REAL-WORLD ANALYSIS OF FATAL RUN-OUT-OF-LANE CRASHES USING THE NATIONAL MOTOR VEHICLE CRASH CAUSATION SURVEY TO ASSESS LANE KEEPING TECHNOLOGIES

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ABSTRACT

Lane Departure Warning (LDW), Lane Centering Control (LCC) and Lane Keeping Support (LKS) are three advanced crash avoidance technologies intended to prevent vehicles from inadvertently running off the roadway or out of the lane of travel. All three systems utilize a camera based vision system to monitor the vehicle's forward position with respect to the roadway. Depending on the level of system authority, the technology is intended to warn the driver that they are leaving the travel lane, continuously maintain the lateral position of the vehicle within the lane of travel, or redirect the lateral path of the vehicle to stay in the lane. A real-world analysis of run-out-of-lane crashes where at least one of the involved vehicles' occupants sustained fatal injuries was conducted. The study utilized the National Motor Vehicle Crash Causation Survey (NMVCCS) to better understand why drivers depart the roadway and under what conditions and circumstances the crashes occur to begin to assess the potential effectiveness of these countermeasures.

NMVCCS was a nationally representative survey conducted by National Highway Traffic Safety Administration from 2005-2007. Trained researchers conducted on-scene investigations of nearly 7,000 crashes during the project, focusing on the pre-crash phase. The ability to investigate the selected crashes on-scene, in most cases within minutes, allowed the researchers to make better assessments of the events that led up to the crash. To evaluate the potential effectiveness of a vision system that monitors the position of the vehicle on the roadway, it was important to use a dataset that assessed the environmental and roadway conditions as soon as possible after the crash occurred.

For each crash identified, a review of the accompanying investigation was conducted. The intent was to identify any attributes or factors that were consistent among the cases and any environmental or roadway conditions that may impact the performance of a crash avoidance countermeasure, such as poor lane markings, sensor blindness attributable to darkness, or weather conditions.

This broad study identified 72 NMVCCS cases where the subject vehicle left the travel lane and resulted in a crash where an occupant in an involved vehicle sustained fatal injuries. Specifically, 43 cases were identified where the subject vehicle drifted out of the lane, resulted in a crash, and was relevant to assessing the real-world applicability of LDW/LCC/LKS crash avoidance technologies. This study found that a robust LKS/LCC should make it more difficult for the driver to drift out of their lane. With sufficient lateral control authority, an LKS/LCC system could have effectively prevented many of the 43 cases reviewed in this study. In other words, unless there were other factors present which prevent the driver from reengaging in the driving task, a robust LKS/LCC would likely have prevented the driver from running out of the lane, which started the chain of events that led to the fatal crashes. LKS/LCC appears to have more potential in crash reduction than LDW since the system does not rely on alert modality effectiveness or the driver taking corrective action. Lastly, environmental and roadway conditions at the time of the crash would likely not have compromised the performance of the vision system to detect the roadway boundary at the moment the vehicle left the lane.

INTRODUCTION

In 2015 there were 35,092 fatalities in vehicle crashes on U.S. roadways, an increase from 32,744 in 2014. The estimated number of people injured on the U.S.'s roads increased in 2015, rising from 2.34 million in 2014 to 2.44 million [NHTSA, 2016]. This paper will address the portion of crashes resulting from drivers inadvertently running off the roadway or lane of travel.

To identify the target population, pre-crash scenarios identified in a recent study using the National Automotive Sampling System (NASS) General Estimates System (GES) and Fatality Analysis Reporting System (FARS) 2011-2015 crash databases were reviewed. [Swanson, 2017] That study examined all police-reported crashes involving a light vehicle in the critical event of the crash or the event that occurred which made the crash imminent. Light vehicles include all passenger cars, vans, minivans, sport utility vehicles, or light pickup trucks with gross vehicle weight ratings less than or equal to 10,000 pounds. Common crash types were analyzed to produce a list of representative pre-crash scenarios based upon NASS pre-crash variables which is the pre-crash movement or the vehicle's action prior to an impending critical event or prior to impact if the driver did not make any action. From the pre-crash scenarios identified in the report, Table 1 lists those relevant to the inadvertent run-out-of-lane crash problem. This approach identified, on average, over 760,000 run-out-of-lane crashes annually, over 9,600 of which were fatal.

Table 1.
2011 – 2015 FARS and GES Run-Out-Of-Lane Light Vehicle Target Population

Scenario	Avg. FARS	Avg. GES
Road Edge Departure/No Maneuver	6,284	472,182
Opposite Direction/No Maneuver	2,983	96,095
Drifting/Same Direction	196	120,223
Object/No Maneuver	151	80,088
Target Population	**9,615**	**768,588**

An earlier study conducted an in-depth clinical analysis of 111 fatal National Motor Vehicle Crash Causation Survey (NMVCCS) crashes, assigning the critical and secondary factors that led to the crash. [Mynatt, 2011] The study also identified potential crash prevention measures at the driver, vehicle, and environmental levels. The results indicated that crash avoidance technologies including lane departure warning/lane keeping, electronic stability control (ESC), alcohol detection, and auto/assisted braking could have been beneficial in preventing many of the fatalities. Specifically, this study found that 32% of the cases reviewed may have been prevented with Lane Departure Warning/Lane Keeping Support technologies. However, this study was a high-level assessment of available technologies which did not analyze the potential effectiveness of the systems recommended in reducing crashes.

A recent study reanalyzed the NMVCCS data to study unintentional lane departure crashes. [Cicchino, 2016] That study quantified the proportion of drivers involved in unintentional lane drift crashes who would be unable to regain control of their vehicles if the vehicle was equipped with a lane keeping crash avoidance technology. The paper identified 631 crashes which represented 259,034 crashes nationally where the driver drifted out of the lane independent of injury severity. The physical state of the driver was characterized for these cases. The study found that 34 % of drivers who crashed because they drifted from their lanes were sleeping or otherwise incapacitated. These drivers would be unlikely to regain full control of their vehicles if an active safety system prevented their initial drift. An additional 13% of these drivers had a non-incapacitating medical issue, blood alcohol concentration (BAC) ≥ 0.08%, or other physical factor that may not allow them to regain full vehicle control. When crashes involved serious or fatal injuries, 42% of drivers who drifted were sleeping or otherwise incapacitated and an additional 14% were impacted by a non-incapacitating medical issue, BAC ≥ 0.08%, or other physical factor. The study raised potential concerns that lane keeping technologies may prevent unintentional lane departure crashes, but to be effective, strategies need to be considered in designing these systems to account for drivers who are not engaged for the reasons discussed above.

