Run-Off-Road Collision Avoidance Using IVHS Countermeasures

Final Report

ABSTRACT

This document presents performance guidelines for the design and development of road departure warning systems to improve vehicle safety by eliminating or mitigating road departure crashes through driver notification or warning. Performance guidelines are presented for two classes of road departure warning systems, Lane Drift Warning Systems (LDWS) and Curve Speed Warning Systems (CSWS). A LDWS is designed to warn in the event of an unintentional drift out of the travel lane, typically due to driver drowsiness, distraction or inattention. A CSWS is designed to warn if the vehicle is approaching a curve too fast for the current conditions.

All aspects of system performance are addressed, including sensing requirements, warning algorithm requirements, driver interface requirements, test procedures, and estimation of associated benefits.

These guidelines are intended to be used by manufacturers and developers of road departure warning systems as a tool to:

1. Standardize system requirements

2. Standardize driver interface and control across systems developed by different manufacturers

3. Standardize test procedures to verify proper system operation.

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PREFACE

This document presents performance guidelines for the design and development of road departure warning systems to improve vehicle safety by eliminating or mitigating road departure crashes through driver notification or warning. Performance guidelines are presented for two classes of road departure warning systems, Lane Drift Warning Systems (LDWS) and Curve Speed Warning Systems (CSWS). A LDWS is designed to warn in the event of an unintentional drift out of the travel lane, typically due to driver drowsiness, distraction or inattention. A CSWS is designed to warn if the vehicle is approaching a curve too fast for the current conditions.

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These guidelines are intended for use by manufacturers and developers of road departure warning systems as a tool to:
1. Standardize system requirements

2. Standardize driver interface and control across systems developed by different manufacturers

3. Standardize test procedures to verify proper system operation.

The guidelines specified within this document should be considered recommendations for achieving acceptable performance in a road departure warning system. These guidelines are the culmination of nearly 6 years of NHTSA sponsored investigation. These guidelines are intended to be as technology-independent as possible and allow for the development of systems that are solely vehicle-based, as well as systems that require some form of cooperative infrastructure.

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INTRODUCTION

This document presents performance guidelines for road departure warning systems for improving vehicle safety by preventing or mitigating road departure crashes through driver notification or warning.

The intent of these guidelines is to aid the developer in the design and deployment of a minimum acceptable system. Systems that significantly deviate from these guidelines are expected to be unacceptable by the driving public, because they do not provide sufficient safety benefits, are too difficult to use, or provide too high a nuisance/false alarm rate.

1.1 SCOPE

This document is specific to those systems that detect potential road departure crash situations and provide a warning to the driver as an aid in avoiding the crash. Systems that provide active vehicle control, either momentarily to avoid the crash, or continually to keep the vehicle on the road, are excluded from the scope of this document.

1.2 OBJECTIVE

The objective of a road departure warning system following these guidelines is to increase driver awareness and subsequently reduce deaths, injuries and economic losses resulting from road departure crashes.

1.3 BACKGROUND

A statistical review of the 1992 General Estimation System (GES) and Fatal Accident Reporting System (FARS) databases indicate that run-off-road crashes are the most serious of crash types within the US crash population. The crashes account for over 20% of all police reported crashes (1.6 million / year), and over 41% of all in-vehicle fatalities (15,000 / year).

Some of the most important characteristics of road departure crashes are the following:

- They occur most often on straight roads (76%)

- They occur most often on dry roads (62%) in good weather (73%)

- They occur most often on rural or suburban roads (75%)

- They occur almost evenly split between day and night

Unlike many of the other crash types, run-off-road crashes are caused by a wide variety of factors. Detailed analysis of 200 NASS CDS crash reports indicates that run-off-road crashes are primarily caused by the following six factors (in decreasing order of frequency):

- Excessive speed (32.0%) - traveling too fast to maintain control

- Driver incapacitation (20.1%) - typically drowsiness or intoxication

- Lost directional control (16.0%) - typically due to wet or icy pavement

- Evasive maneuvers (15.7%) - driver steers off road to avoid obstacle

- Driver inattention (12.7%) - typically due to internal or external distraction

- Vehicle failure (3.6%) - typically due to tire blowout or steering system failure

This document focuses on two primary functions for the road departure warning systems, which we termed "lateral" and "longitudinal" road departure warning.

A lateral warning system (also called a Lane Drift Warning System or LDWS) is designed to detect when the vehicle begins to drift from the road. It utilizes data about the dynamic state of the vehicle, in combination with information about the geometry of the road ahead to determine if the vehicle's current position and orientation will likely lead to a road departure. If the likelihood of departure exceeds a threshold, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash. A LDWS is designed to prevent those run-off-road crashes caused primarily by driver inattention and driver incapacitation.

The goal for a longitudinal warning system (also called a Curve Speed Warning System or CSWS) is to detect when the vehicle is traveling too fast for the upcoming road segment. The longitudinal warning system utilizes vehicle dynamic state and performance data in combination with information about the current pavement conditions and upcoming road geometry to determine the maximum safe speed for the vehicle. If the vehicle's current velocity exceeds the safe speed, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash. A CSWS is designed to prevent those run-off-road crashes caused by excessive speed and lost directional control.

The two warning system types (LWDS and CSWS) do not address all the causal factors for road departure crashes listed above. Other functions, such as direct driver impairment detection, forward obstacle detection (to prevent the need to depart the road to avoid an obstacle) and vehicle component failure warning (to warn the driver of mechanical problems which could result in a road departure crash) could also be investigated as a means of preventing road departure crashes. However these alternative functions are addressed by other USDOT programs and are not the focus of this document.

1.4 APPROACH

The purpose of this document is to provide designers of road departure warning systems with practical performance guidelines for the development of acceptable and effective systems. The general approach to the development of these guidelines has been to:

- Identify the functions these warning systems must perform.

- Determine either analytically or through experimentation how the functions may be performed.

- Determine either analytically or through experimentation the level of performance required for an acceptable and effective system.

Whenever possible, the functions and level of performance are generalized so that they are independent of the technology used to implement them. This technology independence must be balanced against the need to provide concrete recommendations that can help guide system designers, who must implement these guidelines.

The performance guidelines presented in this document are the result of nearly 6 years of investigations as part of the NHTSA-sponsored Roadway Departure Countermeasures Specifications Program. These guidelines are primarily based on the results generated in the following program activities:

- Analysis of actual road departure crashes involving passenger vehicles, as well as road departure crashes involving commercial trucks

- Over 60,000 miles of in-vehicle sensor, warning algorithm and interface testing by project personnel

- Several thousand miles of sensor and warning algorithm tests (without driver interface) by naïve drivers

- Driver interface experiments of complete warning systems on the Iowa Driving Simulator

- Mathematical modeling and computer simulations of both normal driving and road departure crash scenarios with and without warning system support.

To definitively specify performance guidelines for acceptable and effective road departure warning systems will require a field trial of complete systems (including a driver interface) in the hands of naïve drivers. Such a field trial is beyond the scope of the program on which this document is based. Therefore this document contains performance guidelines based on educated extrapolations from the tests listed above. As a result, the performance guidelines take the form of recommendations, with the qualifier "should", instead of performance requirements, with the qualifiers "shall" or "must". In circumstances where there is not enough data from the above experiments to make an educated extrapolation, specific values in the performance guidelines are left as "TBD" – to be determined.

The remainder of this document is divided into two major parts, addressing performance guidelines for Lane Drift Warning Systems (LDWS) and Curve Speed Warning Systems (CSWS), respectively. Within these two major parts, there are individual sections containing guidelines for sensing, warning algorithm and driver interface performance. Each major part also contains sections on test procedures for evaluating the performance of LDWS and CSWS.

2 DEFINITIONS

The following definitions form a basis for further discussions of road departure warning systems.

2.1 SYSTEM DEFINITIONS

Road departure crash – Any single vehicle crash where the first harmful event occurs off the roadway, except for backing and pedestrian related crashes. Road departure crashes are also referred to as "run-off-road crashes", or "lane departure crashes".

Run-Off-Road (ROR) Program – The NHTSA-sponsored six-year program to develop performance guidelines for road departure warning systems. This document is the culmination of the ROR program.

Road departure warning system – A system designed to aid the driver in avoiding or mitigating road departure crashes through warnings to the driver. A road departure warning system does not attempt to control the host vehicle in order to avoid an impending crash; any interaction with driver controls, such as a steering wheel shaker, is only designed as a haptic interface to the driver. Two types of road departure warning systems are addressed in this document, lane drift warning systems (LDWS) and curve speed warning systems (CSWS).

Lane Drift Warning System (LDWS) – A road departure warning system designed to help prevent crashes resulting from an unintentional drift of the vehicle out of its travel lane.

Curve Speed Warning System (CSWS) – A road departure warning system designed to help prevent crashes resulting from excessive speed for the upcoming road conditions, particularly on the approach to curves.

Host Vehicle – The vehicle on which the road departure warning system is installed and operating.

Autonomous system – A system that requires no modification or additions to the infrastructure in order to perform the intended function. Autonomous systems are the focus of these guidelines, although cooperative systems will not be excluded.

Cooperative system – A system that relies on modifications to the existing infrastructure to perform its intended functions.

Automatic control system – A system that provides temporary vehicle control such as braking and/or steering to avoid a collision. These systems are excluded from the scope of this document.

Lane - The area of roadway that a vehicle would be expected to travel in the absence of any obstruction or desire to change route.

Travel lane – The lane that the host vehicle is following, or is intending to follow.

Lane boundary – The outer edge of the lane.

Lane departure - The situation when any part or whole of any wheel is outside the lane boundary. A lane departure can be intentional or unintentional. Also called a "lane excursion".

Virtual boundary – An imaginary boundary defined to be a short distance beyond (outside) the actual lane boundary. Used as a threshold by some LDWS algorithms to reduce nuisance alarms.

Lateral position – The position of the geometric center of the host vehicle relative to the center of the travel lane.

Lateral velocity – The rate at which the vehicle is traveling towards or away from the center of the travel lane.

Time To Line Crossing (TLC) – The time (typically measured in seconds) until the outer edge of one of the host vehicle's tires crosses the lane boundary.

Lane markings - Visible or implied patterns along the road that indicate the lane boundary.

Visible Lane Marking - A man-made type of lane marking in the form of continuous or regular intermittent visible elements along an edge of the lane.

Reflective marker - Device that reflects electromagnetic radiation (including light), generated by in-vehicle devices, back to the vehicle generating the radiation.

Magnetic markers - Magnetic materials or devices that delineate the location of the lane.

Visible road surface features - Visible patterns on or near the lane that can be used to determine the position of the lane. These could include, but are not limited to, visible edges caused by adjacent road surface types, or caused by roadside objects such as barriers, guard rails etc. Visible road features may also include transient or semi-permanent features such as tracks or ruts left by previous vehicle (e.g. in snow or with road surface discoloration).

Global Position System (GPS) – A technique based on satellite triangulation that allows estimation of a vehicle's absolute position in the world.

Differential GPS (DGPS) – A GPS system that has been augmented with local corrections to make its position estimates more accurate.

Digital map – A computer database of road geometry information, such as the location of the road center, number of travel lanes, lane width, road curvature, position of intersections, etc.

2.2 DRIVER DEFINITIONS

Mental model – The mental model refers to the system performance that would reasonably be anticipated by a naïve (untrained) driver of a vehicle equipped with a road departure warning system. Drivers would reasonably expect a road departure warning system to behave like an "ever-vigilant" observer monitoring the vehicle trajectory and the road ahead to provide warnings when necessary to avoid a road departure crash.

Attentive driver – An attentive driver is alert and in full control of the host vehicle. The driver is able to perceive the situation and make corrections to the vehicle's speed and direction to avoid a road departure crash without assistance from the system.

Inattentive / distracted driver – An inattentive or distracted driver is not focused on the vehicle control task. Inattentive or distracted drivers are assumed to have longer reaction times than attentive drivers.

Drowsy / impaired driver – A drowsy or impaired driver is being influence by a physiological condition that reduces his driving competence. He is assumed to have a longer reaction time, and may not react as appropriately to stimuli as an attentive driver.

Availability – The fraction of the time the system is operating correctly, ready to support the driver with warnings if necessary.

Efficacy rate – The number of times the system provides a correct warning compared to the number of times that a warning is required according to the following table. Efficacy rate is also known as the "hit" rate and the complement is known as the "miss" rate.

		Situations Requiring a Warning	Situations NOT Requiring a Warning
System Response	Warning	Correct Warning (hit or true positive)	Incorrect Warning (false alarm, nuisance alarm, or false positive)
	No Warning	Incorrect Non-Warning (miss or false negative)	Correct Non-Warning (true negative)

False alarm – An incorrect warning that occurs because the system has incorrectly interpreted its sensor data, and therefore does not appropriately model the situation.

Nuisance alarm – A situation where the system has modeled the situation correctly based on its sensor data and given a warning, but which does not constitute a true crash threat for the subject driver. "A nuisance alarm represents a difference of opinion between the system designer and an individual driver of the situations where is signal is necessary" [Burgett, 1995].

Miss – A situation that requires a warning by the system does not provide a warning to the driver.

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3   LDWS PERFORMANCE GUIDELINES

This section presents guidelines for Lane Drift Warning Systems (LDWS). These guidelines are operating performance parameters that should be considered as part of the design of such systems.

These systems are designed to help prevent crashes resulting from an unintentional drift of the vehicle out of its travel lane. These crashes are typically caused by driver inattention / distraction, or by driver drowsiness / impairment.

A block diagram of a representative LDWS is shown in Figure 3-1. The LDWS uses sensors to determine the vehicle's state (position/velocity) relative to the road. A collision warning algorithm interprets this state to determine if the vehicle is in danger of unintentionally drifting out of the travel lane. If so, the system provides a warning to the driver.
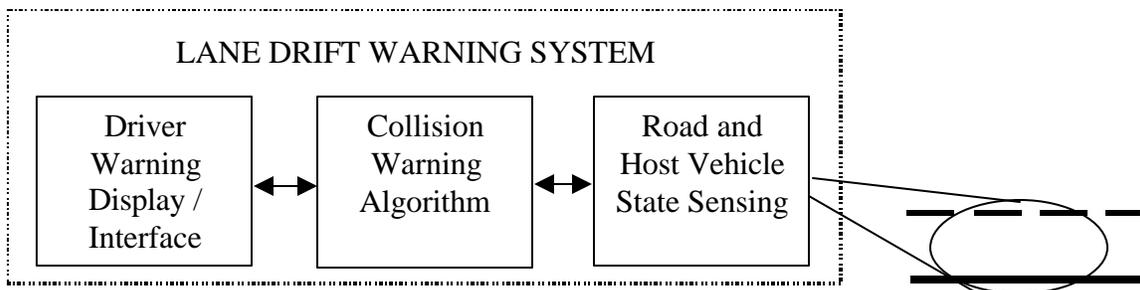
Figure 3-1: Lane Drift Warning System Block Diagram

As can be seen from Figure 3-1 there are three functional blocks in a LDWS. They are sensing module, the warning algorithm and the driver interface. Within each of these blocks are a number of functions that the system must perform. These individual functions, along with guidelines for how these functions may be accomplished, and the level of performance required for an acceptable and effective system, are presented below. The guidelines themselves are in **BOLD** text, and are preceded by a numerical designation like **[L-1]**, to indicate the first LDWS guideline.

3.1   SENSING FUNCTIONS AND GUIDELINES

Sensing is almost certainly the most challenging aspect of LDWS design. The sensing functions that need to be performed by a LDWS include:
- Determine vehicle position and orientation relative to the road
- Determine geometric characteristics of upcoming road segment
- Determine elements of the vehicle dynamic state relative to the road
- Determine driver intention

3.1.1   DETERMINE VEHICLE POSITION AND ORIENTATION

In order to determine if the vehicle is in danger of departing the road, a LDWS must accurately and reliably estimate the vehicle's position and orientation relative to the road. It should be able to make these estimates (as well as the other sensor estimates outlined later) in the range of environmental conditions a typical user would expect the system to operate under. But the reality is that no sensor is perfect, and there will be environmental conditions that make it difficult or impossible to estimate the vehicle's position and/or orientation on the road. Examples of these conditions for a video-based sensor might include a road entirely blanketed in snow or a road obscured by street light reflections off wet pavement at night. As will be seen in the driver interface guidelines in Section 3.3, when environmental conditions are so severe as to significantly degrade system performance, the system should recognize this, discontinue operation and report the situation to the driver.

[L-1]   A LDWS should be capable of determining the vehicle's position and orientation relative to the lane in all reasonable environmental conditions. This should include both day and night operation. It should also include operation in rain, snow, sleet and fog.

