping/road departure performance. The quantitative estimates were obtained from national crash databases, namely, 2004 General Estimating system (GES) and 2004 Fatality Analysis Reporting system (FARS). There were 10,945,000 vehicles involved in crashes in 2004, of which 1,114,000 and 977,000 vehicles were involved in multi-and single-vehicle lane-keeping/ road-departure type crashes, respectively. Other factors such as trafficway flow, alignment, curvature, and speed were also analyzed to determine appropriate test conditions.

The results provide separate test conditions for single-and multi-vehicle crashes. The tests for multi-vehicle crashes include testing vehicles traveling in both directions; same and in opposite directions. Tests for vehicles traveling in the same direction involve driving that simulates undivided multi-lane roads. Testing for vehicles traveling in opposite directions involves driving that simulates both straight and curved two-lane undivided roadways. Single-vehicle crashes involve one test that represents a curved two-lane undivided highway with a narrow shoulder and another that represents a multi-lane undivided highway with a shoulder having a parked vehicle. All tests involve a driver traveling at speeds between 30 and 50 mph.

This is the first application of the new crash-analysis-based process for developing test procedures. Additional challenges in performing the tests and using the results to estimate crash avoidance benefits are not discussed in detail in this paper

INTRODUCTION

As new safety-related technologies are introduced into motor vehicles, there is a need to be able to assess the safety impact prior to production. Meeting this need requires new evaluation procedures. This paper addresses one aspect of a new methodology that is being developed for this purpose. The overall methodology is summarized in Figure 1. The complete development and methodology is contained in a forthcoming report [1].

Each of the rectangles in Figure 1 represents an activity and each parallelogram represents an output. The overall process begins with the identification of a candidate system or technology. The intermediate steps or activities create a database that is then used in the final activity to estimate the safety benefit (reductions in the number of crashes, injuries and fatalities).

The activities in this methodology include:

Activity 1. Describe the system design and performance.

The output of this activity is a detailed engineering description of the system and its performance. The performance description from this activity is the starting point for the remainder of the process.

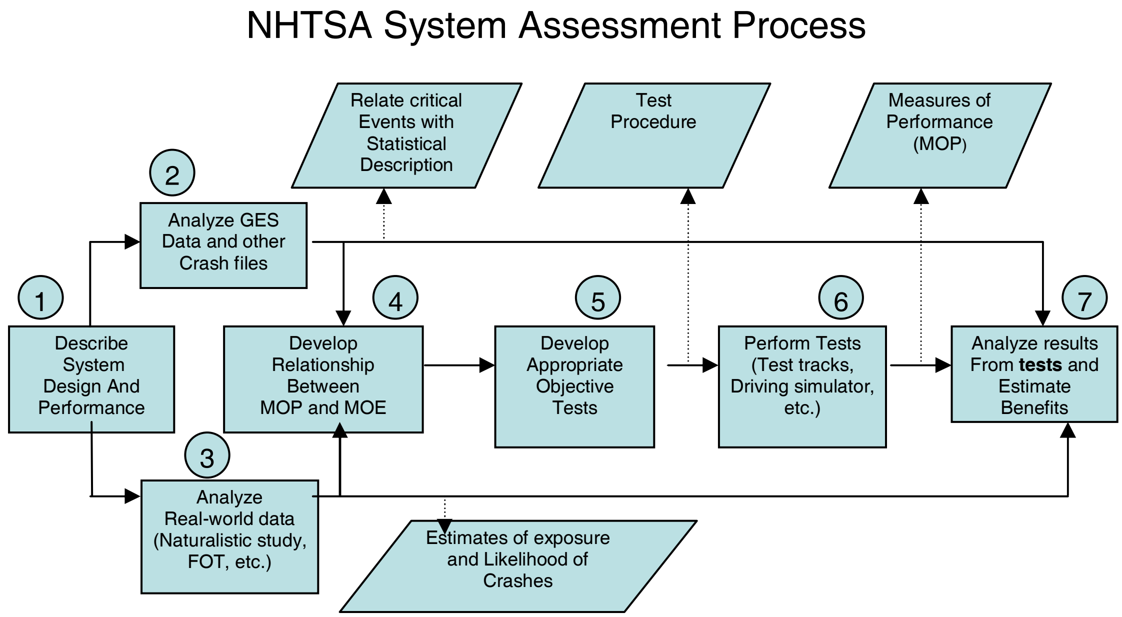

Figure1. Flowchart for NHTSA system assessment process.

Activity 2. Analyze GES and other crash data files.

The complete picture of the chain of events for each vehicle in the GES file (critical event, driver response, first harmful event) is summarized in Table 1. The Universal Description provides a high-level, but complete picture of crashes, the critical events that precede crashes, and how drivers try to prevent the crash. In this activity, variables and data elements are identified based on the performance description from Activity 1. The analyses in this activity are the foundation for most of the other activities.

Activity 3. Analyze real-world data such as naturalistic driving and field operational tests.

In this activity, data from naturalistic driving studies are analyzed to determine the level of exposure of critical events. The level of exposure from naturalistic driving data complements the results from analysis of the crash data files. These results are used for refining test conditions and for providing the baseline for estimating benefits.

Activity 4. Develop Relationships between Measures of Performance and Measures of Effectiveness.

The linkage between *Measures of Performance* from objective tests and *Measures of Effectiveness* is a key element of the benefit estimation process and quantifies how the system will assist drivers.

Activity 5. Develop Appropriate Objective Tests.

In this activity, test conditions for the system are developed. This activity is tightly coupled with Activity 2; and in practice, these two activities will probably be done simultaneously.

Activity 6. Perform tests.

In this activity, the tests developed in Activity 5 will be performed. The outcomes from these tests will include the Measures of Performance that are identified in Activity 4.

Activity 7. Analyze results from tests and estimate benefits.

This activity consolidates results from all of the preceding activities into the estimation of benefits.