Lane Departure Warning (LDW), Lane Centering Control (LCC) and Lane Keeping Support (LKS) are three advanced crash avoidance technologies intended to prevent the vehicle from leaving the travel lane unintentionally. All three systems utilize a camera based vision system to monitor the vehicle's forward position with respect to the roadway. Depending on the level of system authority, the technology is intended to warn the driver that they are leaving the travel lane, continuously maintain the lateral position of the vehicle within the lane of travel, or redirect the lateral path of the vehicle to stay in the lane. The vision based systems generally identify the lane markings on the roadway and monitor the position of the vehicle with respect to those lane markings. More advanced systems can identify the edge of the roadway as another attribute to monitor the position of the vehicle, including estimating the future path the vehicle should be following. The effectiveness of these systems is dependent on not only the warning or steering authority, but also on being able to know where the vehicle should be in the lane. Therefore, it is important to understand if lane markings were present or if there were environment factors such as rain or poor lighting conditions that may have prevented the vision system from being able to monitor the position of the vehicle. For that reason, the cases were reviewed to not only understand the driver's state, but also the environmental and roadway conditions at the time the vehicle left the roadway, which started the chain of events that led to the fatal crash.

This paper, building on the previous studies, examined NMVCCS crashes where the driver departed the lane of travel resulting in a crash where an occupant in an involved vehicle sustained fatal injuries. The cases were reviewed and characterized to better understand the potential benefits and limitations of crash avoidance technologies intended to prevent lane departure.

METHODOLOGY

A detailed review of real-world run-out-of-lane crashes was conducted where an occupant sustained fatal injuries in an involved vehicle using the NMVCCS dataset. The review focused on coded and non-coded data (photographs, crash summaries, scene diagrams, etc.), and resulted in the identification of critical characteristics contributing to the fatal injuries in run-out-of-lane crashes. NMVCCS was a nationally representative survey conducted by the National Highway Traffic Safety Administration (NHTSA) from 2005 - 2007. Trained researchers conducted on-scene investigations of nearly 7,000 crashes during the project, focusing on the pre-crash phase of the sequence of events. The ability to investigate the selected crashes on-scene, in most cases within minutes, allowed the researchers to make better assessments of the events that led up to the crash. The survey collected up to 300 data elements on the driver, vehicle, and environment. Important components of NMVCCS were based on a methodology originally outlined by Perchonok, [Perchonok, 1972] including coding of the critical event, critical reason, and the associated factors that were present at the time of the crash.

All fatal cases from the NMVCCS dataset that met the following Crash Type Code were selected: 01, 02, 04, 05, 06, 07, 09, 10, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 64, 65, 66, and 67 (a chart explaining the crash types is provided in the Appendix of this paper). The intent was to capture fatal crashes resulting from the vehicle leaving the original travel lane. The broad selection criteria included 72 fatal cases in the dataset.

A multi-disciplinary team of NHTSA crash investigators, engineers, and researchers analyzed the 72 fatal crashes identified using the previously discussed selection criteria. Using a technique similar to Bean et al. [Bean, 2009], a detailed review of real-world run-out-of-lane crashes was conducted to better understand the crash types where an advanced technology intended to keep the driver in the lane would be applicable. In addition, those cases identified were then reviewed to assess how the crash avoidance technologies may have prevented the crashes given the environmental and roadway characteristics and driver condition from the on-scene investigations.

For each of the cases, the following characteristics of the crash were noted:

- Environment (weather/lighting)
- Presence and condition of lane markings and rumble strips
- Road curvature
- Type of crash (head on, rollover, single vehicle, etc.)
- Vehicle defects
- Physical and cognitive state of the driver

The intent was to identify any attributes or factors that were consistent among the cases and any concerns that may impact the performance of a crash avoidance countermeasure, such as poor condition of lane markings, sensor blindness attributable to darkness, or wet conditions.

RESULTS

Run-Out-Of-Lane Fatal Crash Characteristic

As stated above, this was a broad review of crashes where the driver of a vehicle departed the travel lane and the selection criteria identified 72 fatal cases in the dataset (see Appendix for cases). Overall, the driver drifted out of the lane and crashed in 43 of the 72 cases (59 %). In three cases, an involved driver crashed while changing lanes. There were 24 cases where the driver lost control of the vehicle, departed the travel lane, and crashed, and two cases where the driver was traveling in the opposing lane of traffic and caused a crash. Details of the analysis and finding will be presented below.

Drifting Cases. Common among 43 of the 72 crashes was that the driver drifted out of the lane resulting in a crash. When analyzing the cases, it appeared that the driver did not aggressively drive out of the lane, and therefore, a minor steering correction would have likely prevented the crash. However, from a countermeasure effectiveness standpoint, the team believed more system authority would be required when the vehicle was driving on curved roads. In the context of this paper, the term system "authority" is used to describe the amount of intervention provided by a technology (magnitude and duration) to actively adjust the path of the vehicle. System designers must carefully balance the benefits associated with high system authority (i.e., a greater ability to successfully remedy the pre-crash scenario that invoked the system activation) with the dis-benefits associated with an unintended or unnecessary activation (e.g., crashes resulting from a misinterpretation of the driving environment, customer complaints resulting from false positive events, etc.). For that reason, the drift-out-of-lane cases were grouped into two high-level categories: crashes on straight roads and those where the driver was negotiating a curved road.

The review indicated 17 drift-out-of-lane cases occurred on straight roads, and 26 on curved roads. In the straight road cases, the team believed only a minor course correction was necessary to likely prevent the crash. In the 26 cases on curved roads, even though the driver drifted out of the lane, any countermeasure would have required a higher level of authority for the vehicle to both negotiate the curve and make any trajectory adjustment to stay within the travel lane. Figure 1 shows the posted speed distribution for all 43 drift-out-of-lane cases.