Occasionally, a LDWS may experience brief periods during which an accurate estimate of the vehicle's position relative to the road may not be possible. For example, this might occur when there is a short gap in the lane markings at an intersection, or when entering/exiting a tunnel due to the extreme lighting conditions. A LDWS needs to be able to handle these situations reasonably by extrapolating previous estimates for a short time. Measurements conducted in support of this document show that extrapolating for a distance of up to 15m is appropriate to cover most situations where it is not possible to estimate the vehicle's position and orientation relative to the road.

[L-2]   A LDWS should function without interruption during brief periods when it cannot accurately estimate the position of the vehicle relative to the road. During these periods, the system should use previous estimates of roadway geometry and vehicle trajectory to extrapolate the current position of the vehicle relative to the road. The system should be capable of extrapolating for at least the lesser of 15m of vehicle travel, or 0.5 seconds.

To ensure adequate coverage, a LDWS should rapidly reacquire lock on the lane after a brief interruption, enabling it to resume accurately estimation of the vehicle's position and orientation within a short time. Such brief interruptions might result from temporary dropout of the features being tracked, or from a lane change, where the system needs to begin tracking new features.

[L-3]   Following a brief interruption caused by feature dropout or lane change, a LDWS should resume accurate estimation of the vehicle's position and orientation within 5 seconds.

As will be addressed in the driver interface guidelines in Section 3.3, if the LDWS continues to be unable to estimate the vehicle's lateral position and orientation for an extended period of time, it should discontinue operation and non-intrusively make the driver aware of the system's degraded performance status.

While it is acceptable for a LDWS to be unable to operate effectively under some circumstances, in order to be effective and acceptable to drivers there are two criteria a LDWS should meet. First, the situations that preclude effective performance must be rare. In other words, the system's overall availability must be high. Second, the LDWS must quickly detect and inform the driver of its degraded performance status in nearly all circumstances. To determine the precise values for "high" and "nearly all circumstances" above will require field trials with naïve drivers. As a result, the following two guidelines contain TBD values.

[L-4] The LDWS availability due to degraded environmental conditions, momentary signal loss or system malfunction should not fall below TBD percent of the total time the vehicle is operating on roads.

[L-5] If the LDWS is unable to accurately estimate the vehicle position and orientation relative to the road due to degraded environmental conditions, momentary signal loss or system malfunction, the system should detect its degraded performance status within at most TBD seconds in TBD percent of cases. Upon detecting its degraded performance status, the system should discontinue operation and inform the driver of its status.

Tests conducted for the ROR program with video-based road sensing systems indicate that system availability in the 95-99% range is achievable with existing technology across a range of road types, weather and lighting conditions. In over 99% of the remaining situations where it is unable to operate effectively, the system can detect its degraded performance status in less than 5 seconds. Whether these performance characteristics will be acceptable to the average driver requires a field trial to determine.

For a LDWS to be effective and acceptable, it must accurately estimate the position of the vehicle in the lane. This position estimate may be the position of the center of the vehicle relative to the lane center, or alternatively, the position of the outer edge of the vehicle relative to the closest lane boundary. The choice of reference is left to the discretion of the system designer. Whatever reference for lateral position is chosen, the accuracy of the lateral position estimate is crucial.
Analysis of a range of alternative LDWS warning algorithms described in Section 3.2 indicate that errors of 10cm in lateral position have an acceptably small impact on LDWS warning onset time and nuisance alarm rate. Furthermore, in-vehicle experiments conducted for the ROR program suggest that errors of at least 10cm in a driver's estimate of where the edge of the vehicle is relative to the lane boundary are quite common. This suggests that a 10cm error may not even be easily detectable by many drivers. On-road

tests with video-based road sensing systems indicate that better than 10cm lateral position accuracy is achievable with existing technology.

[L-6] The LDWS should measure the lateral position of the vehicle within the lane to an accuracy of 10cm.

There are many conceivable ways of estimating the lateral position of the vehicle relative to the lane, including:
- A forward-looking video-based sensor to track visible road features
- A downward looking video-based sensor to track visible lane markings
- Sensors to detect continuous or intermittent magnetic markers placed down the center or edge(s) of the lane
- A laser or millimeter wave radar transmitter/receiver pairs to actively illuminate and measure the position of special targets/markers placed in or on the roadway infrastructure
- A high accuracy DGPS receiver with an accurate digital map of the road network.

The choice of technology for sensing vehicle position relative to the lane is left to the system designer.

Local orientation of the vehicle relative to the road centerline is an important factor in determining the danger of a road departure crash. The larger the angle between the vehicle centerline and the road centerline, the more quickly the vehicle will diverge from the lane, resulting in an increased risk of road departure. Therefore an accurate estimate of the vehicle's orientation can significantly improve the performance of a LDWS. However not all warning algorithms require vehicle orientation information to operate. The electronic equivalent of "rumble strips" is an example of an algorithm that only uses vehicle position information to estimate the risk of a road departure. Furthermore, as is evident from the results in Section 3.2, those algorithms that employ vehicle orientation estimates vary in their sensitivity to errors in the estimates. As a result, the accuracy with which the sensors of a LDWS should estimate vehicle orientation cannot be specified in absolute terms.

[L-7] The sensing of the vehicle orientation relative to centerline of the road is optional for a LDWS, but its use is recommended to improve the timeliness of warnings. The accuracy required for the sensing of vehicle orientation will be determined by the choice of warning algorithm. The choice of vehicle orientation sensor and warning algorithm should be made in order to provide as early warning as possible, while maintaining a nuisance alarm rate that is acceptable to drivers.

There are many conceivable ways of estimating vehicle orientation, including:
- Direct measurements of the angle between the road and the vehicle using a video-based system

- Measurement of the change in lateral position over time
- Comparing the heading of the vehicle from a digital compass with the heading of the road at the current vehicle location as stored in a digital map.

The choice of technology for sensing vehicle orientation is left to the system designer.

3.1.2 DETERMINE GEOMETRY OF ROAD AHEAD

Any effective and acceptable LDWS needs to account for the range of road geometry. As will be seen in Section 3.2, some LDWS algorithms required detailed information about geometric characteristics of the road ahead. The guidelines in this section address the issues associated with road geometry.

First, the LDWS should be able to determine whether the vehicle is traveling on a road.

[L-8]   A LDWS should be capable of detecting when the vehicle is traveling on a road, as opposed to a parking lot or other unstructured environment.

[L-9]   When traveling in an unstructured environment, the LDWS should suppress road departure warnings to avoid nuisance alarms.

When the vehicle is on a road, it is recommended (although not required) that the system be capable of handling the full range of improved road types common in the US. These do not include dirt or gravel roads; but do include roads with degraded or missing lane markers, as these conditions are relatively common on US roads, particularly in rural areas. Other special road types, like those delineated only by small raised pavement markers, or by painted markers down only one side of the lane, should also be handled. Specifying the appearance of visible markings (or lack thereof) might be considered by some to be too technology specific for inclusion in these guidelines. However it is felt that the first systems to be deployed will likely rely on detecting some form of visible road features to estimate vehicle position on the road and the upcoming road geometry. Therefore, it is important to insure that LDWS can operate in the range of road characteristics typical in the US, and do not make incorrect assumptions about the roads physical characteristics. Furthermore, a LDWS that does not rely on visible road features can simply ignore these visible road appearance guidelines.

[L-10] It is recommended that a LDWS be capable of operating on the range of typical US road types, including those where visible lane markings are worn or in some other way degraded. Ranges for important characteristics of typical US roads are listed below:

Characteristic	Minimum Value	Maximum Value	Nominal Value
Lane width	2.6m	4.5m	3.66m
Visible lane marker width	0.1m	0.25m	0.15m
Dash length (for intermittent visible	2.0m	6.0m	4.0m

markers)			
Gap length (between intermittent visible markers)	**4.0m**	**8.0m**	**6.0m**

[L-11] Other common US road characteristics that a LDWS should be capable of handling include:

- **Roads made of asphalt or concrete**
- **Lanes delineated by white or yellow visible markings**
- **Lanes delineated by visible markings made from paint or tape**
- **Lanes delineated by intermittent raised pavement markings (typically 12cm in diameter)**
- **Lanes delineated by visible markings on only one side of the lane**
- **Lanes delineated by dashed (intermittent) lane markings**
- **Lanes delineated by visible markings composed of a single stripe or a double stripe (two single stripes separated by approximately 10cm).**

[L-12] The system should be capable of estimating the width of the travel lane with an accuracy of 10cm.

Since the lane width will typically be used to estimate the lateral position of the vehicle relative to the lane boundaries, the accuracy of the lane width estimate needs to be similar to the accuracy required for the vehicle's lateral position estimate. This is to ensure an acceptably low number of nuisance alarms, and consistent warning onset time. The lane width may be determined by directly sensing the lane boundaries. Other possible methods for determining the lane width include encoding it in the infrastructure (e.g. in the polarity of magnetic markers), or in a digital map. The choice of technology for sensing lane width is left to the system designer.

[L-13] On roads where lane width cannot be accurately estimated, the LDWS should use a nominal lane width of 3.66m (12ft).

The nominal lane width is particularly important on roads delineated by markings on only one side of the lane.

Another useful measurement a LDWS should attempt to make is the width of any improved shoulder next to the travel lanes. This information could assist the warning algorithm in determining the time available to the driver for a recovery maneuver, if he departs from the travel lane. This information could be used to reduce nuisance alarms when a wide shoulder is available or to warn earlier when only a narrow shoulder is present. Shoulder width could even be used to suppress warnings entirely (after informing the driver) on roads where little or no shoulder is available. System operation in conditions of little or no shoulder could instill a false sense of security in the driver,

since in some circumstances mathematical analysis shows (see Section 4) that it is unlikely a driver could respond to a warning in time to prevent a crash.

[L-14] If possible, a LDWS should attempt to estimate or infer the width of any improved shoulder adjacent to the travel lanes.

Another form of sensing that could potentially improve LDWS performance is the sensing of roadside obstructions such as guardrails and bridge abutments or parked vehicles. Like the sensing of shoulder width, this information could be used to warn earlier when a roadside obstruction reduces the vehicle's maneuvering room. Of course, reliable detection of stationary obstacles is a significant challenge for existing sensors (see: NHTSA Rear-End Collision Warning Systems Performance Specifications, 1998) and may not be practical with existing technology.

[L-15] If possible, a LDWS should attempt to sense the positions of any roadside obstructions such as guardrails, bridge abutments or parked vehicles.

Another important road geometry characteristic is road curvature. Ideally, a LDWS should handle all road curvatures found on US roadways, which can sometimes be as sharp as 60m radius. However, such sharp curves are rare. Furthermore, analysis conducted for the ROR program shows that the effectiveness of a LDWS on such sharp curves is likely to be very low. This is due to the short time available (< 1 second) before road departure if the vehicle stops tracking the sharp curve due to driver inattention or relinquishing of steering control. Finally, the international consensus reached through the development of the draft ISO standard for lane departure warning systems is for a LDWS to operate on roads with a minimum radius of 125m.

[L-16] A LDWS should be capable of operating on curves with a radius of curvature as small as 125m. It shall disable wa rnings and inform the driver when the road curvature is determined to be smaller than it can accommodate.

Some LDWS warning algorithms require estimates of road curvature to determine the likelihood of a road departure. The analysis presented in Section 3.3 indicates that in order to produce timely warnings and to maintain an acceptable level of nuisance alarms, these algorithms need a road curvature estimate with an error of less than 0.0005 m^{-1}.

[L-17] For a LDWS that employs a warning algorithm requiring road curvature, the system should determine the curvature of the upcoming road segment to an accuracy of 0.0005 m^{-1}.

A LDWS needs to be able to handle reasonable rates of changes in road curvature. "Spiral" entries to curves of approximately one second of travel time at the posted speed limit are fairly typical on US roads. Transitioning from a straight road to a 125m radius curve in one second at 35mph translates to a rate of change of road curvature of 0.0004 m^{-2} .

[L-18] A LDWS should accommodate rates of change in road curvature of as high as 0.0004 m^{-2}.

Changes in grade (vertical curvature) are a common occurrence, particularly on rural roads. Changes in grade have the potential to provide difficulty for a LDWS. For instance, when cresting a hill the road ahead may leave the sensor's field of view for some sensor configurations. Comprehensive data on the rate of change of grade is not available for US roads, so the rate of change of grade that a LDWS should handle cannot be specified absolutely at this time.

[L-19] A LDWS should accommodate rates of changes in grade (vertical curvature) typically found on US roads.

3.1.3 DETERMINE VEHICLE DYNAMIC STATE

In order to determine if the vehicle is in danger of departing the road, some LDWS warning algorithms require an accurate and reliable estimate the vehicle's dynamic state, including its velocity and its yaw rate. The sensitivity analysis in Section 3.3 indicates that in order to produce timely warnings and to maintain an acceptable level of nuisance alarms, these algorithms need a vehicle velocity estimate with an error of less than 3mph, and a vehicle yaw rate estimate with an error of less than 1 degree per second.

[L-20] For a LDWS that employs a warning algorithm requiring vehicle velocity, the system should determine the vehicle velocity to an accuracy of 3mph.

[L-21] For a LDWS that employs a warning algorithm requiring vehicle yaw rate, the system should determine the vehicle yaw rate to an accuracy of 1 degree per second.

3.1.4 DETERMINE DRIVER INTENTION

In order to minimize nuisance alarms, a LDWS should attempt to detect intentional lane excursions, whether due to lane changes maneuvers, evasive maneuvers or even simply pulling off to the side of the road.

[L-22] A LDWS should attempt to determine driver intentions in order to minimize nuisance alarms. It should attempt to avoid issuing warnings for intentional lane excursions which can result when performing a lane change, driving onto the shoulder to avoid obstacles in the travel lane, or stopping beside the road for a vehicle or passenger emergency.

Driver intention determination could potentially be accomplished using one or more of the following techniques:

- Monitoring the vehicle's brake and turn signal indicators.

- Monitoring the pattern of lane markings for likely lane change, merge or exiting situations.
- Consulting a digital map for the existence of exit ramps or cross streets that could provide reasons for intentional lane excursions.
- Distinguishing between unintentional control inputs and intentional control inputs, such as a sudden large steering input which could indicate an evasive maneuver.
- Monitoring other on-board collision warning systems for indications that the driver may be about to execute an intentional maneuver to avoid a crash.

The choice of method for determining driver intentions is left to the system designer. The level of reliability for intentional maneuver detection methods necessary to minimize nuisance alarms to an acceptable level will require field testing to determine, and will likely vary from one driver to another.

This concludes the sensing-related functions and guidelines for LDWS.

3.2   WARNING ALGORITHM GUIDELINES

The job of a LDWS warning algorithm is to process the data from sensors characterizing the vehicle's position/trajectory, the road geometry and driver's intentions to assess the danger of a lane departure crash in the current situation.

While road departure crashes are one of the most frequent and serious of crash types, they are still extremely rare. Statistics show that a road departure crash is literally a "once-in-a-lifetime" event, occurring on average once every 84 years of passenger vehicle driving, and once every 47 years of commercial vehicle driving [SVRD Problem size assessment report, Oct. 93]. As a result, the odds are extremely small that any particular situation will lead to a road departure crash. Therefore the warning algorithm for a LDWS must do a very good job at minimizing nuisance alarms if it is to be acceptable to drivers. Of course, minimization of nuisance alarms should not result in a substantial increase in missed alarms, since to be beneficial a LDWS must be effective at detecting and preventing road departure crashes.

There is a wide range of possible LDWS algorithms a developer/manufacturer could employ. Instead of prescribing a particular algorithm as appropriate, this section presents the alternative algorithms in a hierarchy of increasing complexity. Also discussed are the benefits and drawbacks of each of the algorithms. In general, the more complex algorithms model the geometry of the road departure sequence with higher fidelity. This higher fidelity means the more complex algorithms have the potential to provide fewer false alarms and also provide warnings somewhat earlier, allowing the driver more time to react. On the downside, the more complex algorithms typically require extra sensors to provide the required additional information they require. The more complex algorithms are also more sensitive to errors in the sensor data, which could potentially result in more, not fewer, false alarms than the simpler algorithms.

Note1: For simplicity of presentation and comparison, each of the algorithms presented below is portrayed as triggering a warning at some time or distance prior to the vehicle crossing the edge of the lane. Each of the algorithms can easily be generalized to trigger relative to a "virtual" lane that is slightly wider or narrower than the physical lane. As is shown in Section 4.3.3, this concept of a virtual lane can greatly reduce the false alarm rate, while maintaining high effectiveness.

Note2: All these algorithms share a common term, and that is the distance between the outside edge of the vehicle's tire and the edge of the lane boundary. In the descriptions below, this distance will be abbreviated as d:

$$d = \frac{(w_l - w_v)}{2} - p_l$$

where:

p_l = lateral position of the centerline of the vehicle relative to the center of the lane
w_l = the width of the current lane
w_v = the width of the subject vehicle

3.2.1 ALGORITHM 0: 0TH ORDER, OR "ELECTRONIC RUMBLE STRIPS"

Description:
Algorithm 0 is the simplest algorithm, and is really only included for completeness. Algorithm 0 ignores time entirely, triggering a warning solely based on the lateral position of the vehicle's outside tire relative to the lane boundary. If one of the vehicle's tires strays beyond the edge of the lane, a warning is triggered.