Table 1.
Universal description: Showing the pre-crash critical event, crash avoidance maneuver, and type of crash for each crash-related vehicle (Imputed values from GES 2004)

Critical Event	Avoidance Maneuver \ First Harmful Event	Non-Collision	Collision with non-fixed object	Collision with fixed object	Total
Subject vehicle loss of control	No maneuver	99,000	54,000	262,000	415,000
	Braking	22,000	46,000	71,000	139,000
	Steering	38,000	16,000	47,000	101,000
	Braking and steering	5,000	2,000	7,000	14,000
	Accelerating/Others	0	0	2,000	2,000
	Total	**164,000**	**118,000**	**389,000**	**671,000**
Action by subject vehicle	No maneuver	25,000	2,284,000	195,000	2,504,000
	Braking	6,000	215,000	44,000	265,000
	Steering	64,000	109,000	89,000	262,000
	Braking and steering	3,000	12,000	7,000	22,000
	Accelerating/Others	1,000	26,000	2,000	29,000
	Total	**99,000**	**2,646,000**	**337,000**	**3,082,000**
Action by another vehicle in subject vehicle's lane	No maneuver	2,000	3,064,000	1,000	3,067,000
	Braking	3,000	721,000	6,000	730,000
	Steering	7,000	199,000	18,000	224,000
	Braking and steering	2,000	64,000	6,000	72,000
	Accelerating/Others	0	21,000	0	21,000
	Total	**14,000**	**4,069,000**	**31,000**	**4,114,000**
Encroachment by another in subject vehicle's lane	No maneuver	3,000	1,413,000	1,000	1,417,000
	Braking	7,000	482,000	6,000	495,000
	Steering	21,000	395,000	79,000	495,000
	Braking and steering	4,000	80,000	6,000	90,000
	Accelerating/Others	1,000	11,000	1,000	13,000
	Total	**36,000**	**2,381,000**	**93,000**	**2,510,000**
Pedestrian and other non-motorist	No maneuver	0	60,000	0	60,000
	Braking	0	30,000	0	30,000
	Steering	0	12,000	1,000	13,000
	Braking and steering	0	7,000	2,000	9,000
	Accelerating/Others	0	1,000	0	1,000
	Total	**0**	**110,000**	**3,000**	**113,000**
Object or animal	No maneuver	2,000	217,000	2,000	221,000
	Braking	1,000	91,000	2,000	94,000
	Steering	13,000	70,000	42,000	125,000
	Braking and steering	0	11,000	3,000	14,000
	Accelerating/Others	0	1,000	0	1,000
	Total	**17,000**	**390,000**	**48,000**	**455,000**
Grand Total		**330,000**	**9,716,000**	**899,000**	**10,945,000**

FOUNDATION FOR OBJECTIVE TESTS

The analysis in this paper addresses driver assistance systems that help drivers in lane change/ road departure situations. The analysis uses GES data and forms the foundation for defining objective tests. The methodology for developing objective tests that can be used to establish the safety-related performance of driver-assistance systems builds on data from crash data files. The process consists of the following three steps:

1. Select the subsets of the Universal Description that are relevant to the safety performance of the system being evaluated.

2. Consolidate the analysis of these subsets into basic test conditions.

3. Refine the test conditions, including consideration of distributions of crashes, injuries, and fatalities.

Step#1. Select the subsets of the Universal Description that are relevant to the safety performance of the system being evaluated.

The process for identifying test procedures for lane-keeping/road departure systems begins with a detailed analysis of critical events that precede these crashes.

From the Universal Description, the following groups of the Critical Event (GES Variable V26) data elements have the potential of producing a lane-keeping/road departure-related crash [2,3,4]. Thus, they form the basis for identifying potential test-conditions. The numbers beside each data element are the SAS Code value.

- <u>Subject vehicle loss of control:</u>
  - 6; Traveling too fast for conditions
- <u>Action by subject vehicle:</u>
  - 10; Over the lane line on left side of travel lane
  - 11; Over the lane line on right side of travel lane
  - 12; Off the edge of the road on the left side
  - 13; Off the edge of the road on the right side
  - 15; Turning left at intersection
  - 16; Turning right at intersection
- <u>Action by another vehicle in subject vehicle's lane:</u>
  - 50; Other vehicle stopped
  - 51; Traveling in same direction with lower steady speed
  - 52; Traveling in the same direction while decelerating
  - 53;Traveling in same direction with higher speed
  - 54;Traveling in opposite direction
- <u>Encroachment by another vehicle into subject vehicle's lane:</u>
  - 60; From adjacent lane (same direction) over left lane line
  - 61; From adjacent lane (same direction) over right lane line
  - 62; From opposite direction over left lane line
  - 63; From opposite direction over right lane line
  - 64; From parking lane
  - 74; From entrance to limited access highway
- <u>Pedestrian/animal etc:</u>
  - 80-92; All pedestrian and animal data elements

Similarly, the major First Harmful Events (GES Variable A06) that are likely outcomes of lane or road departure events are:

- <u>Non-collision</u>
  - 1; Rollover/Overturn
- <u>Collision with non-fixed object</u>
  - 25; Motor vehicle in transport
  - 21, 22, or 24; Pedestrian, cyclist, or animal
  - 26; Parked motor vehicle
- <u>Collision with fixed object</u>
  - 31-59; All fixed objects

Step #2. Consolidate the subsets into basic test conditions.

In this section, crashes that result from these critical events are assessed to determine common characteristics. One obvious feature of these events is that the critical events lead to both multi-vehicle crashes and single-vehicle crashes. The predominant features of these two types of crashes are not the same, so they are analyzed separately in the following sections.

<u>Multi-vehicle crashes</u> - This section addresses critical events that lead to lane-keeping/ road-departure-related multi-vehicle crashes. The starting points for the analysis of multi-vehicle lane-keeping/road-departure-related crashes are those vehicles that were traveling too fast for conditions, plus the two groups of vehicles that experienced a critical event where there was excursion into another lane or encroachment by another vehicle from an adjacent lane and the first harmful event was collision with another moving vehicle.