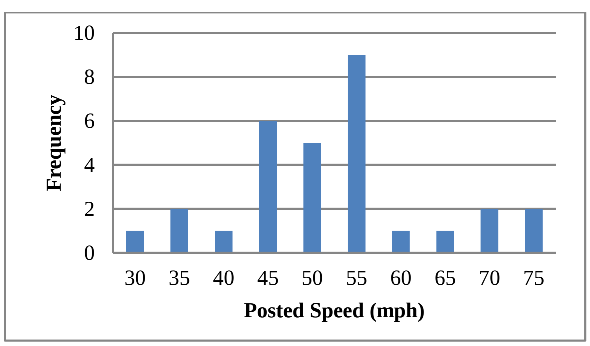

Figure 1. Drifted out-of-lane cases, post speed vs. frequency.

For the cases where the road was straight, the median posted speed was 55 mph and where there was curvature the median posted speed was 45 mph.

The data in Table 2 includes the side of the travel lane the driver departed, but this does not necessarily represent where the vehicle left the roadway. For example, in Case No. 2007-81-007 the vehicle departed the lane on the left side but over-corrected, lost control and departed the lane and roadway on the right side resulting in a rollover. In assessing cases such as this, the team believed that if the vehicle did not depart the lane on the left side, the driver likely would not have over-corrected, and the subsequent right roadside departure would not have occurred.

Table 2.
Drift-Out-of-Lane Cases Side of Lane Departure

Curve	Left	Right	Total
No	12	5	**17**
Yes	12	14	**26**
	24	**19**	**43**

On straight roads, there were seven cases where the driver over-corrected after driving out of the original travel lane. Of these seven cases, six resulted in rollover crashes. On curved roads, 12 drivers over-corrected, which resulted in seven rollover crashes (Table 3).

Table 3.
Drift-Out-of-Lane Cases Driver Over-Corrected

Curve	Over-Corrected
No	7
Yes	12

Of the 43 drift-out-of-lane cases, there were 11 single vehicle crashes on straight roads and 14 on roads with curvature. There were a total of 18 rollovers, 16 frontal impacts with another vehicle, and nine frontal crashes with objects (Table 4). Note that, although there may have been multi-impact events, the most severe event is listed in the table. For example, in Case No. 2006-43-117, a 1994 Honda Civic was traveling north and a 1996 Chevrolet Lumina was traveling south. As the Honda rounded a curve, it departed the left side of the road and entered a downhill slope of a grass median. Once the Honda tripped in the median, it became airborne, struck a small tree, rolled, and traveled into the southbound lanes where it was struck by the Chevrolet. This case was tabulated in Table 4 below as a rollover as it was assessed to be the most severe event.

Table 4.
Crash Type Post Run-Out-Of-Lane

Curve	Lane Markings Both Sides	Lane Markings One Side Only	No Lane Markings	Total
No	15	0	2	**17**
Yes	23	3	0	**26**
	38	**3**	**2**	**43**

The analysis also included the presence of lane markings, their condition, and if there was a clearly defined road edge. Table 5 provides a summary of the results. There were only two cases where there were no lane markings on either side (Case Nos. 2005-11-061and 2007-11-082). There were only three cases where there were only lane markings on one side. In all of these cases, markings were on the left side only (Case Nos. 2006-13-053, 2006-48-064 and 2007-48-009). Of these cases, only in Case No. 2006-13-053 does the subject vehicle depart the road on the right side where there were no markings.

Table 5.
Drift-Out-of-Lane Cases Lane Markings

Curve	Rollover	Frontal Head On	Frontal w/ Tree or Pole	Frontal w/ Barrier	Totals
No	8	6	3	0	**17**
Yes	10	10	4	2	**26**
	18	**16**	**7**	**2**	**43**

For the cases where there were lane markings on at least one side of the lane, the markings were generally some combination of solid or dashed yellow or white lines, with the exception of Case No. 2007-78-054 where the lane markings on the road were round yellow and white reflectors and not painted lines.

There were six drift-out-of-lane cases (Case Nos. **2005-78-051**, **2005-78-092**, 2007-08-001, 2007-78-071, 2006-48-040 and **2006-78-073** (bold denotes over-corrected)) where there were rumble strips on the side of the lane the vehicle departed the lane of travel leading to the crash. In three of these cases, the driver of the vehicle over-corrected. Lastly, in all the cases reviewed there was a clearly defined road edge.

There were only four cases where the environmental conditions were wet. Case No. 2007-48-006 occurred on a straight road when it was daylight. Case Nos. 2005-02-49 and 2007-11-002 occurred on a curved road at night and Case No. 2006-76-18 occurred on a curved road when it was daylight.

Table 6 shows the lighting conditions in the 43 drift-out-of-lane cases.

Table 6.
Drift-Out-of-Lane Cases Lighting Conditions

Curve	Light	Dark	Total
No	12	5	17
Yes	19	7	26
	31	**12**	**43**

There was only one crash, Case No. 2007-81-007, where a vehicle factor was believed to have contributed to the severity of the crash. In this case, the vehicle had an underinflated front tire. The driver of the vehicle crossed over the center lane of a two-lane undivided roadway and over-corrected and ran off the right side of the road. In this case, it was quite possible that the underinflated front tire contributed to the loss of control after the driver's over-correction.

As Table 7 shows, alcohol was involved in 11 of the 43 fatal cases (Case Nos. 2005-11-061, 2005-78-092, 2006-013-002, 2006-43-067, 2005-45-046, 2006-13-053, 2006-43-073, 2006-45-63, 2007-11-002, 2007-48-009, and 2007-76-021). Four occurred on straight roadways and seven on roads that were curved.