Equation:
$$\text{if } d \leq 0 \Rightarrow \text{warn}$$

Data Required:
d = the distance between the outside edge of the tire and the lane boundary

Assumptions:
Because of the simplicity of this algorithm, there are really no assumptions it makes beyond the requirement that d can be measured accurately.

Advantages:
- It makes no assumptions about the geometry of the upcoming roadway geometry.
- It utilizes only a relatively easy to measure variable 'd'. 'd' can be measured accurately with a number of different sensors (forward video, downward video, downward laser) looking at the road in close vicinity to the vehicle (as opposed to having to look far ahead).

- Mathematically stable - Since there are no high order terms, small errors in the estimates of the parameters lead to only small errors in the warning onset time.
- Predictability - It is simple to understand for a driver. The driver can quickly understand that the moment his tire drifts past the lane edge, he will receive a warning. This algorithm is really the electronic equivalent of rumble strips, as the name implies, since rumble strips provide a warning at the moment one of the vehicle's tires gets a certain fixed distance past the lane boundary.

Disadvantages:
- It ignores time and the trajectory of the vehicle entirely. In particular, it will warn at the same position relative to the lane edge regardless of whether the vehicle is heading off the road at a steep angle, or driving nearly parallel to the road. In high departure angle conditions, this will give the driver less time to react prior to departing from the shoulder than the algorithms described below, which warn earlier if the vehicle is heading off the road quickly or at a steep angle.
- The lack of vehicle trajectory in this algorithm will result in increased nuisance alarms in small departure angle conditions. For example, if the vehicle is driving nearly parallel to the lane, and barely touches the lane boundary, this algorithm will trigger a warning, whereas the algorithms described below which take vehicle trajectory into account will recognize the small departure angle, and not trigger a warning as early.

3.2.2 ALGORITHM 1: 1ST ORDER TIME-TO-LINE-CROSSING

Description:

Algorithm 1 is the simplest algorithm that takes vehicle trajectory into account. The algorithm takes the vehicle's current lateral position and lateral velocity, and projects forward in time to determine how long it will be until one of the vehicle tires crosses the lane boundary. If that time until line crossing falls below a threshold (typically in the neighborhood of 1 second), a warning is triggered. Note: If the threshold lookahead time is set to 0, this algorithm is equivalent to Algorithm 0, since it will only trigger a warning at the moment the vehicle's tire crosses the lane boundary.

Equation:

$$\text{if } \frac{d}{v_l} < t_l \Rightarrow \text{warn}$$

Data Required:

d = the distance between the outside edge of the tire and the lane boundary

v_l = lateral velocity of the vehicle towards the edge of the lane

t_l = lookahead time threshold. If vehicle is projected to cross boundary in less than this amount of time, trigger warning.

Assumptions:

The primary assumption this algorithm makes is that the vehicle's lateral velocity is a constant over a short period of time (over the next one second or so). In other

words, it assumes that the vehicle will continue traveling towards the edge of the lane at its current rate. This algorithm is basically assuming the heading angle between the road and the vehicle is constant. This may or may not be true, depending on the steering input provided by the driver and the geometry of the road ahead.

Advantages:
- It utilizes only relatively easy to measure variables. The only additional parameter that needs to be estimated over the 0th order model is lateral velocity (V_1), which can easily be estimated based on recent changes in lateral position.
- Mathematically stability - It is more stable than the algorithms that follow, but not as stable as Algorithm 0 (see disadvantages below).
- The big advantage of this algorithm over the 0th order algorithm is that it warns earlier if the vehicle is departing from the road more quickly (i.e. if lateral velocity is high). This will give the driver more time to react, and hopefully avoid a crash. Instead of warning at a constant distance from the edge of the road, this algorithm is designed to warn at a constant time prior to the road departure.

Disadvantages:
- It is not quite as stable as the 0th order model, since lateral velocity will typically be computed as the derivative of lateral position. As a result, errors in lateral position may be amplified when computing lateral velocity. This will result in increased error in the time to line crossing estimate and therefore increased false alarms or delayed warning onset.
- It assumes the vehicle's lateral velocity will be constant over a short period, which may not be true, depending on driver's steering input and the upcoming road geometry. This can potentially result in later warnings than would be possible with a better model of the vehicle's trajectory. For example vehicles follow a nearly circular arc if the steering wheel is held at a constant position. As a result, on a straight road the vehicle's lateral velocity will not remain constant. Instead, the vehicle's lateral velocity will increase as the vehicle's heading angle increases relative to the road centerline as the vehicle follows a circular arc. If the road curvature is changing and/or the driver is turning the steering wheel, this change in lateral velocity over time may be amplified.

The following algorithms keep the same basic approach as the 1st order TLC algorithm - warn a fixed time prior to lane departure. They differ in how they model the vehicle trajectory. Each successive algorithm tries to model the vehicle's trajectory relative to the lane a little more accurately, to improve the estimate of how long it will be until the vehicle crosses the lane boundary.

3.2.3   ALGORITHM 2: 2$^{\text{ND}}$ ORDER TIME-TO-LINE-CROSSING

Description:

Algorithm 2 is an extension of Algorithm 1 to utilize not only the vehicle's lateral position and lateral velocity, but also its lateral acceleration relative to the lane in an attempt to improve the prediction of the vehicle's upcoming trajectory. It uses the same basic Time-to-Line-Crossing concept as Algorithm 1. The algorithm takes the vehicle's current lateral position, lateral velocity and lateral acceleration, and projects forward in time to determine how long it will be until one of the vehicle tires crosses the lane boundary. If the time until line crossing falls below a threshold (typically in the neighborhood of 1 second), a warning is triggered.

Equation:

$$\text{if } \frac{-v_l + \sqrt{v_l^2 + 2a_l d}}{a_l} < t_l \Rightarrow \text{warn}$$

Data Required:

d = the distance between the outside edge of the tire and the lane boundary

v_l = lateral velocity of the vehicle towards the edge of the lane

a_l = lateral acceleration of the vehicle towards the edge of the lane. Note: a_1 must not equal 0, if it does, use Algorithm 1.

t_l = lookahead time threshold. If vehicle is projected to cross boundary in less than this amount of time, trigger warning.

Assumptions:

This algorithm relaxes the assumption that the lateral velocity must be constant over a short period, and instead assumes that the vehicle's lateral acceleration (relative to the center of the lane) will remain constant over a short period. This may or may not be true, depending on the steering input provided by the driver and the geometry of the road ahead. Note that the assumption of constant lateral acceleration is, for small angles, equivalent to assuming constant vehicle curvature, which is equivalent to a fixed hand wheel position.

Advantages:

- The major advantage of this algorithm over the 1st order algorithm is that it warns earlier if the vehicle is accelerating towards the lane boundary, instead of simply projecting forward at the current lateral velocity.
- It utilizes only relatively easy to measure variables. Lateral acceleration as referred to here measures the rate of change in the vehicle's lateral velocity relative to the lane center. This can be calculated by taking the derivative of lateral velocity, which in turn is the derivative of the lateral position. It is therefore trivial to compute lateral acceleration from a series of lateral positions.

Disadvantages:

- Mathematical stability - While theoretically easy to compute, lateral acceleration relative to the road centerline is very hard to calculate accurately. The reason is that small errors in lateral position get compounded twice, first to compute lateral velocity from the rate of change in lateral position, and then to compute lateral acceleration from the rate of change in lateral velocity.

- Latency - One way to reduce the mathematically stability problem is to compute lateral acceleration based on lateral position data over a relatively long period of time (e.g. the last one or two seconds). However the older the data used to in the calculation, the less reflective of the current lateral acceleration the estimate will be.

These disadvantages make it unlikely that the 2nd order Time-to-Line-Crossing algorithm can be used effectively in a lane departure warning system. The next algorithm, Kinematic Time-to-Line-Crossing, has the potential to overcome these disadvantages by using additional sensors.

3.2.4   ALGORITHM 3: KINEMATIC TIME-TO-LINE-CROSSING

Description:

Algorithm 3 is designed to improve on the above algorithms by utilizing additional information about the road geometry and vehicle trajectory. Algorithm 3 incorporates information about the vehicle's forward velocity, yaw angle relative to the lane centerline, the radius of curvature the vehicle is following, and the radius of curvature of the upcoming road segment. Using these parameters, it projects the vehicle's trajectory forward to determine how long it will be until the vehicle crosses the lane boundary. If the time until line crossing falls below a threshold (typically in the neighborhood of one second), a warning is triggered.

Equations:

$$\text{if } t < t_l \Rightarrow \text{warn}$$
$$\text{where :}$$

$$t = \frac{-v_f \tan\theta \;+\; \sqrt{(v_f \tan\theta)^2 + 2v_f^2 d\left(\dfrac{1}{r_r} - \dfrac{1}{r_v}\right)}}{v_f^2\left(\dfrac{1}{r_r} - \dfrac{1}{r_v}\right)}$$

$$r_v = \frac{360 v_f}{2 p\, y_v}$$

Data Required:

d = the distance between the outside edge of the tire and the lane boundary
v_f = forward velocity of vehicle
θ = yaw angle of vehicle relative to the lane centerline
r_r = radius of curvature of road
y_v = yaw rate of vehicle
t_l = lookahead time threshold. If vehicle is projected to cross boundary in less than this amount of time, trigger warning.

Assumptions:

This algorithm assumes the curvature of the upcoming road segment is constant i.e. a circular arc). On the entrance to curves this is not the case, as the road curvature is typically changing smoothing (spiral entrance). This algorithm also assumes the vehicle trajectory is a circular arc of constant radius, and will remain constant over a short period. This will not be the case if the driver is changing or will change the steering wheel position during over the short period being considered.

Advantages:

This algorithm uses curvature preview information to account for the changes in road geometry ahead, which the other algorithms do not. This has the potential to provide an earlier warning on the approach to a curve, since this algorithm should detect the reduced time until road departure due to the fact that the road ahead is curving away from the vehicle's projected trajectory. In general, given accurate estimates of the required parameters, this algorithm will provide a more accurate estimate of the Time-to-Line-Crossing than the previous algorithms.

Disadvantages:

- Challenging sensor requirements - This algorithm requires sensing several quantities that the previous algorithms did not require. Forward velocity of the vehicle is relatively easy to sense, and is available "for free" on most vehicles. The yaw rate (or rate of change of vehicle heading) is relatively straightforward to measure with a yaw rate gyro. One caveat, yaw rate gyros that are found today on some vehicles (for functions like stability control) may not be sufficiently accurate for this purpose. Small yaw rate gyros with a sufficiently fast update rate and accuracy are currently available for $150-200. More difficult to measure is vehicle yaw angle relative to the road centerline. While it is theoretically possible to compute yaw angle from a forward looking vision sensor, the level of accuracy required (see below) makes this very difficult. It is especially difficult since this algorithm requires distinguishing between vehicle yaw angle and road curvature, both of which have very similar effects on the appearance of the road ahead in a forward camera image. For the same reason, road radius of curvature is very difficult to measure independently using a forward looking imaging sensor. An alternative method that may be more accurate and reliable for computing road curvature and vehicle yaw angle is to use differential GPS and an accurate map of road geometry. The GPS would provide accurate estimates of the vehicle's current heading and position. The vehicle's position would be used to look up the heading of the road and the upcoming road curvature in a digital map. The difference between the heading of the vehicle and the heading of the road is the vehicle's yaw angle. This solution requires a high update rate, low latency GPS receiver (not the type of receiver currently employed in navigation systems). The receivers currently cost in the neighborhood of $2000. In addition, substantial additions and improvements to the currently available digital maps (e.g. from Navtech) would be required to estimate road heading and curvature accurately enough for this application.
- Sensitivity to sensor error - This algorithm may be more sensitive to errors in sensor estimates than the previous algorithms. See analysis below for more details.

Algorithm 3 is not the last one in the hierarchy. In particular, Algorithm 3 assumes a constant radius of curvature for both the road and the vehicle trajectory. More sophisticated algorithms could model the changes in road curvature and vehicle trajectory over the upcoming road segment. But as will be seen in the following analysis, Algorithm 3 does a good job at estimating TLC, even on roads with non-constant curvature.

3.2.5   PERFORMANCE COMPARISON

In this section, the performance of the algorithms described above is compared. They are compared on a set of typical driving scenarios, based on how accurately they estimate the time until the vehicle will cross the lane boundary.

The baseline parameters used in the following analysis include:
- 3.66m (12ft) lane width

- 1.8m vehicle (typical sedan)

- 25m/sec (55mph) vehicle velocity

- Assume the vehicle starts out centered in the lane, and travelling parallel to the lane (except in Scenarios 2 and 6).

The basic strategy used to evaluate each algorithm is as follows:
1) Select scenario from set described below

2) Simulate scenario for 0.5 seconds to give sensors a chance to "settle" and detect the changes occurring in the current situation (e.g. compute lateral velocity based on change in lateral position during that half-second period).

3) Use current algorithm to estimate time until first tire will cross lane boundary

4) Compare estimated TLC with actual TLC as calculated by simulating vehicle trajectory. The difference is the TLC error.

Scenarios:

The eight scenarios modeled in this analysis are shown below. They are meant to cover a fairly representative range or road geometry / vehicle trajectory situation encountered in the real world.

1) Straight road, straight trajectory

2) Straight road, 1°

3) Straight road, 1000m radius departure

4) Straight road, 300m radius departure

5) 300m radius road, straight departure

6) straight road, 300m radius trajectory, 1° yaw

7) 300m radius road, opposite 300m radius departure

8) 30m spiral entry, 300m radius road, straight departure
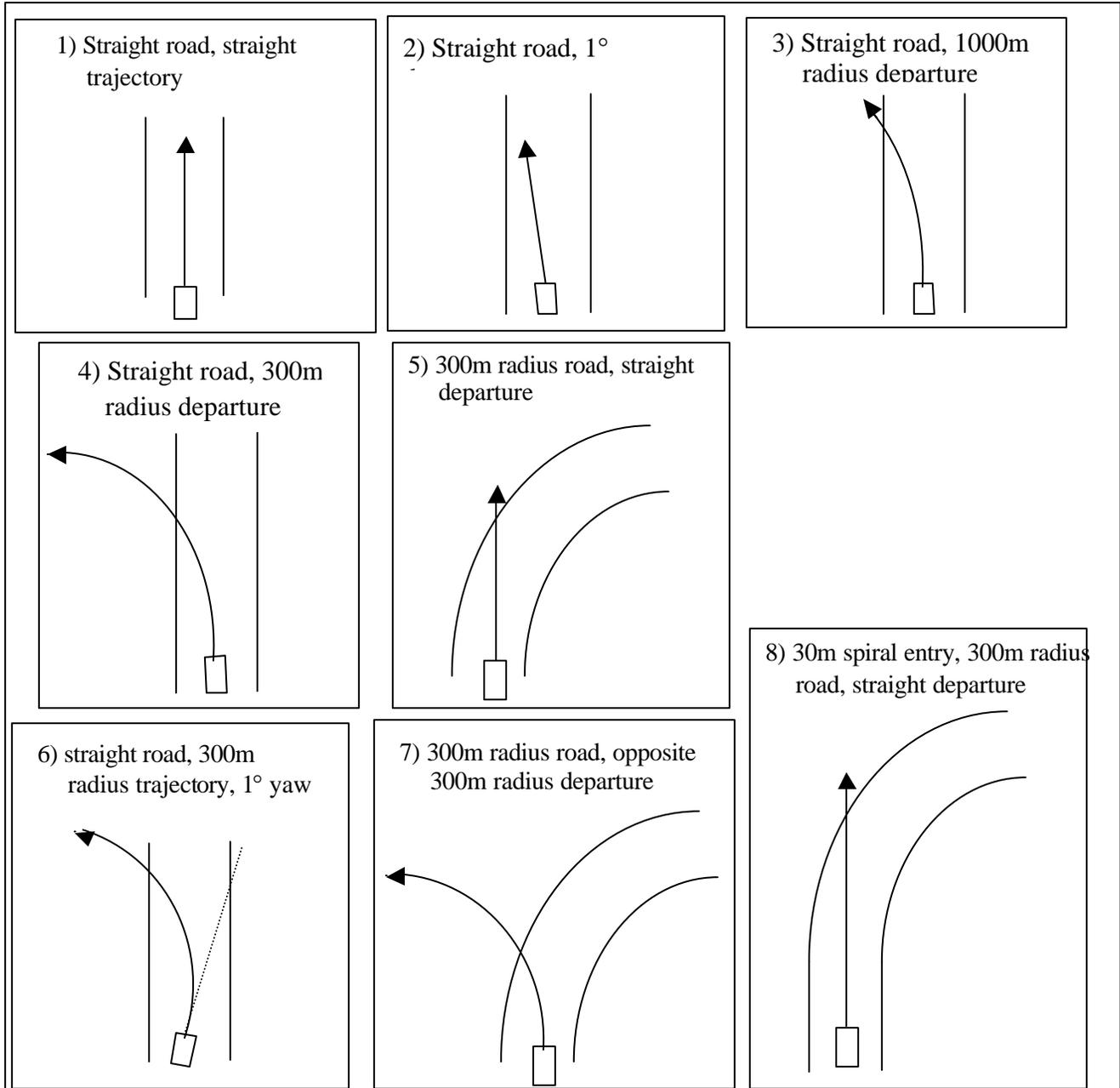
The table below contains the actual TLC (in seconds), and the TLC estimates for each of the four algorithms on each of the eight scenarios listed above. The errors in the TLC estimates (in seconds) are shown in ( ) for each of the four algorithms.