A multi-vehicle crash is any crash that involves two or more vehicles. Each vehicle involved in a multi-vehicle crash interacts with one or more other vehicles during the crash. However, the data are not coded in a way that makes it possible to determine the details of these inter-vehicle combinations. This complicates more detailed analysis. To circumvent this problem, the following analysis uses only two-vehicle crashes. Also, since the objective of the analysis is to provide data for determining possible test procedures, the use of only two-vehicle crashes is justified. This judgment is supported by the fact that in this subset of crashes, more than two vehicles account for only 6% of the crashes, as is seen in Table 2.

Table 2.
Distribution of critical events leading to lane keeping/road-departure-related multi-vehicle crashes (Unimputed)

Critical Event (V26)	Two vehicle crashes	Greater than two-vehicle crashes	Total
Excessive Speed (6)	17,000	2,000	19,000
Over the lane line on the left side (10)	143,000	5,000	148,000
Over the lane line on the right side (11)	93,000	3,000	96,000
Off the edge of the road on the left side(12)	2,000	0	2,000
Off the edge of the road on the right side(13)	2,000	0	2,000
Turning left at intersection (15)	207,000	10,000	217,000
Turning right at intersection (16)	23,000	1,000	24,000
From adjacent lane (same direction) over the left lane (60)	117,000	11,000	128,000
From adjacent lane (same direction) over the right lane (61)	119,000	9,000	128,000
From opposite direction over the left lane line (62)	228,000	23,000	251,000
From opposite direction over the right lane line (63)	3,000	1,000	4,000
Total *	**956,000**	**64,000**	**1,019,000**

The description of the situation for each of the vehicles that experience a two-vehicle crash can be improved by comparing the critical event for both vehicles. This is accomplished in Table 3.

Legend for Table 3 and Table 4

Critical Event Number	Critical Event data element
6	Excessive speed
10	Over the lane line on the left side
11	Over the lane line on the right side
12	Off the edge of the road on the left side
13	Off the edge of the road on the right side
15	Turning left at intersection
16	Turning right at intersection
60	From adjacent lane (same direction) over the left lane
61	From adjacent lane (same direction) over the right lane
62	From opposite direction over the left lane line
63	From opposite direction over the right lane line

In Table 3 there are three broad combinations of critical events that describe the lane departure scenario:

- One vehicle exceeding a safe speed and the other is encroaching across a lane line(one vehicle is coded as 6 and the other is coded as 60-63)
- Both vehicles are encroaching across a lane line (both vehicles are coded as either 10-16 or 60-63)
- One vehicle is encroaching over a lane line and that encroachment is reflected in the critical event for both vehicles (one vehicle is coded as 10-16 and the other is coded as 60-63

From Table 3 it is seen that several combinations describe unattainable circumstances like combinations of 60 and 10 and the presence of code 63. Other combinations are intersection crashes where the vehicles are turning or traveling in opposite directions that do not include a relevant lane-crossing. These combinations are excluded from further consideration.

** The number of vehicles in Table 2 is based on unimputed values for the respective critical events, rather than the imputed values used in the Universal Description.*

Table 3.
Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes. (Unimputed)

Vehicle 2 / Vehicle 1		This vehicle…					Other vehicle…				
		6	10	11	15	16	60	61	62	63	Grand Total
This vehicle..	6	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	8,000	125,000	57,000	1,000	203,000
	11	0	4,000	1,000	0	0	120,000	4,000	3,000	0	132,000
	15	0	2,000	1,000	4,000	1,000	6,000	26,000	258,000	1,000	299,000
	16	0	0	0	2,000	1,000	23,000	2,000	1,000	2,000	31,000
Other vehicle..	60	2,000	3,000	44,000	2,000	11,000	2,000	3,000	1,000	0	68,000
	61	1,000	48,000	1,000	17,000	1,000	2,000	2,000	0	0	73,000
	62	3,000	19,000	1,000	88,000	1,000	0	0	1,000	0	113,000
	63	0	1,000	1,000	1,000	0	0	0	0	0	3,000
	Grand Total	6,000	83,000	54,000	115,000	15,000	170,000	167,000	341,000	4,000	**948,000**

Table 4.
Distribution of critical events for all two-vehicle lane-keeping/road-departure-related crashes. Excludes irrelevant and inconsistent data (Unimputed)

Vehicle 2 / Vehicle 1		This vehicle…					Other vehicle…				
		6	10	11	15	16	60	61	62	63	Grand Total
This vehicle..	6	0	0	0	0	0	6,000	4,000	17,000	0	27,000
	10	0	6,000	5,000	1,000	0	*	125,000	57,000	*	194,000
	11	0	4,000	*	0	0	120,000	*	*	0	124,000
	15	0	2,000	1,000	*	*	6,000	25,000	*	*	34,000
	16	0	0	0	*	*	22,000	2,000	*	*	24,000
Other vehicle..	60	2,000	*	44,000	2,000	11,000	*	3,000	*	*	62,000
	61	1,000	48,000	*	17,000	1,000	2,000	*	0	*	69,000
	62	3,000	19,000	*	*	*	0	0	1,000	*	23,000
	63	0	0	0	*	0	0	*	*	*	0
	Grand Total	6,000	79,000	50,000	20,000	12,000	156,000	159,000	75,000	0	**557,000**

Table 4, with the excluded combinations marked by the * , summarizes the critical events for each of the two vehicles in these crashes where at least one of the vehicles has a critical event of crossing a lane line or road edge. Each cell in this table represents the basic outline of a test procedure. The number of vehicles from the GES in each cell is a measure of the importance of that test procedure. From Table 4 it is seen that there are eight vehicle configurations that produce multi-vehicle lane-keeping/road-departure related crashes.

These lane-keeping / road departure related critical events that lead to two-vehicle crashes are summarized (in rank order) in Table 5.