Table 7.
Drift-Out-of-Lane Cases Driver Factors Alcohol

Curve	Alcohol
No	4
Yes	7

In NMVCCS, the critical pre-crash event is the action or event that placed the vehicle on a course such that the collision was unavoidable. In other words, the critical event makes the crash inevitable. NMVCCS coding of the critical reason, which is the immediate reason and the failure that led to the critical event, [Perchonok, 1972] also proved to be a valuable tool in this analysis. Although the critical event and critical reason are important parts of the description of the crash, they do not imply the cause of the crash or assignment of fault. Rather, the primary purpose of the variables is to enhance the description of events and allow analysts to better analyze similar events. [Toth, 2003] The critical reason for the critical event, which is typically assigned to one party in a crash, was attributed to driver-related factors in all the crashes. Table 8 shows that "driver error unknown" was the most frequent critical reason with 14. In these cases, since the driver was typically killed, identifying the driver's actions which led to the critical reason is difficult. The second most common critical reason in these cases was driver over-compensation with seven. Sleeping was the critical reason in four cases, and internal distraction and physical impairment were the critical reason in two cases each. With respect to the cases identified where alcohol was involved, the critical reason in Case No. 2005-78-092 was coded as sleeping. All other alcohol cases were coded as a driver performance issue such as aggressive driving, over-compensation, poor directional control, etc. Therefore, there were 14 cases where the state of the driver was determined to contribute to the crash. It should be noted that alcohol use is not considered a critical reason for the crash in the methodology used in NMVCCS.

Lane Change Cases. Three cases were identified where a lane change maneuver resulted in a fatal crash. Case Nos. 2005-12-083 and 2005-79-053 involved a non-contact vehicle leaving its travel lane for an unknown reason resulting in a subject vehicle taking an evasive maneuver prior to the crash. In both cases, the coded driver related factor was overcompensation in response to the non-contact vehicle. Case No. 2007-75-097, involved the subject vehicle intentionally changing lanes and subsequently impacting the side of a vehicle in the adjacent lane prior to losing control and rolling over. The driver related factor for the subject vehicle was coded as inadequate surveillance. Given the lack of data, an analysis of the crash characteristics could not be conducted.

Other Cases. Of the 72 cases, there were 26 that did not involve a slow drift out of the lane leading to a crash event. Generally, in these crashes the driver was actively controlling the vehicle but lost control, leading to the vehicle leaving the lane and crashing. For a high-level analysis (Table 9), there were 24 cases where the reason the driver left the lane was because of loss of control. In two cases the driver was active and engaged but drove the wrong way, resulting in a head-on impact with a vehicle in the opposing lane. Note that these cases were included in the analysis for completeness.

Table 8.
NMVCCS Coded Driver Related Factor for Drift-Out-of-Lane Cases

Driver Related Factor	Curve		Totals
	No	Yes	
Driver Related Factor- Type of driver error unknown	8	6	**14**
Driver Related Factor- Over-compensation	2	5	**7**
Driver Related Factor- Sleeping, that is, actually asleep	1	3	**4**
Driver Related Factor- Poor directional control (e.g., failing to control vehicle with skill ordinarily expected)	1	3	**4**
Driver Related Factor- Too fast for curve/turn	0	4	**4**
Driver Related Factor- Unknown critical non-performance	1	1	**2**
Driver Related Factor- Internal distraction	1	1	**2**
Driver Related Factor- Heart attack or other physical impairment of the ability to act	1	1	**2**
Driver Related Factor- Other	2	2	**4**
Totals	**17**	**26**	**43**

Table 9.
Summary of Other Cases

Classification	Counts
Loss of Control	24
Active Control	2
Total	26

For the cases classified as loss of control (Table 10), 13 cases were attributed to driving-related factors such as aggressive driving, speeding, or some sort of performance issue. In these cases, it was assessed that there were no factors external to driving performance that caused the driver to lose control given the roadway conditions.

Table 10. Other Cases Factors for Loss of Control Cases

Driving Related	Evasive Maneuver	Pre-Existing Physical Condition	Vehicle Issue	Un-known	Total
13	2	6	2	1	24

In many of these cases, electronic stability control (ESC) was an applicable technology that would likely have mitigated these crashes had the vehicles been so-equipped (the vehicles involved were older models and not equipped with ESC). In two cases the driver lost control because of reacting to an external factor and had to take an evasive maneuver resulting in a loss of control. There were six cases where it appears the driver of the vehicle had a pre-existing medical issue that likely caused the driver to lose control. In these cases, the crash was generally not severe and it appears likely the driver died as a result of the medical condition, not crash injuries.

Lastly, there were two cases where the vehicle was a factor when there was a tire failure which resulted in the vehicle leaving the lane, and one loss of control case where the reason for the loss of control was not clear. A summary table of the cases and factors are provided in the Appendix. The table lists factors assessed during the review of the cases and are not the NMVCCS coded critical reason for the crash.

Going forward, the paper will only focus on the 43 of the 72 cases identified as drifting out of the lane crashes since these crashes appear to be most relevant in assessing the benefits of LDW, LCC, and LKS crash avoidance systems.

Exemplar Cases

Straight Road Drift. Case No. 2007-74-95 occurred on a clear day with no adverse weather conditions present, on a two-lane undivided roadway, crossing a bridge. The roadway was level and had a posted speed of 60 mph. A 2000 Ford Taurus was traveling west and a 2000 Buick Park was traveling east. The Ford crossed the centerline and struck the Buick head-on. The driver of the Buick died on the scene and the passenger died later that day. The driver of the Ford expired a few days later in the hospital.

The lane markings were in good condition. The driver of the Ford was not under the influence of alcohol. The reason for the crossing over into oncoming traffic is unknown driver error. The scene diagram and vehicle approach can be seen in Figures No. 2 and 3.

Assessment: The team agreed that if the vision system could detect the free space of the roadway and the clearly defined lane markings, with a minor steering correction to maintain its forward heading, the crash would likely have been avoided.