		Scenario							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Actual TLC		∞	2.13	1.72	0.94	0.94	1.18	0.66	1.32
Algorithm	**0**	NA	NA	NA	NA	NA	NA	NA	NA
	1	∞ (0.00)	2.13 (0.00)	5.96 (4.24)	1.79 (0.85)	1.79 (0.85)	10.57 (9.39)	0.89 (0.23)	8.56 (7.24)
	2	∞ (0.00)	2.13 (0.00)	1.78 (0.06)	0.95 (0.01)	0.95 (0.01)	1.13 (-0.05)	0.62 (-0.04)	1.77 (0.45)
	3	∞ (0.00)	2.13 (0.00)	1.73 (0.01)	0.94 (0.00)	0.94 (0.00)	1.18 (0.00)	0.67 (0.01)	1.46 (0.14)

As can be seen from the above table, Algorithm 0 does not estimate time-to-line-crossing. Each of the other three algorithms is highly accurate in Scenarios 1 and 2, where the vehicle is traveling along a straight trajectory on a straight road. In each of the other six scenarios, Algorithms 1 overestimates the true TLC, sometimes by a large amount. This is because Algorithm 1 does not model the fact that the road and/or vehicle are curving, which results in an ever increasing rate of departure. Algorithm 2 estimates TLC almost perfectly in all but Scenario 8, by modeling the curvature of the scenario as a constant lateral acceleration, a_l. Some error creeps in for Algorithm 2 on Scenario 8, since in this case the road curvature is changing. Algorithm 3 is slightly more accurate than Algorithm 2. This is because Algorithm 3 explicitly measures and models the curvature of the road and vehicle. Algorithm 3 has some error on Scenario 8 because it assumes a constant radius of curvature, while the actual road curvature is changing.

These results indicate that TLC estimation accuracy improves with increasing sophistication of the algorithm employed, assuming that accurate estimates of the required data elements for each algorithm are available.

3.2.6   SENSITIVITY ANALYSIS

An important question is how sensitive the algorithms are to errors in the vehicle state and road geometry parameters they require as input. In short, an algorithm may not be useful if its accuracy degrades rapidly when small amounts of sensor noise are introduced. In this section, the ability of the algorithms to tolerate noisy sensor input is tested, by choosing a single scenario (Scenario 1 from above), adding noise to the relevant parameters, and testing each algorithm to see how its TLC estimation accuracy degrades.

To test the sensitivity of Algorithms 1 and 2, noise is injected into the vehicle's lateral position estimate at the end of the 0.5 second "settling time" (see above). This lateral position noise not only effects the d term that both Algorithms 1 and 2 employ, but also the v_l term (both algorithms) and the a_l term (Algorithm 2 only). Algorithm 3 utilizes the d term, as well as v_f (vehicle forward speed), θ (vehicle yaw angle), r_r (road radius of curvature), and y_v (vehicle yaw rate). Errors are added to each of these variables to test the sensitivity of Algorithm 3 to noisy sensor inputs.

The amount of noise added to each variable is meant to roughly correspond to the error that would be expected from a sensor measuring that variable, based on either measurements taken with actual sensors or knowledge of the accuracy of these sensors. For lateral position, a typical error is estimated to be ±10cm. For vehicle velocity, a typical error is estimated to be ±3mph. For vehicle yaw angle relative to the road centerline, a typical error is estimated to be ±1 degree. For road curvature, a typical error is estimate to be ±2000m radius of curvature. For vehicle yaw rate, a typical error is estimated to be ±1 degree / second.

The sensitivity of the algorithms to each of these errors is shown in the table below. The new, noise-degraded TLC estimates (in seconds) for Scenario 1 are shown in each cell. Recall from the previous table, that the true TLC for this scenario (straight trajectory on a straight road) is infinite, the vehicle should never depart the road.

		Error Introduced in Scenario 1					
		d +10cm	v_f + 3mph	q + 1deg	$r_r = ¥$ to 2000m	y_v + 1deg/sec	Combined
Actual TLC		∞	∞	∞	∞	∞	**¥**
Algorithm	**0**	NA	NA	NA	NA	NA	**NA**
	1	4.55	∞	∞	∞	∞	**4.55**
	2	1.15	∞	∞	∞	∞	**1.15**
	3	∞	∞	2.10	2.43	2.06	**0.96**

As can be seen from the table, sensor noise degrades the performance of Algorithms 1 through 3 to a certain degree. An offset error (error in d) effects Algorithm 2 most, dropping its TLC estimate to 1.15 seconds. This is because the offset error is magnified when computing the lateral velocity and lateral acceleration, which Algorithm 2 uses to makes its estimate. Algorithm 3 is relatively unaffected by the lateral position error.

Algorithm 3 is influenced by noise in more variables than the other two algorithms, since it uses extra vehicle state and road geometry information in its computation. Individual errors in the range that could be expected for vehicle yaw angle (θ), road curvature (r_r), and vehicle yaw rate (y_v) result in a drop in the TLC estimate to around 2 seconds.

The "Combined" column is perhaps most telling. It shows the error that could be expected in each of the three algorithms if there were reasonable errors in all of the sensor inputs at the same time, instead of each sensor input individually. Algorithm 1 and 2 only utilize lateral position in their calculations, so their TLC estimates are the same as in column 1 (4.55 and 1.15 seconds, respectively). Algorithm 3 is more sensitive to combinations of errors in the sensor inputs. Its TLC estimate drops to 0.96 seconds when noise is introduced in all the sensor inputs.

The next table is the same as the table above, except a baseline offset of 30cm (about 1 foot) is added to the vehicle's lateral position at the start of Scenario 1. This is to simulate the fact that driver's don't always keep the vehicle perfectly centered in the lane. Note that the correct TLC estimate for this scenario remains infinity, since the vehicle is still driving parallel to the centerline of a straight road and will therefore never cross the boundary.

		Error Introduced in Scenario 1 (with 30cm baseline vehicle offset)					
		d +10cm	v_f + 3mph	q + 1deg	$r_r = \infty$ to 2000m	y_v + 1deg/sec	Combined
Actual TLC		∞	∞	∞	∞	∞	∞
Algorithm	**0**	NA	NA	NA	NA	NA	**NA**
	1	2.65	∞	∞	∞	∞	**2.65**
	2	0.95	∞	∞	∞	∞	**0.95**
	3	∞	∞	1.20	1.84	1.56	**0.87**

As can be seen from the **Combined** column, the extra vehicle offset reduces the TLC estimates for all three algorithms in the presence of noise. The TLC estimates for Algorithms 2 and 3 are both under a second, indicating that both algorithms indicate the vehicle will very quickly leave the road, despite the fact that in actuality, the vehicle is traveling perfectly straight down the road, offset by only one foot from the lane center.

The next two tables show the impact of sensor noise in Scenario 3, in which the vehicle is curving along a 1000m radius on a straight road. Recall the correct TLC estimate for this scenario is 1.72 seconds. The first table shows the addition of "positive" sensor noise, which has the effect of reducing the estimated time to road departure.

		"Positive" Errors Introduced in Scenario 3					
		d +10cm	v_f + 3mph	q + 1deg	r_r + 2000m	y_v + 1deg/sec	Combined
Actual TLC		1.72	1.72	1.72	1.72	1.72	**1.72**
Algorithm	0	NA	NA	NA	NA	NA	**NA**
	1	2.75	2.75	2.75	2.75	2.75	**2.75**
	2	1.23	1.23	1.23	1.23	1.23	**1.23**
	3	1.62	1.64	1.16	1.41	1.32	**0.78**

As can be seen from the **Combined** column above, "positive" sensor noise causes Algorithms 2 and 3 to significantly underestimate TLC for Scenario 3 in the presence of noise. Algorithm 1's TLC estimate also drops, but because it significantly overestimated TLC in Scenario 3 to begin with, it still overestimates TLC in the presence of noise.

The second table shows the addition of "negative" sensor noise to Scenario 3, which has the effect of increasing the estimated time to road departure. The ( ) in the table indicate an algorithm is estimating that the vehicle will depart of the opposite side of the lane from its actual departure trajectory.

		"Negative" Errors Introduced in Scenario 3					
		d -10cm	v_f - 3mph	q - 1deg	r_r - 2000m	y_v - 1deg/sec	Combined
Actual TLC		1.72	1.72	1.72	1.72	1.72	**1.72**
Algorithm	0	NA	NA	NA	NA	NA	**NA**
	1	(23.25)	(23.25)	(23.25)	(23.25)	(23.25)	**(23.25)**
	2	(1.43)	(1.43)	(1.43)	(1.43)	(1.43)	**(1.43)**
	3	1.81	1.79	2.56	2.43	3.14	**(8.48)**

As can be seen from the **Combined** column above, "negative" sensor noise can make Algorithms 1, 2 and 3 believe that the vehicle will depart off the opposite side of the lane from its actual departure trajectory. In this case, the sensor noise is masking the true vehicle trajectory causing the algorithms to think the vehicle is headed off the other side of the road. In fact, Algorithm 2 believes the vehicle will be departing off the other side of the road in less than 1.5 seconds. In fact, smaller amounts of noise than those shown in the table would cause each of the algorithms to believe the vehicle is traveling parallel to

the road, and would therefore never depart in Scenario 3. As a result, any value in ( ) in the table could be replaced by ∞.

To summarize the sensitivity tests, sensor noise can significantly degrade the TLC estimation accuracy of Algorithms 1, 2 and 3. The degradation is more pronounced in the more sophisticated algorithms, Algorithms 2 and 3. In particular, benign driving situations can actually appear to be imminent roadway departures to Algorithms 2 and 3 in the presence of reasonable levels of sensor noise. These errors in TLC estimation may result in significant number of false alarms.

3.2.7   LDWS WARNING ALGORITHM RECOMMENDATIONS

In general, LDWS warning algorithms based on time to departure, loosely termed "TLC" algorithms in this analysis, have a significant advantage over algorithms based on position or distance from the lane edge. TLC algorithms are able to provide earlier warnings than position-based algorithms, giving the driver more time to respond and avoid a crash. The "time to departure" in these algorithms need not necessarily refer to the time until the vehicle crosses the actual lane boundary. As will be seen in Section 4.3.3, warnings based on the time until the vehicle is expected to cross a "virtual" lane boundary slightly outside the physical lane boundary appear to significantly reduce nuisance alarms and at the same time provide early warnings in dangerous situations.

[L-23] A LDWS shall quantify the danger of a lane departure and trigger a response if the danger exceeds some threshold. The danger may be measured in terms of time remaining until departure or the position of the vehicle relative to the lane boundary.

[L-24] When possible, a LDWS should employ a warning algorithm based on time to departure, to provide the driver more time to respond and avoid a crash. The time to departure may measure the time until the vehicle crosses the actual lane boundary, a "virtual" lane boundary slightly outside the actual lane boundary, or the shoulder of the road.

[L-25] A LDWS should be able to operate and detect lane departures for a range of vehicle lateral velocities spanning at least 5 cm/s to 100 cm/s.

[L-26] The warning algorithm should consider the expected driver reaction time in determining when to trigger an alarm.

Among the hierarchy of time-based road departure warning algorithms, there is a tradeoff between accuracy and false alarm frequency. Significantly more accurate TLC estimates can be achieved by using more sophisticated models of road geometry and vehicle trajectory. But the gains in TLC accuracy come at the price of increased sensing requirements and increased sensitivity to sensor noise. The increased sensing requirements lead to more complex and expensive warning systems. For example, to

implement Algorithm 3 is likely to require the addition of a high quality differential GPS, and more accurate digital maps than are currently available.

The increased sensitivity of the more sophisticated algorithms to sensor noise is likely to lead to increased rate of false alarms. In particular, a reasonable amount of sensor noise can make a perfectly harmless scenario like Scenario 1, where the vehicle is centered in the middle of a straight road traveling straight ahead, look like an imminent roadway departure situation when using Algorithms 2 or 3. The susceptibility of Algorithms 2 and 3 to false alarms due to sensor noise is magnified by the fact that drivers do not keep the vehicle centered in the lane and traveling parallel to the road centerline at all times.

[L-27] A LDWS should employ a warning algorithm that attempts to maximize the accuracy of the lane departure danger prediction. The choice of algorithm should consider the accuracy and noise characteristics of the sensors upon which the algorithm's predictions are based.

As Burgett [1995] has pointed out, false alarms can reduce driver confidence in warning systems, reducing their effectiveness. It is an open question whether drivers will tolerate the level of false alarms produced by the more sophisticated algorithms and whether the increased accuracy in estimating the time to road departure is worth the increased false alarm rate. The only way to answer these questions is to conduct field tests with complete warning systems using the alternative algorithms, real drivers and actual sensor data. However it is clear that a LDWS should attempt to minimize false alarms, both through its choice of mathematical warning algorithm, and the judicious use of warning suppression rules.

[L-28] A LDWS should attempt to minimize false alarms, both through its choice of mathematical warning algorithm, and the judicious use of warning suppression rules.

In general, warning suppression rules use knowledge of the crash problem and the current circumstances to prevent warnings in situations where they are likely to be inappropriate, to avoid annoying the driver with false alarms.

One such warning suppression rule is to prevent warnings when the vehicle is maneuvering in an unstructured environment such as a parking lot. Such a situation could be detected in a number of ways, such as using image processing to determine the vehicle isn't on a consistent roadway, or using a GPS and digital map to determine the vehicle's current operating environment.

[L-29] A LDWS may temporarily suppress warnings when the vehicle's speed is operating in an unstructured environment. If it does so, it should inform the driver in a non-intrusive manner.

Another method of inferring that the vehicle is maneuvering in an unstructured environment (e.g. parking lot) or executing some other harmless maneuver (e.g. pulling

to the side of the road) is to monitor the vehicle's speed, and optionally suppress warnings while the vehicle is moving slowly. The international consensus (based on the draft ISO LDWS standard) is that a LDWS should operate when the vehicle's forward velocity is greater than 60 km/hr (35 mph) and may optionally suppress warnings at lower speeds. If it does temporarily suppress warnings due to low speed, a LDWS should inform the driver of its "off-line" status.

[L-30] A LDWS may temporarily suppress warnings when the vehicle's speed is below 35mph. If it does so, it should inform the driver in a non-intrusive manner.

To be effective, a LDWS needs to be quite sensitive to lane excursions. Because of this sensitivity, intentional lane excursions, whether due to lane change maneuvers, evasive maneuvers or even simply pulling to the side of the road should be recognized as intentional and not result in a warning. The detection of intentional maneuvers could potentially be accomplished using techniques as simple as monitoring the vehicle's turn signals for indications of a lane change, or as sophisticated as learning to distinguish between intentional and unintentional control inputs for a particular driver. The onset of an evasive maneuver could be detected in several ways, including communicating with other collision warning systems that may have signaled an impending forward or side collision, steering wheel sensors to detect abrupt steering inputs, or excessive lateral velocity or lateral acceleration indicative of an intentional maneuver. The level of reliability for intentional maneuver detection necessary to minimize false alarms to an acceptable level has yet to be determined, and will likely vary from one driver to another.

[L-31] A LDWS should attempt to detect intentional maneuvers performed by the driver, and avoid triggering warnings that could distract or annoy the driver.

Experiments using a warning algorithm that adapts to individual driving characteristics suggest that some reduction in the frequency of nuisance alarms can be achieved with little sacrifice in warning time [Batavia, 1999]. While preliminary, these experiments indicate that improved warning algorithm performance may be achieved by adjusting the warning algorithm based on an individual driver's lane keeping behavior. One example of such an adaptation is to allow slightly larger deviations before warning for a driver that exhibits a large variance in his lane position under normal driving. These types of adaptations appear most useful for drivers with more "erratic" lane keeping behavior. While encouraging, additional naturalistic experiments are required to validate the benefits of automatic warning algorithm adaptation, and to ensure that the benefits outweigh the drawbacks (particularly the slightly delayed warning onset).