Table 5.
Distribution of all vehicles involved in two vehicle lane-keeping/road-departure-related crashes placed in their descending rank order (Unimputed)

Critical events that lead to two vehicle crashes	Number of vehicles	Percentage %
This vehicle over the lane line on the left side (10)	273,000	25%
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	228,000	20%
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	218,000	20%
This vehicle over the lane line on the right side (11)	174,000	16%
Other vehicle encroaching from opposite direction over the left lane line (62)	98,000	9%
This vehicle turning left at intersection (15)	54,000	5%
This vehicle turning right at intersection (16)	36,000	3%
This vehicle, excessive speed (6)	33,000	3%
Total	**1,114,000**	100%

Table 6 organizes these events by actions that were taken by each vehicle.

Table 6.
Summary table of combination of critical events involving encroaching vehicles for lane-keeping / road-departure-related crashes (Unimputed)

Critical event situations	Encroach vehicle	Vehicle going straight	Total
Over the lane line on the left side (same direction)			
Excessive speed	5,000	5,000	10,000
No Excessive speed	221,000	221,000	442,000
Other vehicle over the lane line	14,000	-	14,000
Over the lane line on the right side (same direction)			
Excessive speed	8,000	8,000	16,000
No Excessive speed	206,000	206,000	412,000
Other vehicle over the lane line	14,000	-	14,000
Over the lane line on the left side (opposite direction)			
Excessive speed	20,000	20,000	40,000
No Excessive speed	76,000	76,000	152,000
Other vehicle over the lane line	14,000	-	14,000
Total	**577,000**	**537,000**	**1,114,000**

In summary, the lane-keeping/road-departure-related situations that lead to two-vehicle crashes are:

- **Over the lane line on the left side (same direction)**
    - Without excessive speed
    - With excessive speed
    - Coincident with encroachment by the other vehicle

- **Over the lane line on the right side (same direction)**
    - Without excessive speed
    - With excessive speed
    - Coincident with encroachment by the other vehicle

- **Over the lane line on the left side (opposite direction)**
    - Without excessive speed
    - With excessive speed
    - Coincident with encroachment by the other vehicle

Single-vehicle crashes - This section addresses critical events that lead to single-vehicle crashes. For the purposes of determining meaningful test conditions, not all of these combinations of events will be considered. Most of the events that lead to *Collisions with Non-fixed Objects* such as *Motor Vehicle in Transport*, *Pedestrians, Railway Trains and Animals* are not a relevant group. However, *Collision with a Parked Motor Vehicle* is a relevant combination. For this reason, this subgroup is the only one from this category that has been included for further analysis.

A summary of the relevant combinations of critical event and single-vehicle first harmful event is presented in Table 7.

Table 7.
Distribution of critical events that lead to single-vehicle lane-keeping/road-departure-related crashes subdivided by their first harmful events (Unimputed)

Critical Event (V26) \ First Harmful Event (A06)	Rollover	Parked vehicle	Collision with fixed object	Grand Total
This vehicle, excessive speed (6)	44,000	11,000	267,000	322,000
This vehicle over the lane line on the left side (10)	2,000	23,000	8,000	33,000
This vehicle over the lane line on the right side (11)	1,000	87,000	8,000	96,000
This vehicle off the edge of the road on the left side (12)	11,000	9,000	106,000	126,000
This vehicle off the edge of the road on the right side (13)	20,000	30,000	201,000	251,000
Other vehicle stopped in lane (50)	1,000	3,000	6,000	10,000
Other vehicle traveling in lane in the same direction with lower steady speed (51)	*	*	2,000	2,000
Other vehicle traveling in lane in the same direction while decelerating (52)	2,000	*	10,000	12,000
Other vehicle traveling in lane in the opposite direction (54)	1,000	*	4,000	5,000
Other vehicle encroaching from adjacent lane (same direction) over the left lane (60)	1,000	1,000	15,000	17,000
Other vehicle encroaching from adjacent lane (same direction) over the right lane (61)	3,000	*	16,000	19,000
Other vehicle encroaching from opposite direction over the left lane (63)	2,000	2,000	22,000	26,000
Pedestrian/Pedalcyclist/Animal/Object (80-92)	8,000	3,000	47,000	58,000
Grand Total	96,000	169,000	712,000	**977,000**

* Cells containing no data

This leads to the following six primary conditions that represent events that lead to single-vehicle lane-keeping/road-departure-related crashes.

Inappropriate action by the driver:

- Excessive speed
- Traveling Over the Lane Line
- Traveling off the edge of the road

Outside influence on driving conditions

- Another vehicle in the same lane
- Encroachment by another driver
- Encroachment by pedestrian, animal, etc.

The distribution of these crashes is shown in Table 8.

Table 8.
Distribution of conditions that lead to a single-vehicle lane-keeping/road-departure-related crash, shown by total and percentage (Unimputed)

Single-vehicle crash basic test conditions	Total	Percentage
Traveling off the edge of the road (12,13)	377,000	39%
Excessive Speed (6)	322,000	33%
Traveling Over the Lane Line (10,11)	129,000	13%
Encroachment by another driver (60,61,63)	62,000	6%
Encroachment by pedestrian, animal, etc (80-92)	58,000	6%
Another vehicle in the same lane (50,51,53,54)	29,000	3%
Grand total	**977,000**	**100%**

Summary of Step 2

The analysis during this step for the lane-keeping / road-departure system has identified 15 test conditions that are candidates for inclusion in the test program. Nine of these lead to multi-vehicle crashes and six of them lead to single-vehicle crashes.

Step #3. Refine test conditions using GES data.

In this step, several measures are used as the basis for developing more detailed test procedures. These measures include the type of roadway, the driver's crash avoidance maneuver, curvature of the road, and the distribution of traveling speed. As in Step 2, multi-vehicle crashes are treated separately from single-vehicle crashes.

Multi-vehicle crashes -For the purpose of facilitating the process of analysis, the discussion in this section is limited to two-vehicle crashes.