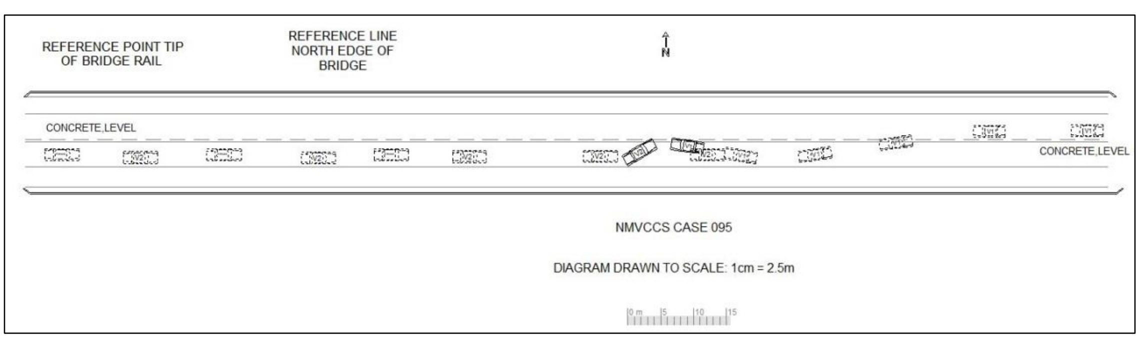

Figure 2. Case No. 2007-74-95 scene diagram.

Figure 3. Case No. 2007-74-95 vehicle approach.

Straight Gravel Road Drift. Case No. 2005-11-61 involves a 2002 Lincoln Continental traveling a straight, level, two-way, rural gravel roadway with no painted lines. At the time of the crash it was dark-unlighted and the roadway was dry. The Lincoln drifted and exited the roadway to the right. The front right of the vehicle contacted a tree. The posted speed was 55 mph. The driver of the Lincoln was intoxicated with a 0.21 BAC. The scene diagram and vehicle approach can be seen in Figures No. 4 and 5.

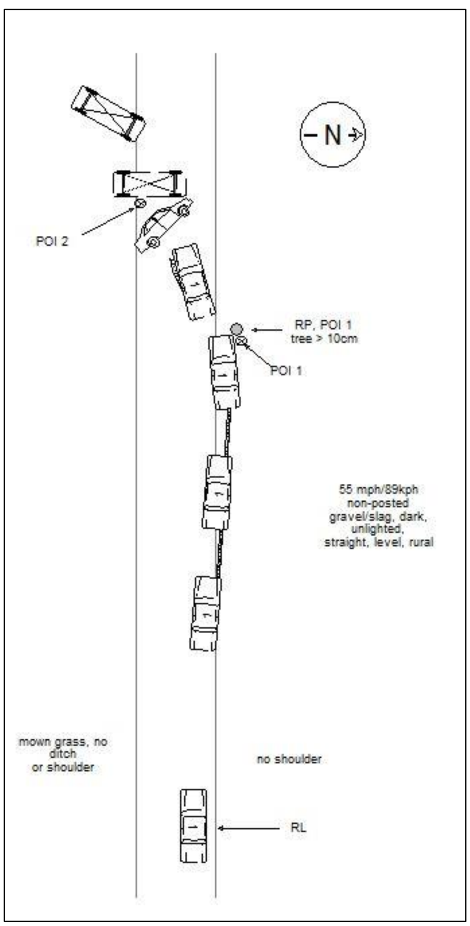

Figure 4. Case No. 2005-11-61 scene diagram.

Figure 5. Case No. 2005-11-61 vehicle approach.

Assessment: Independent of the intoxicated driver, the team agreed that if the vision system could detect the free space of the roadway and the road edge, with a minor steering correction to maintain its forward heading, the crash would likely have been avoided.

Curved Road Drift. Case No. 2007-43-88 was a two-vehicle fatal crash that occurred along an undivided two-lane, north/south S-curved road. The posted speed limit was 45 mph and the conditions were daylight, sunny, and dry. The subject vehicle was a 1995 Ford Mustang with one occupant traveling southbound negotiating a left curve. A 1999 Ford F-550 medium-heavy pickup truck with one occupant was traveling northbound on the same roadway. The Ford Mustang departed the road to the right with its right front and right rear tires. It then traveled an unknown distance while off the road to the right and re-entered the roadway around an area of road edge deterioration in a counterclockwise yaw. When the Ford Mustang re-entered the roadway, it traveled across its original travel lane, crossed the double-yellow lane line, and entered the oncoming lane where it impacted the Ford F-550, resulting in fatal injuries to the occupant of the Ford Mustang. There were no rumble strips present; however, there was a solid white lane marking on the right side and a solid double yellow line dividing the two lanes. The scene diagram and vehicle approach can be seen in Figures 6 and 7.

Assessment: Given that the roadway had lane markings on both sides that were in good condition and the driver was not speeding for the conditions, the team agreed that a vision system should have been able to detect the lane markings, and that a system with active control capable of preventing lane departures while the vehicle was negotiating the S-curve could have prevented the crash. This case differs compared to the straight road cases discussed above because the system would need to have a greater ability to affect directional control (i.e., higher intervention authority) to actively and effectively assist in maintaining the vehicle heading. In the straight road cases, only a minor correction is believed to have been necessary.

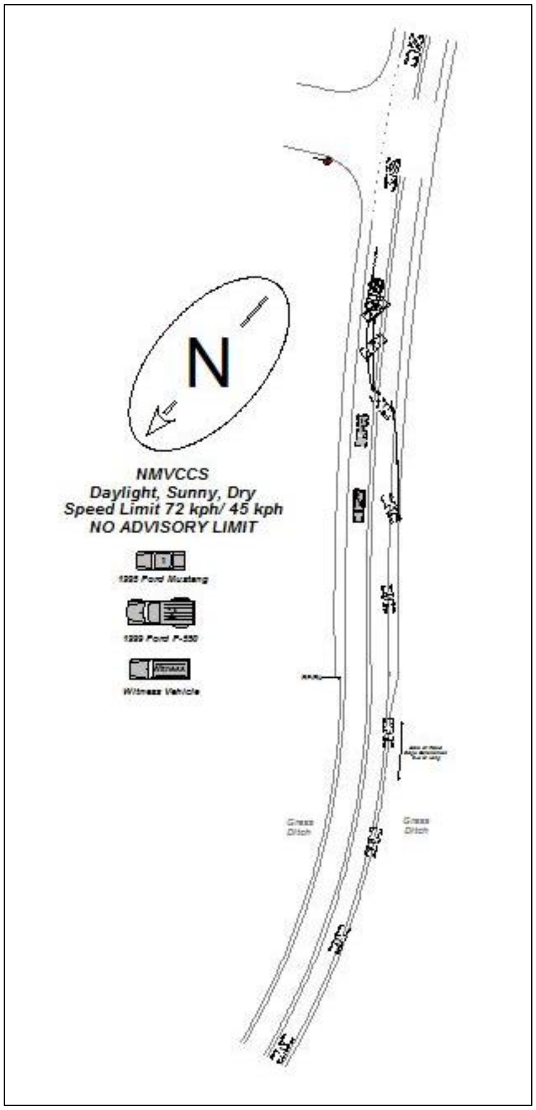

Figure 6. Case No. 2007-43-88 scene diagram.