[L-32] A LDWS may attempt to automatically adapt its warning algorithm to the driving characteristics of an individual driver, to reduce the frequency of nuisance alarms. However care must be taken to ensure these adaptations do not significantly reduce the effectiveness of the LDWS by reducing the time between the warning and the crash.

As was outlined in the sensing section, a LDWS should operate in all reasonable environmental conditions. When environmental conditions are so severe as to significantly degrade system performance, the system should recognize this, discontinue operation and report the situation to the driver.

[L-33] In those rare situations where poor environmental conditions would result in degraded system performance, the system should recognize this, discontinue operation and report the situation to the driver.

Regardless of the warning algorithm employed, there is a range of times (or positions, if a position based warning algorithm is used) relative to crossing the lane boundary within which a LDWS should trigger an alarm. If the warning system triggers outside this range, it will either be too early to be acceptable to the driver, or too late to prevent the crash. Lane keeping data collected for this program and reported in the LDWS benefits analysis section suggests that warnings triggered more than one second or 50cm prior to crossing the lane boundary would result in an intolerable number of nuisance alarms for all but the most precise drivers. Furthermore, assuming a typical shoulder of 3-6 feet, warnings that are not triggered until the vehicle is more than 50cm past the lane boundary would significantly limit the effectiveness of a LDWS, and could potentially lead to driver confusion. Therefore, regardless of the warning algorithm employed, it is recommended that a LDWS should trigger a warning when the vehicle is somewhere in the range of +-50cm of the lane boundary. Requiring a LDWS to warn before the outside tire gets more than 50cm outside the lane is in line with the international consensus, as reflected in the draft ISO standard for LDWS.

[L-34] Regardless of the warning algorithm employed, a LDWS should trigger a warning when the vehicle's outside tire is between 50cm inside and 50cm outside the lane boundary. At high lateral velocities, a warning may be triggered before the vehicle reaches the point 50cm inside the lane boundary. However it is recommended that such an early warning should not occur more than one second prior to any tire crossing the lane boundary, to prevent excessive nuisance alarms.

The range of trigger locations described above gives LDWS developers flexibility in where (or when) they configure their system's to trigger a warning. However this range should not be misinterpreted to mean that it is acceptable to trigger at various locations in similar dynamic circumstances. For example, if LDWS is configured to trigger 10cm beyond the lane boundary, it should consistently trigger at a point quite close to 10cm beyond the lane boundary. If it doesn't, but instead triggers a warning at significantly different points during similar lane departure situations (e.g. same lane width, lateral velocity, road curvature), then a driver is likely to be confused by the system's operation, or believe it to be malfunctioning. Through experimentation as part of this program, it was determined that a 10cm change in the vehicle's lateral position at the time of a warning was the approximate variability that was just detectable by drivers. Therefore it is recommended that for a similar dynamic scenario, a LDWS should trigger a warning within +-10cm of the nominal trigger position chosen by the developer. This +-10cm

variability in warning onset position in similar dynamic scenarios agrees with the international consensus, as reflected in the draft ISO LDWS standard.

[L-35] In similar dynamic lane departure scenarios (i.e. similar lane width, lateral velocity, and road curvature), a LDWS should consistently trigger a warning within 10cm of the nominal trigger position selected by the driver or developer.

Note that the above recommendation does not prevent systems from triggering warnings at different locations, depending on the dynamic situation, driver characteristics or driver input. For example, a LDWS algorithm based on time to line crossing (as recommended previously), might trigger a warning earlier on a high lateral velocity lane departure than in a situation where the vehicle is drifting slowly out of its lane. This will be addressed more in the next section on driver interface functions, but it is worth mentioning here that driver characteristics or preferences, as inferred automatically by the LDWS or input explicitly by the driver, may also be used to adjust the trigger point of a LDWS.

3.3   DRIVER INTERFACE GUIDELINES

The third and final key aspect of LDWS performance is the driver interface. The driver interface is the means by which the driver:

1) Receives warnings of lane departure danger
2) Adjusts the operating characteristics of a LDWS
3) Is informed of the operating status of a LDWS

First and foremost, the purpose of the driver interface is to provide the driver with alerts or warnings about impending crash danger. Such a warning might communicate to the driver through visual (e.g. a light), auditory (e.g. a buzzer) or haptic (e.g. a shaking steering wheel or a vibrating seat). The communication should convey an appropriate sense of urgency. As far as possible, the warning should be quickly interpretable, even by drivers not familiar with the system. Thresholds for when to warn should be determined in accordance with the warning algorithm recommendations. Unfortunately, our research (described more in the LDWS Benefits Estimates section) suggests that the time course of lane departure events will typically not allow for a graded series of warnings - several warnings of increasing urgency. Even if a warning cannot be issued in time to prevent a crash, the system should warn the driver in hopes of reducing the severity of the unavoidable crash.

[L-36] The system should provide one or more signals to alert the driver to the crash hazard. To the extent feasible, the signal onset should be such that the driver has sufficient time to become aware of the alert and execute an appropriate crash avoidance maneuver.

[L-37] The system may signal the driver through visual, audible or haptic means. Due to the importance of visual attention in highway safety, the visual demand on the driver away from the driving scene should be minimized.

[L-38] To the extent possible, the signals should convey the urgency of the danger. Urgency may be conveyed through the choice of modality (e.g. visual for low urgency, audible or haptic for higher urgency) or through the characteristics of the signal itself (e.g. louder or higher pitch audible tones for higher urgency). If sufficient time is available, several signals of increasing urgency may be provided to the driver.

[L-39] The signal should be easily interpretable, and distinct enough so as not to be confused with other in-cab signals. If graded urgency signals are provided, the signal for an imminent crash should be distinct from other warning signals.

Selecting the actual signal for the warning is a challenge, involving many design decisions on many signal attributes such as intensity (e.g., luminance, contrast, polarity, hue, saturation), duration (e.g., rise time, on-off duty cycle, presentation rate), tonality (e.g., pitch, volume, timbre), etc. Also, the stimuli in the cab may come from outside the cab (e.g. glare on a visual display from direct sun, road noise drowning out audible stimuli, etc.). Finally, in-cab masking stimuli may be situation-specific (e.g., only if the radio is on, need it be turned down).

[L-40] The signal should be designed such that they are not masked by other signals or stimuli normally present in the cab. This may necessitate suppression of other in-cab distractions (e.g. radio) during countermeasure signaling.

[L-41] The signal should not be so intense or complex as to overload the driver's sensing and processing capabilities, or startle the driver into an inappropriate response.

[L-42] The countermeasure signal intensity may be adjustable by the driver. However if such an adjustment is provided, there should be a minimum signal intensity, below which it cannot be adjusted. This minimum intensity level will depend on the modality and other characteristics of the signal, but will be no lower than the intensity detectable by 95 percent of the population under typical in-cab conditions. Feedback on the results of driver adjustment of signal intensity should be provided to the driver during the adjustment process.

Results of driving simulator experiments suggest that warnings that help a driver know how to respond are slightly preferable to non-directional warnings. For example, a LDWS might provide a directional signal to tell the driver which way to steer. A directional audible signal might be a tone emanating from the direction of departure. A directional haptic signal might be a momentary torque to the steering wheel in the direction that will return the vehicle to the travel lane. Both direction auditory and directional haptic signals were found to be slightly preferred over non-directional signals in experiments conducted on the Iowa Driving Simulator as part of this program [Task 3 Report, Vol. 2].

[L-43] When practical, the LDWS signal should in some way indicate the appropriate driver response, as long as this information can be conveyed without reducing the signal's interpretability or increasing the driver's confusion.

To account for driver-to-driver variations in such parameters as reaction time and lane keeping precision, as well as differences in vehicle width, the warning threshold for a LDWS should probably be adjustable. For example, analysis we have conducted shows that because of their width, heavy trucks spend approximately 8% of the time with at least one tire touching or beyond the edge of the lane. The warning threshold for a heavy truck may therefore need to be different than the threshold for a much narrower passenger vehicle. Adjustment to the warning threshold may be made through explicit driver input (e.g. turning a knob) or automatically by the system, through knowledge of the vehicle type or analysis of driver behavior. For a LDWS with a manually adjustable warning threshold, the driver should be provided with feedback as to where the threshold is current set during the adjustment process. The range of adjustment should be limited so as not to allow the driver to set the threshold too early or too late, potentially reducing system effectiveness. Our experiments suggest that an acceptable range of user adjustability would allow setting the warning to trigger as early as 50cm inside the lane boundary to as late as 50cm outside the lane boundary.

When practical, a LDWS should provide for adjustment of the warning threshold to cope with variations in driver behavior and vehicle characteristics. These adjustments may be made manually by the driver, or automatically by the LDWS. Manual adjustment of the warning threshold should be accompanied by feedback to the driver as to the current setting. Any manual adjustments should be easy to make and understand. Manual adjustments should not require unnecessary distraction of the driver from the driving task.

[L-44] The allowable range of warning threshold adjustment should be limited to avoid unintentional compromising of system effectiveness. The suggested earliest allowable threshold would trigger a warning when the vehicle's outside tire is 50cm inside the lane boundary, and the suggested latest allowable threshold would trigger a warning when the vehicle's outside tire is 50cm outside the lane boundary.

For any manual adjustments of system operation, the controls should be simply and easy to understand. Performance of adjustments should be accomplished with little diversion of the driver's attention from the driving task. Adjustments that require substantial attention or time, such as initial system configuration should be reserved for times when the vehicle is stopped.

[L-45] Manual adjustment of LDWS operation should not result in a significant distraction of driver attention from the driving task. Complex interaction with the system should be reserved for times when the vehicle is stopped.

In addition to controlling warning intensity and warning threshold, a third control drivers are likely to desire is an on/off switch, to allow the driver to selectively enable or disable

the system. There is some controversy over whether an on/off switch should be provided on collision avoidance system. For example, the guidelines for forward collision warning systems recommend not providing an on/off switch for forward collision warning systems. The reasoning goes that with an on/off switch, people are likely to turn the system off and forget to turn it back on, preventing its benefits from being realized. Because of the likelihood of false alarms under certain circumstances with these systems, we believe drivers will strongly desire an on/off switch to disable it operation. This sentiment seems to be shared by the international community – provisions for a mandatory on/off switch are included in the draft ISO standard for lane departure warning systems.

[L-46] A LDWS should be equipped with a clearly marked on/off switch, to allow the driver to disable warnings.

As mentioned earlier, the developer of a LDWS should attempt to minimize false alarms, to avoid the risk the user will have it turned off at the time of a crash. This would include provisions for the system to temporarily disable itself when external conditions are such that false alarms are likely.

To further reduce the risk that the driver will turn the LDWS off and forget to turn it back on, particularly at vehicle ignition start, the LDWS should power-on with application of ignition power if the on/off switch is in the on position.

[L-47] A LDWS should power-on with application of ignition power if the on/off switch is in the on position.

The final function the driver interface needs to perform is to provide the driver with system status information. The driver must be kept apprised of the system's operating status, to avoid relying on the system when it is not operating effectively.

[L-48] A LDWS should be capable of providing status information to the driver under the following conditions:
  - **The system fails its power-on self test**
  - **The system is not working due to component failure or other cause during operation**
  - **The system detects conditions having rendered it ineffective (e.g., insufficient road markings to track).**

[L-49] A LDWS should provide a continuous visual indication to the driver that the system is on and operating properly.

A continuous visual indication is important to allow the driver to check system status with a quick glance. However with extended use, the driver may stop conducting consistent visual checks of the system status. Therefore it may be necessary to supplement the continuous visual status indicator with a more easily detected audible or

haptic indicator to inform the driver of status transitions, such as when the system goes off-line because external conditions have rendered it ineffective.

[L-50] As a supplement the continuous visual status indicator, a LDWS should employ an audible or haptic signal to indicate system status transitions, as long as the signal does not distract or disturb the driver.

[L-51] If the system goes off-line for one of the above reasons, all warning displays should remain inactive.

Once off-line due to a temporary condition (e.g. insufficient road markings), the driver should not be required to explicitly reactivate the LDWS, since it is likely that driver will either forget about or be confused about this extra step to activate the system. This could result in the system not being available to warn the driver when a crash is imminent.

[L-52] When off-line due to a temporary condition (e.g. insufficient road markings), a LDWS should continuously monitor for disappearance of the condition preventing effective operation. If the condition disappears and proper operation is again possible, a LDWS should automatically transition back to the enabled state, without requiring explicit input from the driver. This transition should be accompanied by an audible or haptic signal, as long as the signal does not distract or disturb the driver.

There are many other general principles of human factors that should be considered when designing a LDWS. These principles and guidelines are covered in other DOT reports, and are mentioned here for reference.

[L-53] Detailed system design features shall incorporate human factors design guidelines and principles as contained in COMSIS report, MIL-STD-1472D, and other human factors documents as appropriate.

As with any new technology, initial user education will be important to insure proper use of the system.

[L-54] User orientation to the system should be provided via documentation, video, demonstration or hands-on training.

Finally, lane departure warning is just one collision warning service. In the future, vehicles will likely be equipped with more than one such collision warning service. In addition to making systems that do not interfere with each other's operation, developers should be encouraged to look for and exploit potential synergies between collision warning technologies. For example, the sensing technology for determining where the vehicle is in the lane could also be used look for erratic steering behavior as a way of assessing the driver's state (e.g. alert, drowsy, intoxicated). This same technology could be used to improve the performance of a side collision warning system, by determining when the vehicle appears to be drifting out of its travel lane. Finally information about

the upcoming road geometry from the lane sensor could be used to improve "threat assessment" in a forward collision warning system. By merging information about where the road and obstacles are ahead, the LDWS could help the forward collision warning system determine if an obstacle is in the travel lane, or just a harmless object on the side of the road. Integrating the LDWS functions with other collision warning services will help to bring costs down, improve overall performance, and reduce driver confusion.

[L-55] When practical, LDWS functions and/or sensing results should be integrated with other collision warning functions to reduce costs, improve overall performance and reduce driver confusion.

4 LDWS BENEFITS ESTIMATES

It is important to estimate the potential benefits of collision avoidance systems as soon as possible, to help federal regulators, manufacturers and the driving public to determine if the technology is worth pursing. The true benefits of a technology are impossible to estimate prior to actual deployment, and even then they are sometimes difficult to quantify due to confounding factors such as changes in driving behavior, and the presence of other technology that may have influenced crash frequency or severity.

Prior to deployment, one way to estimate potential benefits is through mathematical modeling and computer simulation. We have chosen the commonly employed technique of Monte Carlo simulation to estimate potential benefits of a LDWS. The general approach we have taken is as follows:

1) Create realistic computer simulations of road departure crash situations based on data collected from real world crashes.
2) Run these simulations with and without support from various configurations of a LDWS.
3) Estimate performance based on the results of the simulation. Measure the nuisance alarm rate including the false positive and false negative rates and the number of crashes avoided with LDWS support as compared to driving without support.
4) Estimate benefits by extrapolating the performance data from the Monte Carlo simulations to real world crash statistics.

The process of estimating potential benefits from Monte Carlo simulations is based on a number of assumptions and has inherent in it a substantial amount of uncertainty. In this section we present the crash data on which the simulations are based, the effectiveness estimates for a LDWS based on these simulations, and the extrapolated benefits that deployment of a LDWS could potentially realize. The analysis is done for both passenger vehicles and commercial trucks.

4.1 RUN-OFF-ROAD CRASH CIRCUMSTANCES

A statistical review of the 1992 General Estimation System (GES) and Fatal Accident Reporting System (FARS) databases indicates that run-off-road crashes are the most serious of crash types within the US crash population. The crashes account for over 20% of all police reported crashes, and over 41% of all in-vehicle fatalities (15,000 / year).

Some of the most important characteristics of roadway departure crashes are the following:

- They occur most often on straight roads (76%)
- They occur most often on dry roads (62%) in good weather (73%)
- They occur most often on rural or suburban roads (75%)
- They occur almost evenly split between day and night

Unlike many of the other crash types, run-off-road crashes are caused by a wide variety of factors. The most common reason that vehicles leave the road is the driver's failure to control the vehicle.

Table 4-1 lists the relative fraction of run-off-road crashes by causal factor for passenger cars and heavy trucks. Simple inattention to the driving task leads to about one in eight road departures for both passenger cars and heavy trucks. Inattentive drivers may be distracted by, for example, a radio, or they may be daydreaming. The data indicates that truck drivers who fall asleep are the single largest cause of run-off-road truck crashes. However, the sampling method used to select truck crashes for study [Grace et al., 1998] may have caused the number of fatigue-related crashes to be somewhat overestimated. Driving under the influence is a significant problem for passenger car drivers but a relatively small part of the total for truck drivers. Trucks have relatively fewer road departure crashes in adverse conditions. It is significant to note that vehicle failure is a small fraction of the total for both vehicle types.

Table 4-1: Primary causes of ROR crashes for cars and heavy trucks from 1992 GES/NHTSA. (Source: Carnegie Mellon University and Calspan [1994], and Hendricks and Bollman [1996]).