- Travel Speed

The details of traveling speed are summarized in Figure 2 [Two-vehicle, speed distribution]. There is insufficient data to obtain a meaningful distribution of speed for the conditions where one vehicle is encroaching and is traveling at excessive speed. The distributions of travel speed for the other four conditions are shown in this figure. It can also be seen that the distribution of travel speed is essentially the same for both vehicles. Based on these data and the need to address situations that produce significant injury, the 80 percentile speed is used as the basis for the two-vehicle test conditions. This is approximately 40 mph for all four situations. Note that in the opposite direction, this means that both vehicles are traveling at 40 mph. Other research [7] has shown that overtaking vehicles in the adjacent lane are a common element of lane change crashes. Thus, the speed of the confederate in the same direction tests should be higher than the subject vehicle.

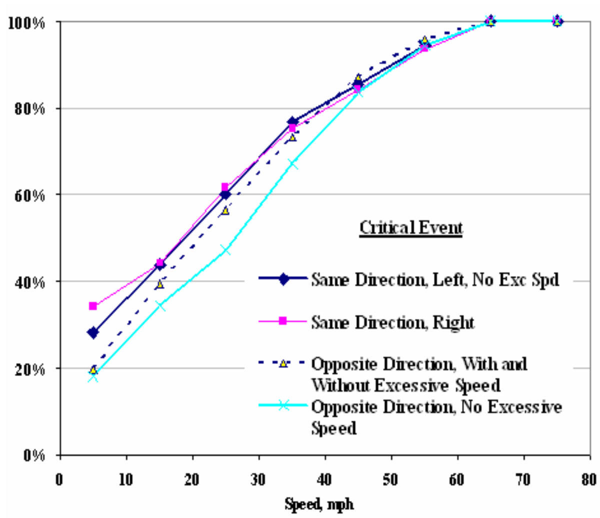

Figure 2. Speed distribution for two-vehicle lane-keeping/road departure -related crashes.

- Traffic way

From the distributions of traffic way for the two-vehicle crash data, situations where both vehicles are traveling in the same direction are evenly divided between undivided traffic ways and multi-lane divided traffic ways. However, the situations where the vehicles are traveling in opposite directions occur predominantly (greater than 80 %) on two-lane undivided traffic ways. Thus, the conclusion is that the test conditions should reflect two-lane undivided traffic ways for the test in opposite directions and should reflect both undivided and divided traffic ways in the tests traveling in the same direction. However, the lane configurations for multi-lane undivided and divided are similar, so there can be a single test for vehicles traveling in the same direction.

- Corrective Action

There is limited data in GES on the corrective action taken by each of the drivers. However, based on these data, it appears that more drivers take corrective action when the vehicles are traveling in opposite directions than when they are traveling in the same direction. These results are summarized in Table 9. Based on these results, the test conditions need to accommodate systems that address the situations where neither driver takes corrective action.

Table 9.
Known avoidance maneuvers in two-vehicle crashes for vehicles traveling the same direction and opposite direction

Same Direction	*Non-Encroaching vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	85%	3%	6%
	Brake	2%	0%	0%
	Steer	3%	0%	2%
Opposite Direction	*Non-Encroaching vehicle*			
		No Maneuver	Brake	Steer
Encroaching Vehicle	No Maneuver	58%	0%	17%
	Brake	8%	0%	0%
	Steer	8%	0%	8%

- Road Curvature

The distribution of road curvature is interesting for these crashes. For the crashes where both vehicles were traveling in the same direction, the likelihood of the crash being on a curve is only 7%. However, for crashes where the vehicles were traveling in opposite directions, the likelihood of the crash being on a curve is 44%. Thus, the test conditions for vehicles traveling in the same direction need only address straight roads; however, the test conditions for vehicles traveling in opposite directions need to address straight and curved roads.

Summary of Multi-vehicle crash test conditions based on GES data - Based on the detailed analysis above, it is concluded that two basic conditions will be tested:
(1) The host vehicle and a confederate vehicle traveling in the same direction and
(2) The host vehicle and a confederate vehicle traveling in opposite directions.

Same Direction:

- The lane-changing vehicle, the subject vehicle, should be traveling at 40 mph on a straight road that emulates either:
    - A divided multi-lane roadway, or
    - A multi-lane undivided roadway

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. Other research [7] has shown that the vehicle that is not changing lanes, the confederate vehicle, is often overtaking the subject vehicle at a higher speed. For this reason it is recommended that the confederate vehicle should be traveling at a speed of 45 mph. A distance that corresponds to a time-to-collision of 3 seconds has been selected as the point at which the lane change begins. This provides an opportunity for warning, or automatic control, systems to effectively intervene. The analysis provided in the Appendix to this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees.

Opposite direction:

- Both vehicles traveling at 40 mph on a two-lane undivided roadway. Two test conditions should be used:
    - A straight road segment, and
    - A curve of appropriate radius

In addition to this basic configuration of the two vehicles, it is necessary to establish the relative position and speed of the two vehicles. The relative distance between the two vehicles is based on time-to-collision. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If both vehicles are traveling at 40 mph, this distance is 350 feet. The analysis provided in the Appendix to this paper supports the additional criteria that the encroaching vehicle should cross the lane line at an angle of 3 degrees. The radius-of-curvature for the second condition has not been established. The crash data files, such as GES and the Crashworthiness Data System do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix, or other sources to determine this value.

The tests in both conditions should accommodate systems that assist drivers who would otherwise take no evasive action.

Single-Vehicle crashes - In the preceding section, it was determined that there are six basic pre-crash conditions that need to be considered. The conditions are summarized in Table 8 and repeated below:

- Excessive Speed
- Traveling over the lane line
- Traveling off the edge of the road
- Another vehicle in the same lane
- Encroachment by another driver
- Encroachment by pedestrian, animal etc

- Travel speed

The details of traveling speed for each of the six conditions are summarized in Figure 3.