Figure 7. Case No. 2007-43-88 vehicle approach.

DISCUSSION

A total of 72 NMVCCS cases were reviewed. In 43 of the cases, the driver of the subject vehicle drifted out of the lane resulting in a crash, and in three cases an involved driver crashed because of a lane change. The 43 cases where the driver drifted out of the lane are relevant to the target population where LDW/LKS/LCC could be beneficial in preventing the crash or reducing the severity. The three lane changing cases could benefit from, at a minimum, a blind spot detection or intervention system. This discussion will focus primarily on the 43 drift-out-of-lane crashes. Based upon the NMVCCS case weights, the 43 cases represent 22,477 crashes for the 3 years of the study, or approximately 7,500 crashes a year.

Many of the NMVCCS cases included crashes that LDW/LKS/LCC systems would not be expected to address. In 24 cases the driver departed the travel lane and crashed after they lost control of the vehicle, and in two cases, the driver crashed while traveling in the opposing lane because they were intoxicated or attempting to pass a slower vehicle. In these types of crashes, LDW/LKS/LCC would not have prevented the vehicle from leaving the travel lane. For that reason, these cases should be excluded in any analysis that attempts to define a target population where LDW/LKS would be applicable.

Any contemporary LDW/LKS/LCC crash avoidance system relies on at least one camera to monitor the roadway and lane markers. Therefore, it is critical for the lane markings to be present and in good condition. Beside the few exceptions discussed earlier, almost all of the crashes occurred where the lane markings were present on both sides of the vehicle and in good condition. Additionally, most of the crashes occurred during the day. For the crashes that occurred at night or when it was raining, it was assessed that the vision system would have likely been able to detect and monitor the lanes based upon the on-scene photos in the case files. There were no indications that the lane markings detection would have been adversely affected because of rain present during low-light conditions. This does not suggest sensor blindness does not happen during real world driving, just that it was not captured in the cases under review. Therefore, to better understand their real-world performance, vision systems should be tested or evaluated with a range of diverse environmental conditions (e.g., in the dark, in situations where sun glare could wash out the image of the travel lane lines, etc.).

In many cases, it was difficult to determine why the driver drifted off the road. In only 14 cases could it be concluded that the state of the driver was a likely known contributing factor in the crash. This was because intoxication, sleeping, distraction, or health related physical impairment was identified in the case. However, in the rest of the cases, where the driver's state was not clear, some level of inattention or distraction was believed to be a likely reason for the lane departure event.

In the cases reviewed, speeding did not appear to be a primary factor in the crash, even though it may have been noted in the case file as a factor in the crash. However, traveling above the posted speed may have contributed to the severity of the crash. For the cases where the road was straight, the median posted speed was 55 mph, and where there was curvature the median posted speed was 45 mph. A prior study [Kusano, 2013] analyzed the pre-crash data collected from 256 Event Data Recorders (EDR) involved in real-world lane departure crashes from the 2000 through 2011 National Automotive Sampling System (NASS) - Crashworthiness Data System (CDS). Kusano found in the NASS-CDS study that 65 % of drivers were traveling above the posted speed limit prior to the crash and that drivers were speeding more often on low speed limit roads. For crashes occurring on straight roads, speeding was not expected to be a significant factor in assessing the benefits of LKS/LCC. For example, in Case No. 2005-76-035 the EDR data identified the driver was traveling 70 mph at the time of a crash on a straight road with a posted speed of 55 mph. In this case the driver drifted over the center line and departed the road on the left resulting in a rollover. From Figure 8, it is reasonable assume that an LKS/LCC could help maintain the position of the vehicle within the lane even 15 mph above the posted speed.

Figure 8. Case No. 2005-76-035 vehicle approach.

In Case No. 2007-43-88 discussed earlier [Figure 6-7] which occurred on a curved road, the vehicle was alleged to be traveling at 45 mph which was the posted speed at the time of the crash. In reviewing this case there was no evidence that the driver lost control. Therefore, it was assessed that within reason, even at the higher travel speed, an LKS/LCC with enough authority should have prevented the driver from departing the lane. In all 43 cases reviewed, speeding above the posted speed was not deemed to be an issue for maintaining lane position or contributed to the driver drifting out of the lane. A robust LKS/LCC should reduce the variability of the lateral position of the vehicle within the lane and thus make it more difficult for the driver to drift within the lane, much less out of it. Under most of the operating conditions present in the cases reviewed, an LDW/LKS/LCC would be expected to detect the lane and, at minimum, provide an alert when the driver is about to cross a lane line. However, with respect to the performance of LKS/LCC, the combination of roadway geometry and vehicle speed would likely play a significant role in the effectiveness of the system. For that reason, the 43 cases were grouped into crashes that occurred on straight roads, and crashes that occurred on curved roads. There were 17 cases that occurred on generally straight roads and 26 that occurred on a curved road. This was done because it was believed that on straight roads, only a minor course adjustment would have been necessary to prevent the fatal crash resulting from the driver drifting out of their lane. On roads with curves, the LKS/LCC would need more directional authority to prevent the drift out of the lane.

For Case No. 2005-76-035, illustrated in Figure 8, the LKS/LCC would have only had to provide minor corrections to keep the position of the vehicle within the lane markings.