Causal Factor	Passenger car	Heavy Truck
Driver inattention	**12.7 %**	**12.4 %**
Driver relinquished steering control	**20.1**	**42.7**
fell asleep	6.9	40.5
Intoxicated	10.9	1.1
physical (seizure, passed out)	1.5	1.1
Other	0.7	
Evasive maneuver	**15.4**	**9.0**
Lost directional control	**16.0**	**6.7**
Wet	6.3	3.4
snow or ice	4.4	1.1
Other	5.3	2.2
Vehicle failure	**3.7**	**5.6**
Engine	1.5	--
Tire	0.8	1.7
brake system	--	1.9
other	1.4	2.0
Vehicle speed	**32.1**	**22.5**

Vision obscured	--	**1.1**
Total	**100.0 %**	**100.0 %**

A significant fraction of crashes for both vehicles is caused by excessive speed for existing conditions such as when a driver is caught unawares by a curve. Requirements for a countermeasures system that warns a driver of the need to slow for an upcoming curve is addressed in the second part of this report on Curve Speed Warning Systems.

If a vehicle begins to leave its lane, the driver's ability to safely return to the lane depends on the width of the shoulder available for maneuvering. A vehicle path may result in a safe recovery if 6 ft of clear pavement is available on the side of the departure. That same path, if it occurs on a different highway with a minimal room for the recovery maneuver, may lead to a crash. The shoulder widths noted in the Task 1 report of this program are presented in Figure 4-1**.** They are for run-off-road crashes where the cause was driver inattention or relinquishment of steering control. In most cases, a shoulder width of at least 3-ft is available. The Federal Highway Administration maintains detailed information on shoulder widths and other road design properties in the Highway Performance Monitoring System. On principal arterials, the right shoulder is usually 10 ft or more and the left shoulder is typically 4 to 10 ft. on divided highways Shoulder widths on minor arterials and collectors are not consistent, and policies vary considerably from state to state. A shoulder width of 4 ft or more is usually available, but there are a significant number of miles with less than that.

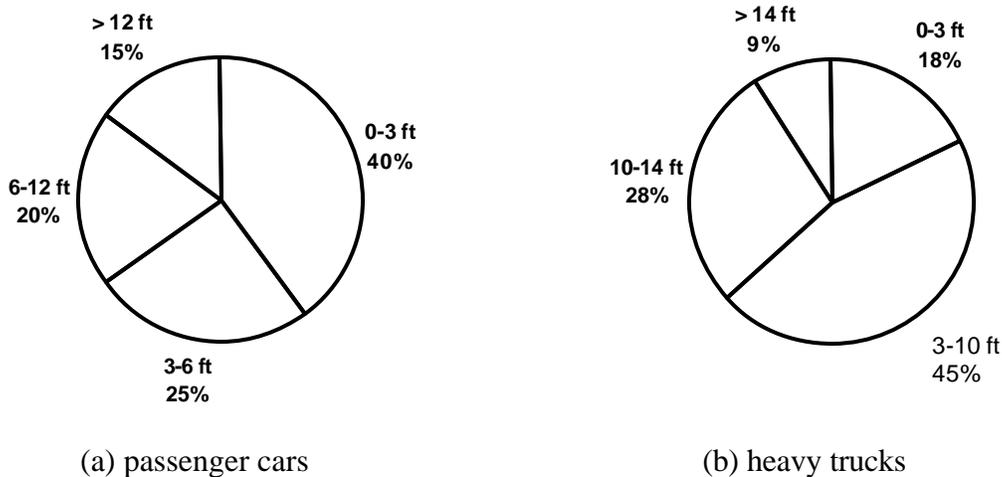(a) passenger cars   (b) heavy trucks

Figure 4-1: **Distribution of shoulder widths on roads where crashes in the sample caused by driver inattention or relinquishing of control occurred from1992 GES data (Source: Carnegie Mellon University and Calspan Corporation [1994], and Hendricks and Bollman [1996]).**

4.2   MODELING APPROACH

The general approach to evaluating a proposed countermeasure system was to develop a computer model of the vehicle, the roadway, the driver (including both appropriate and inappropriate actions), and the countermeasure system itself. The time-domain model simulates a particular combination of circumstances--vehicle speed, road curvature, driver state of mind, countermeasure threshold, and so forth.

To learn the effectiveness of a countermeasure in a variety of situations, we varied the parameters in a fashion like Monte Carlo, and run hundreds of separate simulations. We looked primarily at two performance measures: the crash prevention rate (which ideally would be high) and the nuisance alarm rate (which ideally would be low).

The modeling activities culminated in the development of the software package, RORSIM, which was used in all of the simulation studies. A description of RORSIM is provided in this section, and concise instructions on using it are provided in Appendix A.

4.2.1   DESCRIPTION OF RORSIM

RORSIM is an enhancement to VDANL (Vehicle Dynamic Analysis, Non-Linear), which is a general-purpose rubber-tired vehicle simulation program developed for NHTSA by Systems Technology, Inc. in Hawthorne, California [Allen et al 1992]. VDANL provides the basic vehicle dynamics model for the simulation, as well as the closed-loop driver model. VDANL includes a 17-degree-of-freedom model of a general vehicle. The nonlinear differential equations of motion are integrated numerically by VDANL. The project team has written enhancements to VDANL for use in evaluating Run-Off-Road countermeasure systems. Capabilities have been added to simulate some of the driver' actions, model the performance of various proposed countermeasure systems, and provide representative roadways.

The model is deterministic in the sense that almost every parameter, including the moment when the driver becomes inattentive, is fixed before a simulation begins. When closely related but distinct scenarios were to be simulated, different parameters were explicitly chosen before the analysis.

The RORSIM package can simulate a complete scenario: a situation develops, it is sensed by the countermeasure system, the driver responds to the warning and regains safe control of the vehicle. When applied like in this manner, RORSIM is useful for demonstrating that a countermeasure system can successfully prevent a Run-Off-Road crash under the particular circumstances modeled.

4.2.2   VEHICLE MODEL

The passenger vehicle presently modeled in RORSIM is a Ford Taurus, which was selected by NHTSA as a representative mid-sized sedan to be used in collision avoidance research. The Taurus is defined in RORSIM by a set of approximately 125 parameters, whose values represent all the physical properties of the vehicle, such as total mass,

equivalent spring rates of the suspension, camber angles of the wheels, etc. A number of simulated maneuvers were executed with the vehicle model to verify its performance and to determine the capabilities of the vehicle and driver.   The VDANL model of the vehicle itself was thoroughly analyzed and verified by Christos and Heydinger [1997] Some representative parameters defining the Taurus model are provided in Table 4-.

Table 4-2: Selected Properties of the Ford Taurus Model Used in RORSIM.

Parameter	Value
Weight	3405 lb
Track Width	5.125 ft
Wheel Base	8.83 ft

The truck modeled in this work is a combination tractor and semi-trailer. It approximates an AASHTO WB-67 vehicle. The parameters that describe the vehicle were taken from work for FHWA [Allen et al., 1998]. Properties of the truck are summarized in Table 4-.

Table 4-3: Selected Properties of the Truck Model Used in RORSIM.

Parameter	Tractor	Trailer	Total
Weight	19,320 lb.	26,726 lb.	46,046 lb.
Wheel Base	18 ft	48 ft (hitch to second axle)	66 ft
Track Width	7.5 ft	7.5 ft	7.5 ft

4.2.3   DRIVER MODEL

Three aspects of the human driver are crucial to the modeling approach--lane-keeping under ordinary circumstances, inattention during potential run-off-road circumstances, and response to an alarm.

The validity and credibility of the simulation predictions depend heavily on the accuracy to which driver lane-keeping behavior can be represented. To this end, considerable effort in the final phase of the program was devoted to using recently acquired experimental data to develop driver lane-keeping models for trucks and passenger vehicles. This effort is documented in Section 4.2.5 of this report.

Inattention to the steering task was modeled simply by holding the handwheel angle fixed for a period of time. After an alarm sounded, a randomly selected response time was imposed, and then the driver resumed steering. A mean response time of 0.82 seconds (std. dev. 0.24s) was used in the experiments, based on steering response times of

surprised drivers in a simulator [Malaterre and Lechner, 1990]. No known research in actual automobiles on drivers' response to warnings was available to guide this study, but results of recent work at the VRTC [Mazzae et al., 1999] may be worth including in future research.

4.2.4   WARNING ALGORITHM

The warning simulated in RORSIM was algorithm 2 from Section 3.2.3, the 2nd Order Time-to-Line-Crossing algorithm. The formula in RORSIM projects the vehicle's path assuming the forward speed and curvature remain constant. Time-to-line-crossing (TLC) is typically defined as the projected time that will elapse before the vehicle crosses a lane edge line. The line to which TLC is calculated can be some other line that is parallel to the lane edge line--a "virtual boundary." The concept of TLC and virtual boundary is illustrated in Figure 4-2.

Projected path of the right steer tire
(The curvature is highly exaggerated.)

TLC to the   virtual boundary
is the projected time for a
steer tire to reach this point

TLC to the   lane edge
is the projected time for a
steer tire to reach this point

Virtual Boundary

Berm (6')

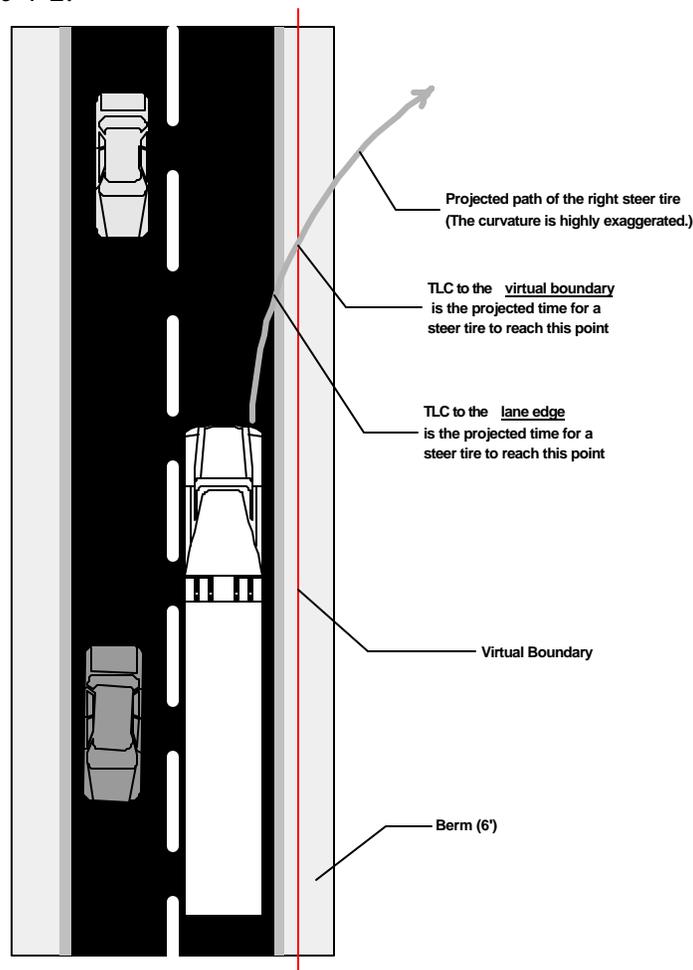**Figure 4-2:** The virtual boundary is an imaginary line beyond the lane edge line. TLC can be calculated as the projected time for the vehicle to reach the virtual boundary. The virtual boundary is used only for calculating TLC; it is not necessarily at any physically significant location. The success of a recovery maneuver is judged by whether all of the vehicle's tires were kept within a

pre-determined distance of the lane edge. In this figure, the road has a 6-ft-wide shoulder, so 6 ft of maneuvering room would be permitted on both sides of the original lane. Of course, the lane on the left side may have other traffic and it is generally not realistic to use the same shoulder width on both sides of the lane.

The use of a virtual boundary was motivated by the desire to model real world conditions such as the presence of lane shoulders and the reality that trucks tend to exhibit more erratic lateral movement than passenger vehicles. The virtual boundary concept, though, was applied to both passenger cars and heavy trucks and proved useful for both.

The virtual boundary on the inside of curves is shifted away from the lane to account for drivers' slight but measurable tendency to drift to the inside of the curve.   The formula for the curve cutting allowance is

$$a \quad = \quad 0.26\text{ft} \bullet \frac{mr}{R} \tag{1}$$

> where   a = the curve cutting allowance, ft
> mr = 6562 ft, the maximum radius at which the allowance is used
> R = the radius of the current curve

The inner virtual boundary is moved an extra 0.86 ft on the inside of a 2000-ft-radius curve and by 0.43 ft on a 4000-ft-radius curve.

4.2.5   DRIVER LANE KEEPING MODEL

The purpose of the lane position model is to guide a simulated vehicle along paths that are representative of specific driving situations to help in evaluating proposed run-off-road countermeasure systems. The behavior of the countermeasure system during normal, controlled driving was essential for predicting its false alarm rate. The lane position model was also used to establish plausible paths from which lane departure trajectories can originate. Departure paths were useful in studying the behavior of a countermeasure system as a possible ROR crash develops.

Lane position models captured the meandering and curve-cutting behavior of drivers in three specific situations--passenger cars on freeways, passenger cars on county roads, and heavy trucks on freeways. Experiments have been conducted for each of the situations.

We fitted statistical models to the observed lane position data. The statistical models generated vehicle paths to be used as inputs to a vehicle dynamics model, RORSIM, to ensure that the simulations are representative of observed "normal" driving behavior. It is recognized that "normal " driving behavior should probably never produce a crash.

There are distinct differences between the lane-keeping behavior of passenger car drivers and heavy truck drivers. Most notably, heavy trucks leave their lane frequently, though briefly. Drivers of passenger cars tend to control their lane position much more carefully on narrow county roads than on freeways. There was a little evidence of curve cutting on freeways, though driver-to-driver variations are much larger than the measured amount of curve cutting. Most drivers in the study kept the vehicle within the lane even on the tight county road curves, but some were clearly cutting the curve and borrowing from the oncoming lane.

4.2.5.1   Review of Earlier Lane-Keeping Models

Many researchers have studied driver lane keeping behavior in general and several have studied driver behavior through curves. Most of the work has been performed in driving simulators. Simulators have the advantage of the ability to control the scenario exactly, but they have at least two disadvantages. The first is that disturbances need to be artificially introduced and that assumptions must be made about their properties. The second disadvantage is that the driver's perception of the curve and the vehicle's motion do not exactly match those on a real road.

Glennon and Weaver [1972] have published the most thorough study of driver behavior in curves. They followed unaware drivers through curves, noting their speed and lane position through the curve. Due to cutting (which increases the effective curve radius if performed skillfully) and meandering (which reduces the minimum effective curve radius), the drivers' maximum lateral acceleration in the curve may be lower or greater than the assumed steady-state acceleration implicit in highway design assumptions. The present study for NHTSA sought to assess precisely the same effects of driver behavior, though in a different way. Unfortunately, Glennon and Weaver's raw data have not been preserved through the quarter century since it was collected [Urbanik, 1997]. Godthelp [1986] studied steering wheel rates for different combinations of speed and curvature on a test track. He used temporary visual occlusion to learn how the drivers used open-loop and closed-loop control. This work is crucial in learning how humans perform the control task, but it does not develop a model for the path that drivers follow through a curve. The only other known research specifically on curve negotiation using real vehicles was conducted on a test track by Afonso et al. [1993]. They reported the qualitative effects on steering anticipation, steering angle, and steering rate, due to curve radius and driver experience. While their work did yield some important findings, they, too, did not attempt to develop a model for driver behavior.

Two publications, Winsum and Godthelp [1996] and Boer [1996], have proposed models for predicting driver behavior in curves. Winsum and Godthelp used their Time-to-Line-Crossing (TLC) metric to relate drivers' speed selection in curves to their steering behavior. Boer developed a geometrical model to predict the mean paths that drivers attempt to steer. Both research projects were based on simulator studies.

Two teams have studied general lane-keeping behavior on public highways. The Rockwell Science Center [1996] collected extensive data on highways, noted the characteristic 1/f shape of the frequency spectrum. In our simulation of driver lane keeping behavior, we noted a similar 1/f shape in the power spectral density curve. A team from Battelle [Tijerina et al., 1995] studied heavy truck driver behavior on public roads. Summary statistics such as mean lane position, variance, and frequency of lane excursion, were calculated for various pairs of conditions such as, rural vs. urban, free flow vs. car following. These results were valuable benchmarks for the research discussed in the text.

Goto et al. [1995] have also published spectra of lane position. Their data were collected in an actual vehicle on a closed course. The subjects were too limited to draw extensive conclusions. The spectra provided valuable guidance in planning the data analysis presented in the text.