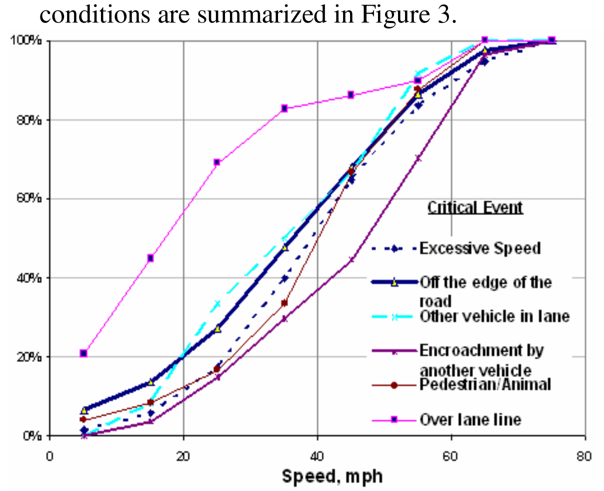

Figure 3. Summary of travel speeds for single-vehicle crashes for various critical events.

From this figure, it is seen that the speed distribution for "over the lane line" events that lead to crashes occur at lower speeds than do the other types of single-vehicle situations; in contrast, the events that begin with "encroachment by another vehicle", occur at higher speeds. Based on these data, and the need to address situations that produce significant injury, the 80 % speed is used as the basis for the single-vehicle test conditions. This is approximately 30 mph for "Over the lane line" situations, 60 mph for "Encroachment by another vehicle" and 50 mph for the other four types of events.

- <u>Traffic Way</u>

From the distribution of traffic way for the single-vehicle crashes, the single most common type of traffic way (ranging from 40 % for encroachment type events to 73 % for pedestrian/animal events) for these events is two-lane undivided highways (one lane in each direction). The second most common type of traffic way is two-lane divided highways (two lanes in each direction). For those events that are initiated by encroachment, about 25 % occur on divided highways with more than two lanes in each direction. Based on these data, the conclusion is that the test conditions should reflect two-lane undivided traffic ways as well as multi-lane divided traffic ways for all six conditions.

- <u>Corrective Action</u>

From Table 10 below, it's seen that, for events where this variable is known, 48 % of the drivers steered and 11 % braked, but 36 % did not attempt an avoidance maneuver.

Table 10.
Distribution of known avoidance maneuvers for single-vehicle lane-keeping/ road-departure-related events

Avoidance Maneuver Critical Event	No Maneuver	Brake	Steer	Brake and steer	Total
Traveling off the edge of the road (12,13)	63,000	11,000	41,000	3,000	118,000
Excessive Speed (6)	48,000	16,000	14,000	2,000	80,000
Encroach by another driver(60-64)	0	3,000	51,000	4,000	58,000
Encroach by pedestrian, Animal (80-92)	2,000	2,000	42,000	2,000	48,000
Traveling Over the Lane Line (10,11)	16,000	2,000	9,000	0	27,000
Another vehicle in the same lane (50-54)	1,000	5,000	16,000	5,000	27,000
Grand Total	130,000	39,000	173,000	16,000	**358,000**
Percentage	36%	11%	48%	5%	100%

Based on these data, the test conditions need to accommodate situations where the driver attempts no maneuver as well as those where the driver either steers or brakes.

- <u>Road Curvature</u>

The percentage of events that occur on curves for each category is shown in Table 11 below.

Table 11.
Percentage distribution of crashes for each critical event on curves

Category	% on Curve
Excessive Speed	50%
Off the edge of the road	35%
Over the lane line from adjacent lane traveling the same/opposite direction	27%
Pedestrian / Pedalcyclist/ Animal/ Object	27%
Other vehicle traveling in the same lane either topped/slower /steady speed	17%
Over the lane line	14%

From this table, it is seen that events that involve lane line crossings and encroachment by other vehicles occur on straight roads. The other four categories of events frequently (between 27% and 50%) occur on curves. Based on these results, the test conditions for single-vehicle events should include both straight and curved roads, except for lane line crossings and encroachment by other vehicles that would be tested only on straight road segments.
Two additional considerations are the types of crash that result from these single-vehicle events and the level of injury that results from these crashes.

- <u>Types of crashes</u>

The distributions of first harmful events for each of the six broad categories of single-vehicle lane-keeping / road-departure–related events are shown in Figure 4 below.

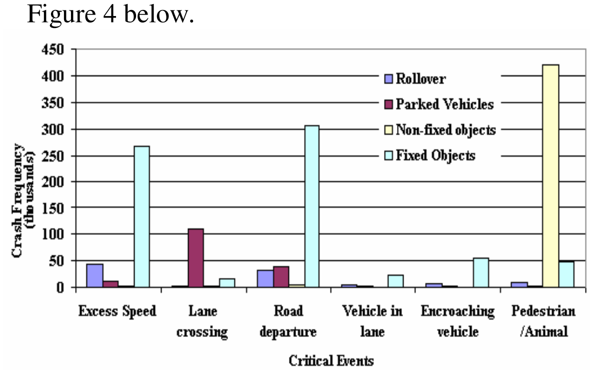

Figure 4. Distribution of first harmful event for single-vehicle lane-keeping/road-departure-related events.

Several helpful observations can be made from this table:

First: Consider the events that result from a pedestrian or animal (Category 6). This category was included in this analysis because of the potential for the avoidance maneuvers in these events leading to off-road crashes. This figure shows that although there are a few crashes of this type, the vast majority of the first harmful events are a collision with the pedestrian or animal. These collisions may occur either on or off the road. Thus, this type of event is not a good choice for evaluating the performance of lane-keeping / road-departure systems. For this reason, it will be dropped from further consideration.

Second: Categories 4 and 5 (actions by other vehicles) contribute only a small fraction to the total problem. For this reason, they will also be dropped from further consideration.