In Case No. 2007-078-071, shown in Figure 9, and 2005-078-092, illustrated in Figure 13, the roadways had rumble strips. These are interesting cases since rumble strips are designed to provide strong auditory and haptic feedback to the driver as they are being driven over, yet the drivers still drifted out of their respective lanes. Since the feedback from rumble strips is expected to be more apparent than an LDW alert, regardless of the LDW alert modality, it is unlikely the presence of an LDW would have prevented the lane or road departures described in these cases. However, because an LKS/LCC system does not require the driver to activate its interventions, and these interventions are designed to actively address the imminent departure, LKS/LCC systems may have effectively prevented the crashes described in these cases. Figure 9 is a photo of the approach of the subject vehicle in Case No. 2007-078-071. In this case the vehicle drifted off to the left resulting in a rollover crash.

Figure 9. Case No. 2007-078-071 vehicle approach.

Cases that involved drifting out of the lane on curved roads were similar to those associated with straight roads; however, for LKS/LCC system to be effective on curved roads, more lateral control authority is required (i.e., the system needs to correct the departure while also compensating for the curve radius). Case No. 2005-045-118 is an example where the driver drifted out of the lane on the right (Figure 10).

Figure 10. Case No. 2005-045-118 vehicle approach.

In Cases 2006-045-063 and 2007-002-032 the driver drifted out of the lane on the left (Figures 11 and 12).

Figure 11. Case No. 2006-045-063 vehicle approach.

Figure 12. Case No. 2007-002-032 vehicle approach.

Of the 43 cases we examined, there was almost twice the number of curved road cases as there were straight road cases. Additionally, in the crashes examined, excessive speed given the posted speed did not appear to be a primary factor in the crashes.

Active lane keeping is an essential component in autonomous driving; however, this study reveals some important considerations for using LKS/LCC or other automated steering systems in the real-world. For example, in Case No. 2005-078-092, the driver was coded as sleeping, drifted off a straight road to the left, over rumble strips, subsequently woke up, over-corrected and rolled the vehicle off the road to the right (Figure 13).

Figure 13. Case No. 2005-078-092 vehicle approach.

The conclusion that arose from this type of case is that a LKS/LCC would have likely prevented the driver from drifting off the road. However, the concern is if the vehicle was equipped with an LKS/LCC and the driver never drifted out of the lane while still asleep, it is impossible to determine when and where the driver would have awoken and regained control. If the driver remained sleeping, the vehicle may have driven through an intersection resulting in a different type of crash, or the vehicle may have coasted to a stop in the middle of the road. The same types of concern arise for any situation where the driver is incapacitated due to sleeping, alcohol use or other physical impairment. This is especially true if a longitudinal control system is also engaged (e.g., adaptive cruise control, or ACC). Therefore, as automatic steering systems become more sophisticated, distracted/drowsy driving/alcohol detection systems may [Ridella, 2015] be required to address such situations in addition to bringing the vehicle to a stop safely if the driver cannot be reengaged. These observations are also consistent with Cicchino, who stated designers should account for the large proportion of drivers who will be potentially shielded from an initial lane departure crash but who nevertheless remain unable to regain control of their vehicles. These drivers remain at a high risk of crashing if their lane-keeping assist systems are incapable of bringing their vehicles safely to a stop off the roadway. [Cicchino, 2016] Given the large target population of crashes this technology can address, an effective implementation strategy is critical in order realize the full safety benefits.

CONCLUSION

From a study of 72 NMVCCS cases, 43 were drift out of the lane type of roadway departures relevant to assessing the real-world applicability of LDW/LKS/LCC crash avoidance technologies. The two high-level crash characteristics identified were related to the roadway geometry; there were 17 cases that occurred on a generally straight road and 26 on a curved road. This was found to be important because the countermeasure for the system to maintain the vehicle's path in the travel lane would be slightly different. For the cases on straight roads, only a minor course correction would have been needed to maintain the vehicle's headway and stay in the lane. For those cases on curved roads, an LKS/LCC would need more authority to not only prevent the vehicle from drifting out of the lane, but also navigate the curved path of the roadway.

A robust LKS/LCC should make it more difficult for the driver to drift out of their lane. With sufficient authority, it is believed that LKS/LCC systems could have effectively prevented many of the 43 cases reviewed in this study. In other words, unless there were other factors present, a robust LKS/LCC would have prevented the driver from running out of the lane and starting the chain of events that led to the fatal crashes. For that reason, LKS/LCC appears to have more potential in crash reduction than LDW since the system does not rely on alert modality effectiveness or for the driver to take corrective action.

More research and evaluations need to be done on the state-of-the-art vision systems. Specifically, there are research needs with respect to the performance of the system, but equally important research is also needed on how real-world drivers interact with these systems and how they may affect driver behavior. Given that many of these crashes involve drivers who are not actively engaged in driving at the time they depart the travel lane, effective strategies to reengage the driver need to be considered. Alternatively, the system needs to bring the vehicle to a stop safely in order to realize the full safety benefits of the technology.