Two publications, Allen et al. [1975] and Carson and Wierwille [1978] have reported lane position variances that have been useful in developing earlier versions of the RORSIM driver model. Both were performed in a simulator and introduced the disturbances artificially.

4.2.5.2   Form of the Lane Position Model

The driver modeling process for RORSIM comprises three steps:

- Recording paths from actual vehicles on roads,
- Developing a statistical model for synthesizing representative paths, and
- Running vehicle dynamics simulations to follow the prescribed paths from Step 2.

Figure 4- outlines the process. The goal is that the vehicle paths in all three stages will be similar in all respects that are relevant to evaluating proposed countermeasure systems.

The actual path followed by a vehicle depends on the vehicle being driven, the peculiarities of the person driving the vehicle, road conditions (including general conditions like curvature and specific conditions like potholes), and external influences such as other traffic and wind gusts. These actual paths, which account for all influences of the real world, are the output of Step 1. The second step is to develop a mathematical model that can generate paths similar to the actual paths. The result of Step 1, considered as the output of a whole system, was the standard for evaluating the result of Step 2. Therefore, separately modeling the numerous influences in the real world is not necessary in Step 2. In Step 3, the simulated vehicle is to follow a path that is, again, like the actual paths in all essential respects. Two inputs were provided to the simulated vehicle, a path command controlling the coarse behavior and wind gusts to provide perturbations to the path accounting for all disturbances. As the simulated vehicle follows a path that is characteristic of an actual vehicle under the conditions being simulated, the performance of a countermeasure system under those conditions might be predicted. However, it is

recognized that these conditions, by definition, do not include conditions that produce a crash.
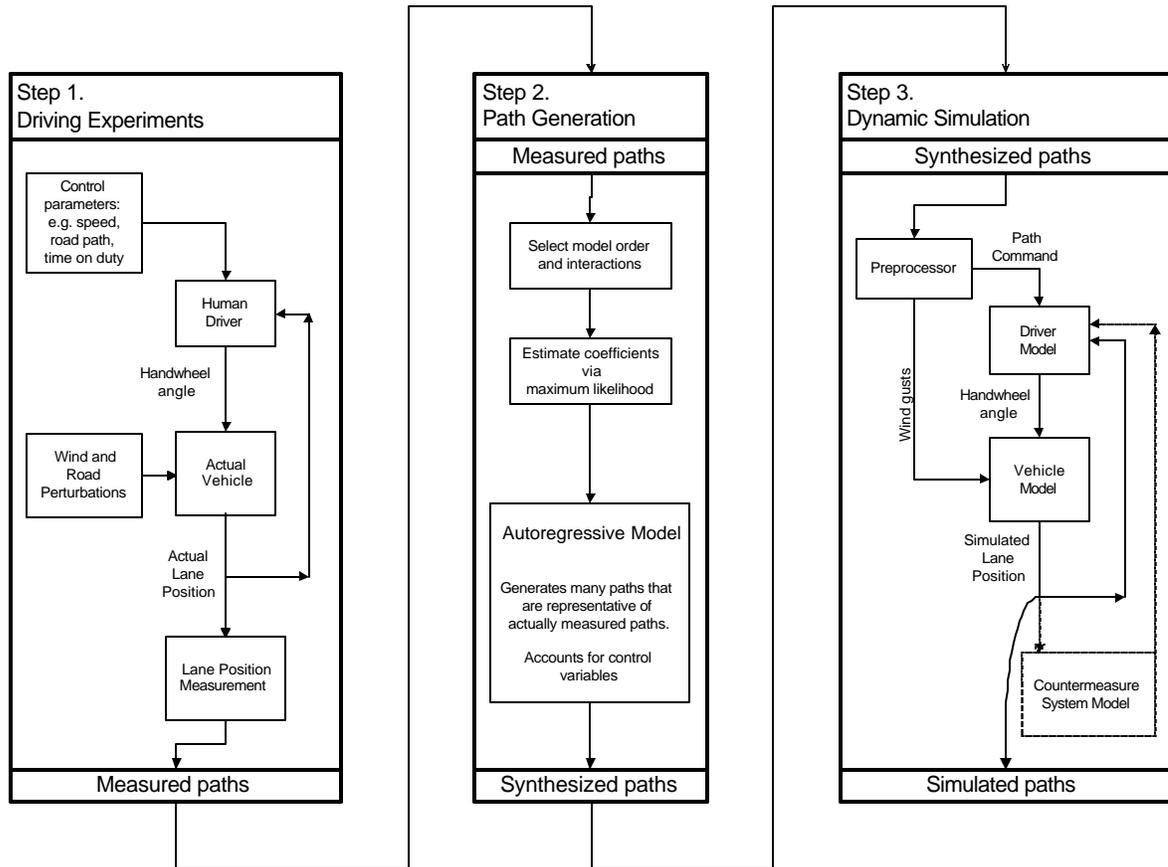
Figure 4-3: Block diagram of the three-step process of simulating paths that are representative of paths measured in real vehicles.

4.2.5.3 Lane Keeping Experiments

Data for the driver lane-keeping model was collected using instrumented vehicles on public roadways. For the passenger vehicle experiments, we selected short, representative segments of freeway and country road data that included a straight, a gentle curve, and a tight curve, where "gentle" and "tight" are relative terms for the two types of roadway. Descriptions of the road segments selected for analysis are in Table 4-. A map of the entire passenger vehicle test route is in Figure 4-4. Because the experimenters had no control over the truck test routes, the road curvature for the truck test routs had to be inferred from the vision system's measurements, and all curves representative of freeway conditions were included in the analysis.

Table 4-4: Road segments where lane-keeping practices were observed.

	Truck	Passenger Car	
	Freeway	Freeway	County Road
Location	various in Pennsylvania	U.S. 33 eastbound, west of Marysville, Ohio	Union County Road 179, westbound northwest of State Road 739
Approximate station	--	348 to 600	188 to 230

"gentle" curve
    degree
    radius, ft
    curvature, 1/ft
	--
	
		1°28'
		3907
		0.000 256
			
			2°00'
			2865
			0.000 349

"tight" curve
    degree
    radius, ft
    curvature, 1/ft
	--
	
		3°30'
		1637
		0.000 611
			
			6°00'
			955
			0.001 047

lane width, ft	usually 11-12	12	10
right shoulder width, ft	unknown	9	5

The data for passenger cars were taken specifically for this project by the staff at NHTSA's Vehicle Research and Test Center (VRTC). The test vehicle was a 1996 Chrysler Concorde, driven in turn by sixty-six paid subjects. The data were recorded at the same time as data for another project [Tijerina, 1999] on the practices of car following distances, and the two studies did not conflict. The test route was modified slightly to accommodate the needs of the present project. Some data (for the speed dependence of lane keeping and curve handling) was not analyzed in this project.
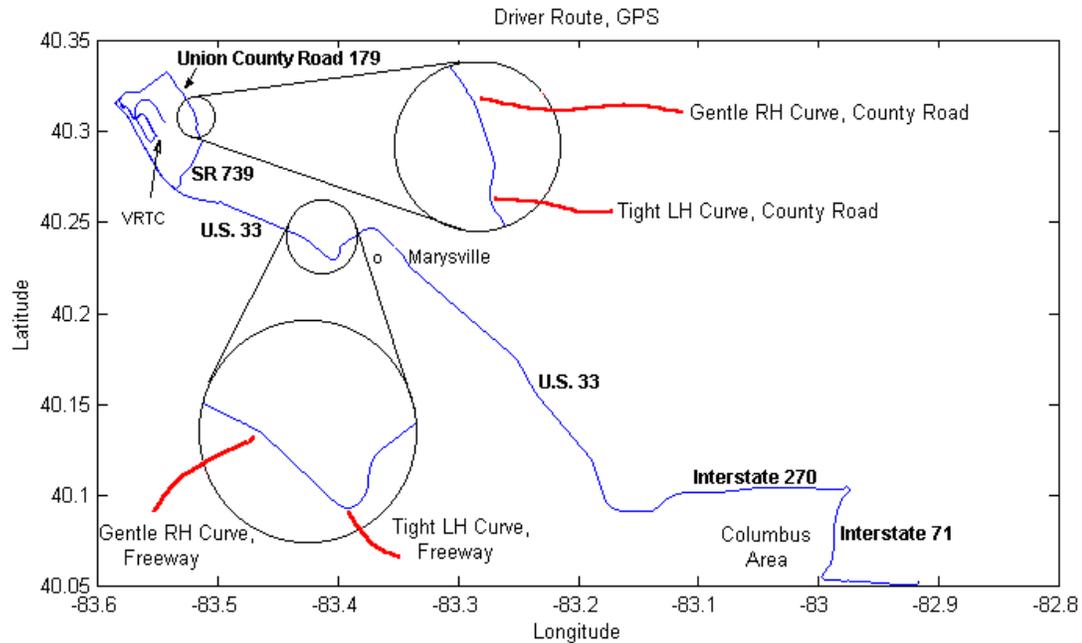
Figure 4-4: A map of the route for observing lane-keeping behavior. This map was made by plotting the latitude and longitude of the vehicle as recorded by a GPS receiver.

The lane position was measured by a pair of video cameras mounted on the rear of the vehicle. Each camera was directed at the lane stripe on one side of the car. The lane position was recorded 30 times per second, in synchrony with the video images of the driver and the road. After they were recorded, the signals were filtered and averaged to produce lane position measurements spaced at 20-ft intervals along the highway.

The lane width on the county road was approximately 10 ft. The paved shoulder extended another 5 ft, but only about the first 2 ft was bare asphalt. On the two S-curves, the gravel was worn away over a wider strip on the inside of the curve than on the outside, suggesting that some people who typically drive this road cut to the inside of a right-hand curve. Guardrails were present along part of the county road route, and were 7-1/2 ft from the lane edge. Along most of the route, the grassy earth was more or less level until 8 to 12 ft from the lane edge. The lane width on the freeway is 12 ft. The shoulder on the freeway segment of the test route was measured to be 9 ft wide. (This is a U.S. highway, but not an Interstate.)

The demographics of the passenger car drivers are listed in Table 4-5. The subject numbers are the designations given by VRTC. The X's in the table indicate which models were developed from a driver's path. To match the design used for the simulation study, thirteen drivers were selected for each condition. As is explained in Figure 4-8 and the accompanying text, separate models were fit for the straight and two curvatures for the freeway. On the county road, because of the limited valid data, a model was fitted only for the straight, but the means and variance were adjusted to duplicate the behavior

on the curves. There were sixty-six participants in the study, but not all drivers' trips yielded data suitable for analysis.

Table 4-5: Demographic characteristics of the drivers used for the study

Subject	Gender	Age	freeway			county road
			straight	tight curve	gentle curve	
1	M	55			x	
4	F	71			x	
6	F	18	x	x		
7	M	21		x	x	
8	M	49	x		x	
9	M	25	x			
10	M	25		x		
11	F	37			x	
13	M	23		x		
14	F	25	x			x
15	M	70				
16	M	20			x	
19	F	43	x			
21	F	42	x			
23	F	18		x		
24	F	69				x
26	F	18		x		x
27	M	71	x		x	
28	F	65	x		x	x
29	F	22		x		x
30	M	24			x	
31	F	41				x
32	F	43	x			
33	M	70	x			x
35	M	67	x			
36	F	24				x
38	M	18		x		x
39	F	41				x
40	M	38	x		x	
42	F	21			x	x
43	M	40		x		
44	M	36		x	x	
46	F	55		x		
47	M	66		x		x
48	F	20		x		x
49	F	41			x	
66	M	74	x			

The truck driver data was collected by Driving Research Center personnel at the Carnegie Mellon Research Institute [Grace, et al., 1998] as part of a study on drowsy driving. Drivers were on their normal early evening to early morning shift in trucks from their firm that were specially instrumented for data collection. The 7 p.m. to 7 a.m. interval was selected to maximize the possibility of incurring drowsy driving episodes. Data

included vehicle speed, lateral acceleration of the vehicle, and vehicle lateral position with respect to the lane boundary.

4.2.5.4   Observations of Lane-Keeping Behaviors

Differences in lane-keeping behavior are immediately apparent when the distribution of all lane position observations is plotted. Figure 4-5 has the distributions for three conditions: trucks on freeways, cars on a freeway, and cars on a county road.

The mix of curvatures is different in the three plots, but three distinct types of behavior are clear. The drivers on the county road are more careful with their lane position, as evidenced by the sharp drop-off in the distribution. The distributions on the freeways, for both heavy trucks and passenger cars are wider when compared to the more narrow distribution obtained on the country road.
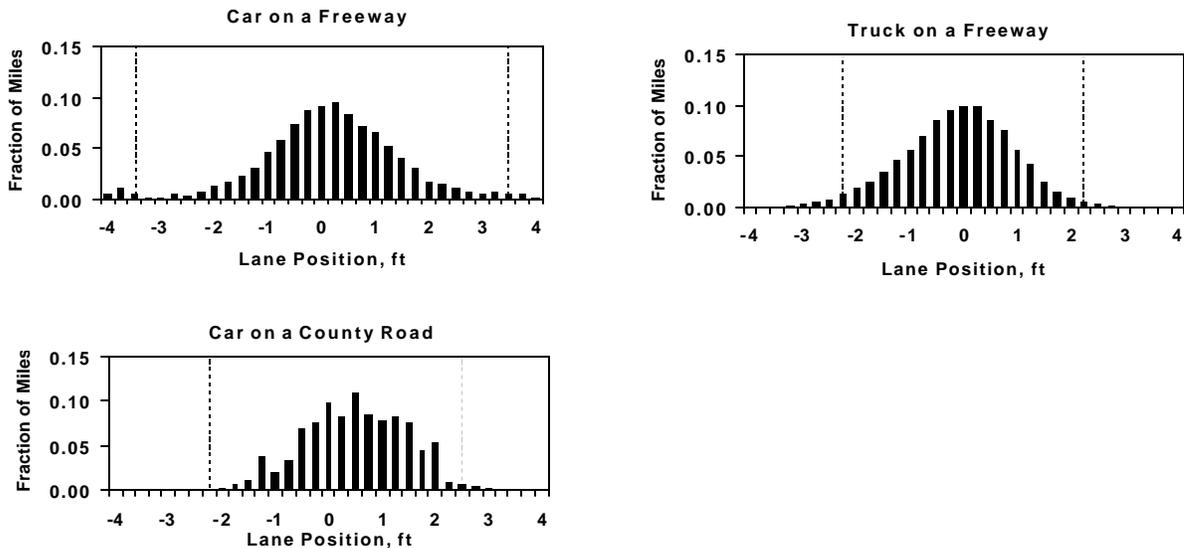
Figure 4-5: Distribution of all measurements of lane position for the respective vehicles and roadways. The dotted lines indicate the position of the center of the vehicle when the tires are at the edge of the lane. Positive values indicate that the vehicle is to the right of the center of the lane.

The passenger car data was separated according to the segment of road (a particular curve or a straight) and to the individual drivers. There were discrete "trips" of continuous observations on a single road condition. The mean and variance of each "trip" was calculated. The distributions of these means and variances show how different drivers handle different situations. Figures in Appendix C show the distributions for the road segments selected for analysis.

Figure 4-6 shows the highest, lowest, and median values of the mean for each road segment used in the passenger car analysis.   On the freeway straights (zero curvature), the median is near zero. That says that about half the drivers' average position on the

straight was left of center, and half the drivers' was right of center. The median for the 3°30' left-hand curve on the freeway was about one foot right of center. That is, more than half the drivers kept their cars generally to the right of the center of the lane on this long left-hand curve. The wide difference between the highest and lowest means shows that there was considerable variation among the drivers. Most drivers generally tend to keep their vehicles to the right of center. The only exception to this in Figure 4-6 is on the tight 6-degree curve to the left on the county road. Most of the drivers cut the curve at least a little bit, but some did not.
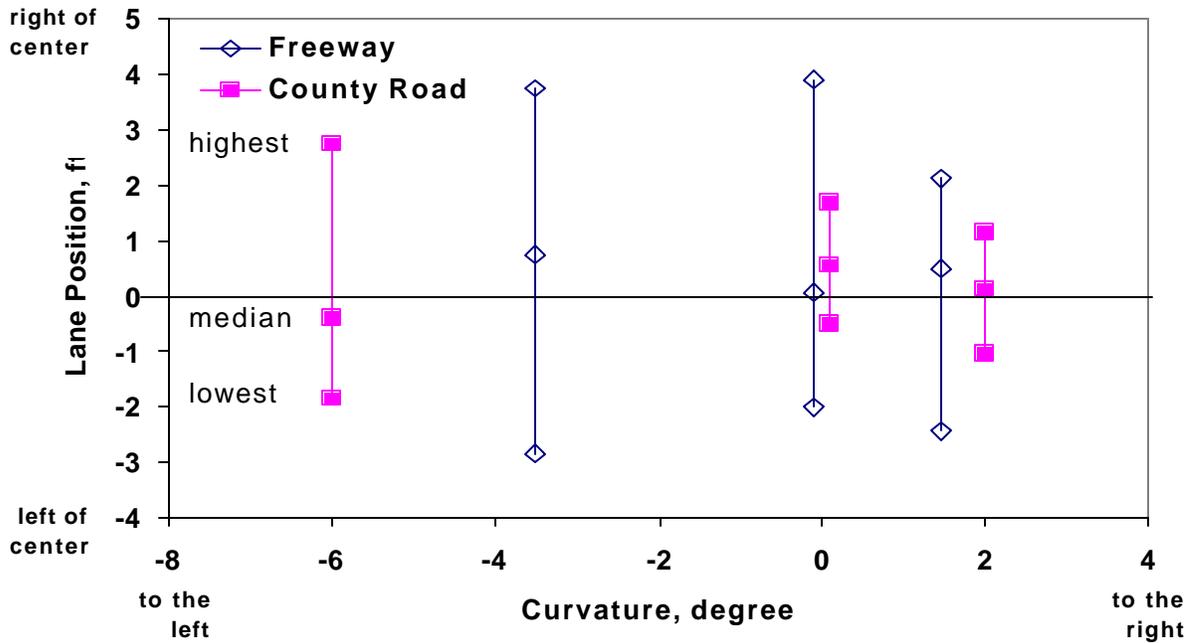
Figure 4-6: The observed passenger car measurements were divided into "trips" of continuous data at a certain curvature for one driver. The mean of each "trip" was calculated for all drivers. This figure shows the range of these means.