Third: The remaining three categories produce three main types of harmful event: (1) impacts with fixed objects (trees, poles, bridges, etc.), (2) rollovers, and (3) collision with parked vehicles.

The conclusions from this part of the analysis are that the test conditions should reflect the first three conditions of critical event (excessive speed, lane line crossing, and road departure) and should be based on environments that may lead to rollovers, crashes with fixed objects, and crashes with parked vehicles.

Summary of single-vehicle test conditions

Based on this analysis, two tests are needed:

- A test that combines the attributes of excessive speed and road departure. This test will be on a roadway that reflects a two-lane undivided roadway (This probably means a narrow shoulder). The vehicle should be traveling at 50 mph, and the event should occur on a curve of appropriate radius.

- A test on a roadway with sufficient shoulder width to accommodate a parked vehicle. The vehicle should be traveling at 30 mph on a straight section of road with a vehicle parked on the shoulder.

The radius-of-curvature for the first condition has not been established. The crash data files, such as GES and the Crashworthiness Data System do not include details on radius-of-curvature. Thus, it will be necessary to do additional analysis of naturalistic driving data, similar to the analysis in the Appendix to this paper, or other sources to determine this value. As noted in the discussion of two-vehicle test conditions, it is necessary to establish the relative position of the two vehicles for the second condition. A distance that corresponds to a 3-second time-to-collision is recommended. This provides an opportunity for warning, or automatic control, systems to effectively intervene. If the subject vehicle is traveling at 30 mph, this distance is 145 feet. The analysis provided in the Appendix supports the additional criteria that the subject vehicle should cross the lane line at an angle of 3 degrees for both test conditions.

The tests in both conditions should accommodate systems that assist drivers who would otherwise take no evasive action, as well as drivers who steer or brake.

CONCLUSIONS

Test conditions have been developed for systems that assist drivers in preventing crashes associated with lane changes or road departures. The resulting test conditions are based on data from GES. Table 12 provides a summary of these test conditions. The speeds shown in this table correspond to the 80th percentile of crashes in GES.

Table 12.
Summary table for test procedures for lane keeping/ road departure related systems based on data from GES conditions

Type	Roadway	Specifics	Speed (80 % of all crashes)
Two-vehicle; Opposite direction	- Two-lane - Undivided - Curve	- 350 ft separation (485 ft at 55mph) - 3 degree approach angle	40 mph, Both vehicles
Two-vehicle; Opposite direction	- Two-lane - Undivided - Straight	- 350 ft separation (485 ft at 55mph) - 3 degree approach angle	40 mph, Both vehicles
Two-vehicle; Same direction	- Multi-lane - Straight	- 3 degree approach angle	-40 mph, Lead vehicle. -45 mph, Following vehicle
Single-vehicle	- Two-lane - Undivided - Curve	- Narrow shoulder - 3 degree approach angle	50 mph
Single-vehicle	- Multi-lane - Straight	- Shoulder with parked vehicle - 3 degree approach angle	30 mph

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APPENDIX

The objective of this analysis is to determine the approach angle with respect to the lane line. The analysis uses data from a recent naturalistic driving study [5, 6]. This study provides details on 200,000 vehicle miles of travel. The data was generated by 241 participants driving for 43,000 hours over a span of 23 months.

There are 828 event files in the data base used for this analysis. Each event is a Crash or a Near Crash. Of these, 762 files were Near Crashes. Each file includes real time video of five views: frontal, rear, left side, right side, and driver's hand position; variables such as lane offset, lane width, delta time frame, vehicle speed, lateral and longitudinal acceleration.

The estimates of approach angle are based on the following variables:

Lane offset,X (in): Distance between vehicle's longitudinal center and the lane center.

Delta Frame, δt (Sec): Time increment between current step and preceding step of data collection.

Lane Width, W (in):Lateral distance across current lane.

Vehicle Speed, V (mph): Vehicle travel speed.

Figure A-1 shows the signature of offset in inches, during a right-to-left and left-to-right lane change maneuver. In these two examples, the right-to-left lane change took about 5 seconds, while left-to-right lane change took 3.5 seconds.

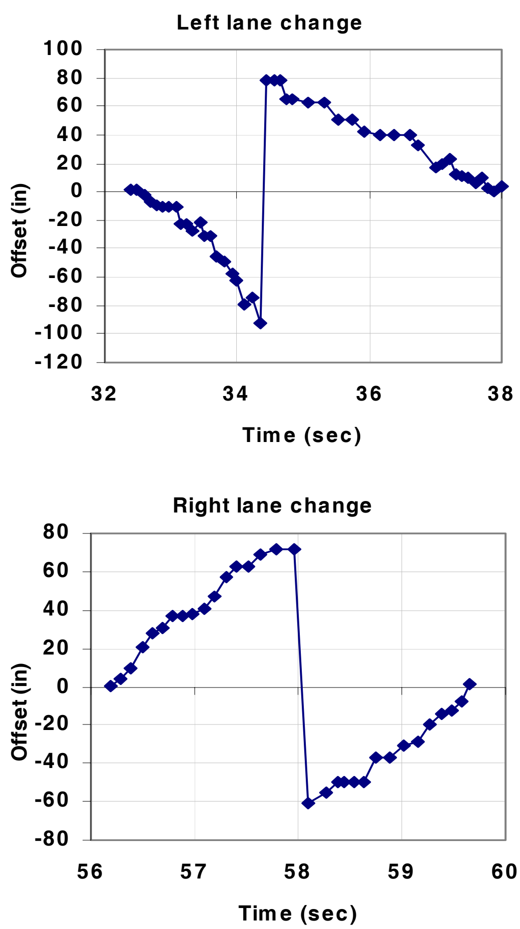

Figure A-1: Offset channel signature during a lane change maneuver.

Once the variables and their values are established, the approach angle is calculated: where

The approach angle is:

$$\theta = Sin^{-1}\left(\frac{V_L}{V}\right)$$

where V_L is the estimated lateral velocity of the vehicle and V is the vehicle travel speed. The angle θ is determined for each time frame by substituting values for V_L and V. If the vehicle's longitudinal center line is in the left of the lane center then the offset has a negative value, while it has a positive value on the right side.