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Appendix

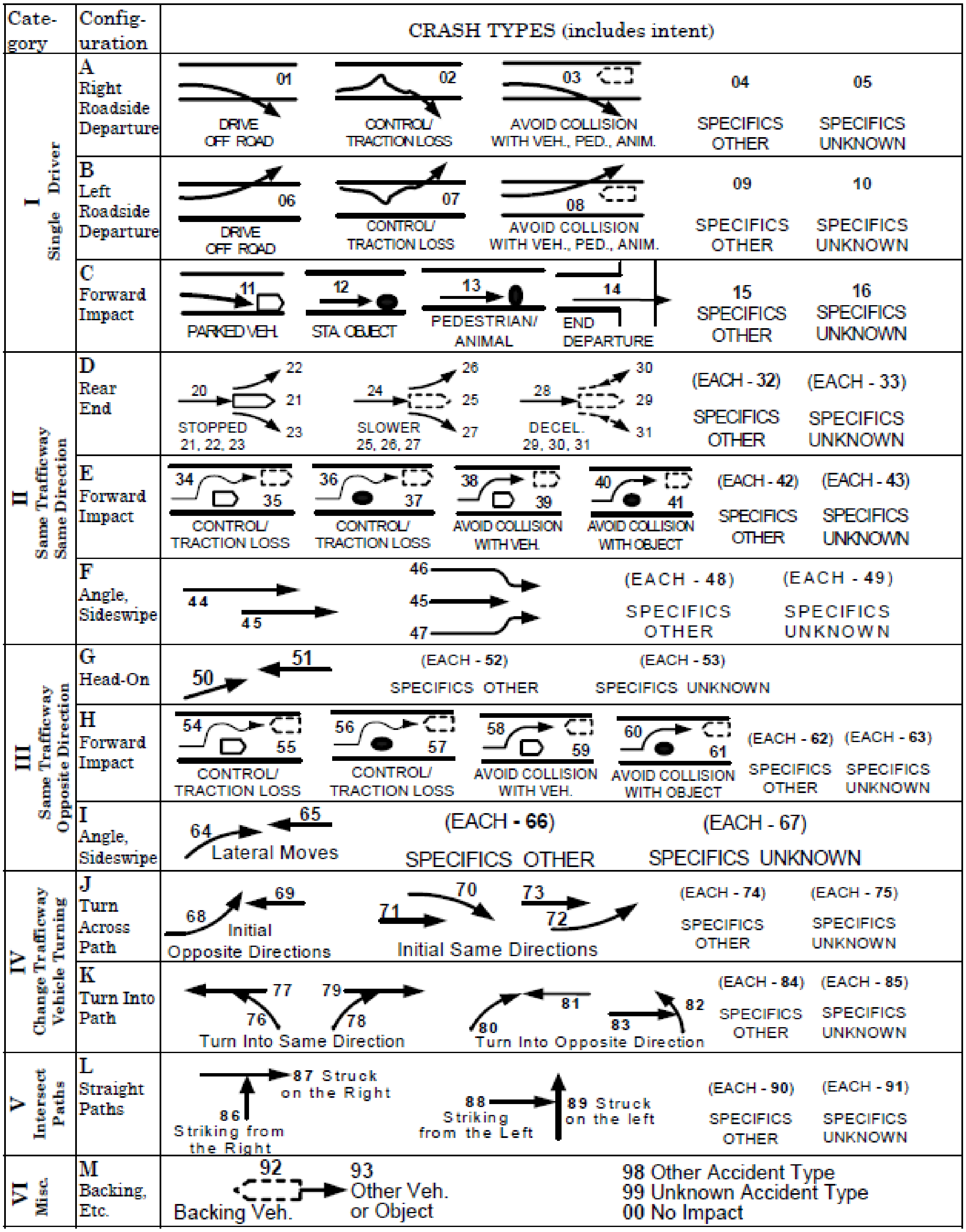

Figure A1. Crash type descriptions.

Table A1.
Cases By Crash Type Code (Italics - Lane Change Cases and Bold - Other Cases)

NASSCASESTR	CRASH_TYPE	NASSCASESTR	CRASH_TYPE	NASSCASESTR	CRASH_TYPE
2005-02-049	1	**2006-41-070**	**6**	**2006-78-125**	**50**
2005-11-061	1	2006-48-064	6	2007-48-091	50
2005-45-118	1	**2006-74-181**	**6**	2007-76-043	50
2005-76-026	1	2007-43-095	6	2007-76-087	50
2006-13-053	1	2007-48-009	6	**2007-76-088**	**50**
2006-43-073	1	2007-49-043	6	2005-45-095	51
2006-49-144	**1**	2007-78-071	6	2006-04-032	51
2006-76-016	1	**2005-12-052**	**7**	2007-02-032	51
2007-08-001	1	*2005-12-083*	*7*	**2007-09-012**	**51**
2007-08-018	**1**	2005-43-117	7	2007-74-095	51
2007-11-082	1	**2006-09-046**	**7**	2007-78-054	51
2007-43-111	**1**	2006-13-002	7	2007-78-061	51
2007-48-006	1	2006-43-067	7	**2006-76-074**	**52**
2007-76-021	1	**2006-78-096**	**7**	**2005-12-077**	**64**
2006-45-063	2	2007-05-039	7	**2005-78-075**	**64**
2006-48-074	**2**	**2007-41-084**	**7**	2006-45-048	64
2006-78-073	2	**2007-76-076**	**7**	**2006-49-078**	**64**
2007-81-007	2	2007-78-065	7	2007-11-002	64
2007-81-066	**2**	**2005-11-010**	**45**	*2005-79-053*	*65*
2005-74-026	**6**	*2007-75-097*	*48*	**2005-12-101**	**66**
2005-76-035	6	2005-45-046	50	**2006-06-100**	**66**
2005-78-051	6	2005-45-072	50	**2006-12-119**	**66**
2005-78-092	6	**2005-81-059**	**50**	2006-45-148	66
2005-81-053	**6**	2006-48-040	50	2007-43-088	66

Table A2.
Summary Table Other Cases by Factors

No.	NASSCASESTR	Primary Factor	Secondary Factor
1	2005-12-052	Loss of Control	Driving Related
2	2006-48-074	Loss of Control	Driving Related
3	2005-81-053	Loss of Control	Driving Related
4	2007-76-076	Loss of Control	Evasive Maneuver
5	2007-09-012	Loss of Control	Driving Related
6	2005-11-010	Loss of Control	Driving Related
7	2005-12-077	Loss of Control	Pre-Existing Medical Condition
8	2005-74-026	Loss of Control	Pre-Existing Medical Condition
9	2005-78-075	Loss of Control	UNK
10	2005-81-059	Loss of Control	Pre-Existing Medical Condition
11	2006-09-46	Loss of Control	Driving Related
12	2006-041-070	Loss of Control	Pre-Existing Medical Condition
13	2006-49-78	Loss of Control	Driving Related
14	2006-49-144	Loss of Control	Driving Related
15	2006-74-181	Loss of Control	Pre-Existing Medical Condition
16	2006-78-096	Loss of Control	Tire Related
17	2006-78-125	Loss of Control	Tire Related
18	2007-08-018	Loss of Control	Pre-Existing Medical Condition
19	2007-41-084	Loss of Control	Driving Related
20	2007-43-111	Loss of Control	Driving Related
21	2005-12-101	Loss of Control	Driving Related
22	2006-06-100	Loss of Control	Evasive Maneuver
23	2007-76-088	Active Control	Passing
24	2007-81-066	Loss of Control	Driving Related
25	2006-76-074	Active Control	Traveling Wrong Direction
26	2006-12-119	Loss of Control	Driving Related