Estimation of lateral velocity at each step uses the expression:

$$V_L = \frac{X_n - X_{n-1}}{\delta t_n}$$

where n is the frame number. These relationships are summarized in Figure A2

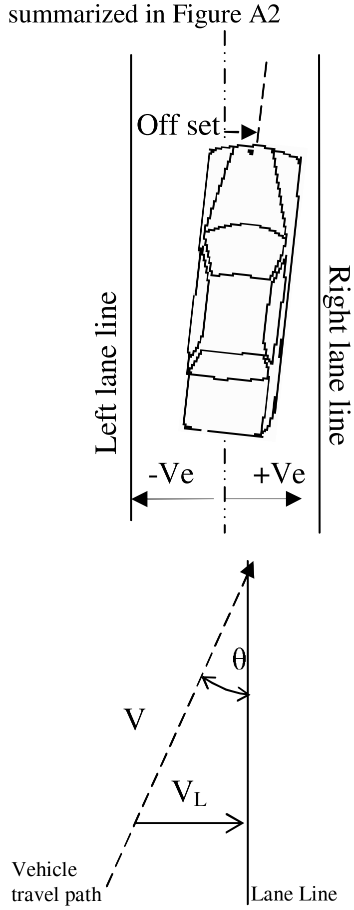

Figure A-2: Offset and angle of approach θ

The time at which the vehicle crosses the lane, T_{lc}, is the time when $Offset + \frac{1}{2} car\ width \geq \frac{1}{2} lane\ width$.

The approach angle θ at this instant is the vehicle's approach angle at the lane change event.

Figure A-3 shows the estimated values of θ for the same two examples in Figure A-1. An eight point moving average filter is used to reduce the noise in the data collection / calculation process. The filtered value of θ is also shown in the Figure A-3 and is used in estimating the value for θ_{lc}

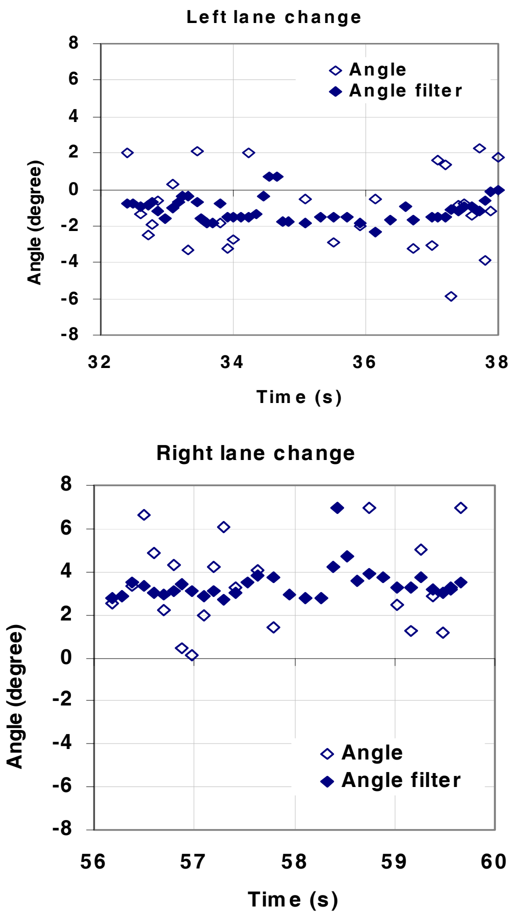

Figure A-3: Estimated angle θ

The lane change signature described in Figure A-1 was applied to the data in each of the 762 near crashes. A total of 223 lane change maneuvers were identified by the algorithm. These selected lane change maneuvers had a minimum speed of 10mph. Distribution of road alignment and road type is shown in Table A-1. Of the 223 lane changes, 30 were completed on curved roads while the rest was completed on straight roads. 53 of the lane changes took place on un-divided traffic way, of which 19 had only 2 lanes.

Table A-1: Distribution of road alignment and road type

Number of lane changes		Road alignment				
Traffic_Flow	# of Travel Lanes	Curve Grade	Curve level	Straight grade	Straight level	Grand Total
Divided (median strip or barrier)	1		3		3	6
	2		5	4	37	46
	3	1	10	7	68	86
	4				27	27
	5		2		2	4
Not divided	2		2	1	16	19
	3		4		9	13
	4		1		9	10
	5				6	6
	6				1	1
One-way traffic	1	1	1		1	3
	2				1	1
	4				1	1
Grand Total		2	28	12	181	223

Summary

The results of the analysis are shown in Figure A-4. From this figure, it is seen that at least 60 percent of the events occur with a lane change angle less than 3 degrees for speeds greater than 20mph. This leads to the conclusion that 3 degrees is an appropriate approach angle for testing lane-keeping/road departure systems.

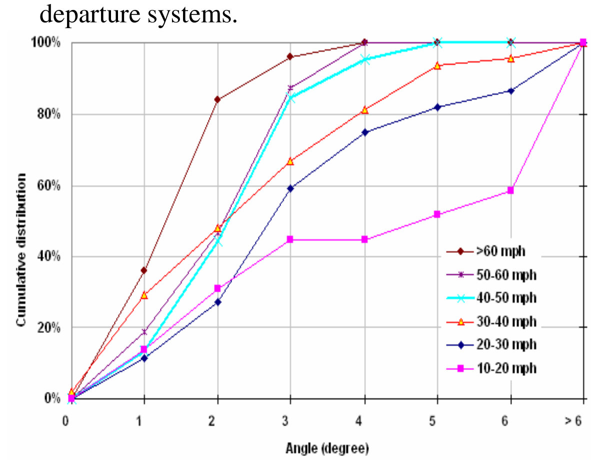

Figure A-4.Cumulative distributions of approach angles during a lane change maneuver.