The most notable difference between the lane-keeping behavior on the freeway and the county road is that the drivers permit their cars to drift much farther away from the lane center on the freeway. The lane on the freeway is two feet wider than on the county road, so this was expected. The behavior in curves is more complicated than was expected. Both the freeway and the county road segments contained a gentler curve, which was to the right, and a sharper curve, which was to the left. On the curves to the right, on both types of road, the mean lane positions tend to be slightly more to the right than on the straights. That is, the drivers are cutting the curve. On the left-hand freeway curve, the means also are to the right, though they are more spread out. We can hypothesize that the behavior is more varied because the curve is unusually long or that some of the drivers drift outwards because the curve is longer and tighter than a typical freeway curve. On the county road, many drivers definitely cut the curve to the left. This curve is tight, even for a county road, and it is coming out of the second half of an S-

curve, so drivers seeing the long straight-ahead are eager to get out of the curve. The right-hand curve on the county road is within guardrails, which may subtly encourage the drivers to stay within their lane. The left curve, on the other hand, does not have guardrails, and drivers may feel emboldened.

There were a few observations of the behavior that are not evident in this summary data. Several drivers on the long freeway stretches drifted gradually across the lane. Over a distance of as much as a mile, the car followed a reasonably straight path from a foot or so on one side of center to the other side of the lane. Many features of the path, in fact, are several thousand feet long, much longer than the "gentle" curve.   Figure 4-7 shows the lane position of one driver over the entire freeway segment.
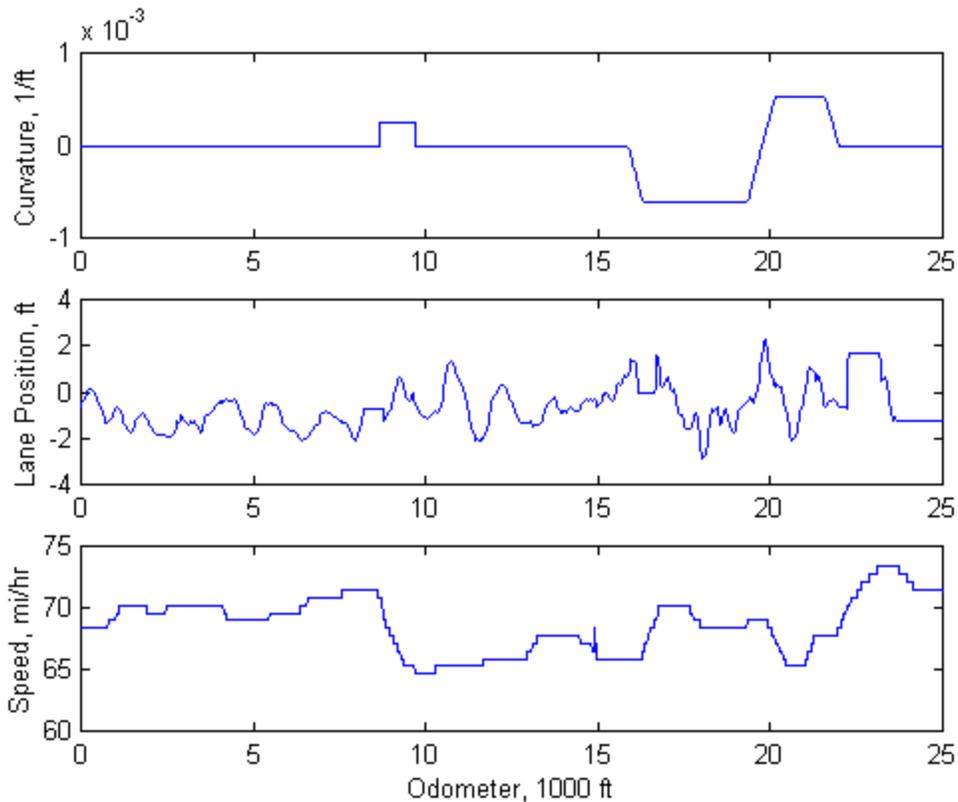
Figure 4-7. The behavior of passenger car Driver #32 on the freeway portion of the route that was analyzed. The "gentle" right-hand curve is just before the 10,000-ft point in the figure, and the "tight" left-hand curve is between 15,000 and 20,000 ft. Note that there are many features in the lane position plot that are longer than the "gentle" curve, especially the gradual drift to the right from about 13,000 ft to 16,000 ft.

The CMRI truck driver data includes ten hours (some early and some late in the shift) of driving data from six truck drivers. Observations with low reliability, low speeds, small lane widths, or other features atypical of freeway driving were ignored. Gentle curves were included in the routes, and their curvature was a part of the analysis. The data were collected in western Pennsylvania, so grades were certainly present, though they have not

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been considered. Time and speed information was used to construct an odometer variable for each hour of driving. The odometer variable was then used to construct average lane position, road curvature, lane width, and velocity variables for each 50-ft increment of driving. Means and standard deviations for each variable are provided in Table 4-6**.**

Table 4-6: Characterization of Truck Driver Data

Early in Shift	Driver							
	1		2		3		4	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Lane Position (ft)	0.22	1.05	-0.02	1.02	-0.23	1.11	-0.55	1.09
Road Curvature (1/ft)	0.0002	0.0002	0.0002	0.0002	-0.0001	0.0004	-0.0003	0.0006
Lane Width (ft)	12.24	0.21	12.03	0.34	10.75	0.46	10.74	0.29
Velocity (ft/s)	86.02	6.02	91.23	7.90	88.42	6.32	85.50	10.91

Late In Shift	Driver							
	1		2		3		4	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Lane Position (ft)	0.01	1.09	0.0004	1.13	0.01	1.49	0.53	0.99
Road Curvature (1/ft)	0.0002	0.0002	0.0002	0.0002	-0.0001	0.0006	-0.0002	0.0004
Lane Width (ft)	12.21	0.26	12.20	0.23	10.92	0.43	10.65	0.36
Velocity (ft/s)	91.69	5.84	90.17	5.58	81.76	9.42	95.46	5.81

4.2.5.5   Modeling the Lane Keeping Data

The lane position data from the experiments was recorded in the form of a sampled time series. We converted this data to the spatial domain, sampled every 20 ft for the passenger car and at 50-ft intervals for the truck.

The basic approach of Figure 4-3, observe, generate, simulate, was followed for the trucks on freeways, the passenger cars on freeways, and the passenger cars on county roads. The details of the middle step, modeling the observed paths and generating representative paths, were different in the three cases because of differences in the amount of data available. The truck drivers selected their own routes according to their business, so all the routes were different. The passenger car drivers, in contrast, were driving solely for the study. Since they were on an assigned route, each driver covered the same, known curves. Figure 4-8 outlines the same process as Figure 4-3, but it shows the differences in the details of Step 2.
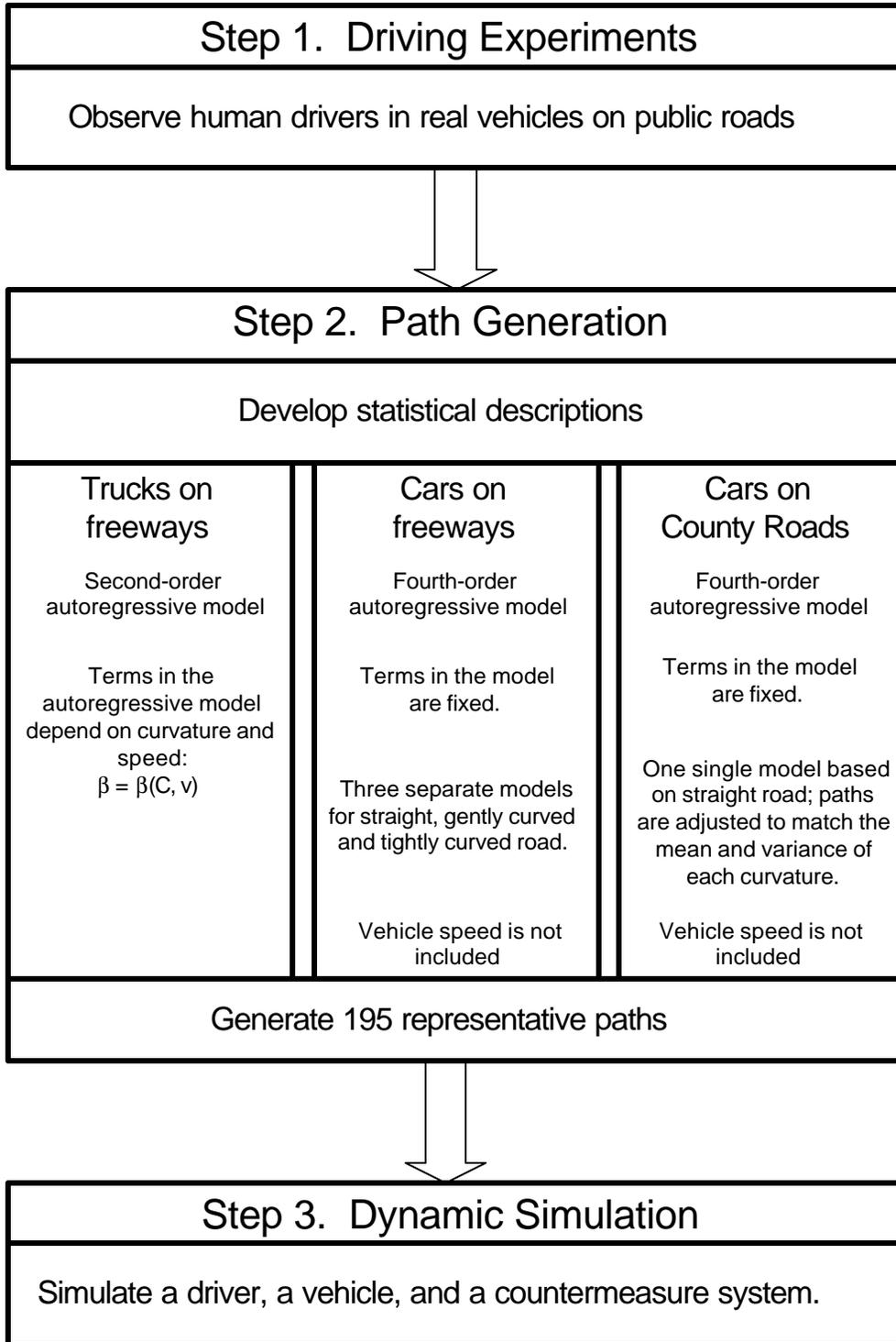
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┌─────────────────────────────────────────────────────────────────┐
│                  Step 1.  Driving Experiments                     │
├───────────────────────────────────────────────────────────────────┤
│       Observe human drivers in real vehicles on public roads       │
└─────────────────────────────────────────────────────────────────┘
                                │
                                ▼
┌─────────────────────────────────────────────────────────────────┐
│                  Step 2.  Path Generation                         │
├───────────────────────────────────────────────────────────────────┤
│               Develop statistical descriptions                     │
├──────────────────┬──────────────────┬──────────────────┤
│    Trucks on      │     Cars on       │     Cars on        │
│    freeways       │     freeways      │   County Roads     │
│                   │                   │                    │
│  Second-order     │   Fourth-order    │   Fourth-order     │
│ autoregressive    │  autoregressive   │  autoregressive    │
│    model          │     model         │     model          │
│                   │                   │                    │
│                   │                   │  Terms in the model│
│  Terms in the     │  Terms in the model│   are fixed.       │
│ autoregressive model│   are fixed.    │                    │
│ depend on curvature and│              │                    │
│    speed:         │                   │ One single model based│
│  β = β(C, v)      │ Three separate models│ on straight road; paths│
│                   │ for straight, gently curved│ are adjusted to match the│
│                   │ and tightly curved road.│ mean and variance of│
│                   │                   │  each curvature.   │
│                   │                   │                    │
│                   │ Vehicle speed is not│ Vehicle speed is not│
│                   │    included       │    included        │
├──────────────────┴──────────────────┴──────────────────┤
│               Generate 195 representative paths                    │
└─────────────────────────────────────────────────────────────────┘
                                │
                                ▼
┌─────────────────────────────────────────────────────────────────┐
│                 Step 3.  Dynamic Simulation                       │
├───────────────────────────────────────────────────────────────────┤
│     Simulate a driver, a vehicle, and a countermeasure system.     │
└─────────────────────────────────────────────────────────────────┘
```

Figure 4-8: The simulation paths used to evaluate proposed countermeasure systems are derived from models based on actual driving experiments. The way the models are developed depends on the way the data was collected and the road geometry.

One convenient means for modeling a stationary and equally spaced time series is an auto-regressive moving average model. The coefficients in such a model determine its properties, and statistical methods exist for estimating the coefficients so that a series generated by the model will have the same properties as the original experimental data. The auto-regressive model alone is appropriate in this case because the process is stationary and moving average terms are insignificant.

The passenger car route segments were chosen because they had curves that were close to the curvatures planned for the simulation parameter study. All drivers went through these same curves, so separate models could be developed for the straight, the "gentle" curve, and the "tight" curve. The speed range of the drivers was narrow (roughly 60 to 70 mph on the freeway and 45 to 55 mph on the county road), so speed was not included in the passenger car driver model at all.

For the passenger car freeway data, we selected representative drivers with sufficiently long segments of valid data, thirteen each for the straight, the gentle curve, and the tight curve. We fit fourth-order autoregressive models to each of the 39 segments. The formula for these models is

$$y_n = \beta_1 y_{n-1} + \beta_2 y_{n-2} + \beta_3 y_{n-3} + \beta_4 y_{n-4} + \varepsilon_n \qquad (1)$$

where the coefficients are selected so that the series generated from the equation will best match the observed points. This form is called an autoregressive model because the next value in a series depends on the previous few values plus a random noise term.

When the model in Equation (1) is driven by white noise, it produces an output series y that has all the essential properties of the actual vehicle paths. Using different random seeds, we generated three paths for each of the straight segments and six for each of the curved segments. Half of the generated curved paths were reflected about the lane center because the observations were made in only one direction (to the right for the gentle curve and to the left on the tight curve), but the simulations included an equal number of right and left hand curves. These then became the 195 generated paths for the 195 cases in the simulation test plan. (The 195 cases were 5 road designs x 3 speeds x 13 replications.)

Substantially fewer passenger car drivers were available on the county road than on the freeway because of scheduling constraints and other experimental difficulties. The procedure for generating representative paths for the county road was to select thirteen drivers' straight-road paths and fit a forth order autoregressive model for each. The curved-road paths were generated by adjusting the means and variances of the paths to match those observed in the respective curves. As is typical on secondary roads of this sort, the constant-curvature segments were too short (less than 500 ft) to allow a good autoregressive model to be fit. A more sophisticated means of modeling driver behavior through curves such as these has been proposed [McMillan et al., 1998], but time and budget constraints did not allow it to be implemented here.

The model for the truck driver paths was slightly more sophisticated. Driver-to-driver variability was incorporated into the lane position model by assuming that all drivers' lane keeping behavior could be described by the same auto-regressive model but that each driver has a unique set of coefficients. (Analysis of individual drivers' behavior has supported this assumption.) Coefficients were assumed to follow a multivariate Gaussian distribution with unknown mean and covariance. The form of the model for each driver is:

$$
\begin{aligned}
y_n = \beta_0 \; &+ \beta_1 y_{n-1} \;\; + \beta_2 y_{n-2} + \\
&\beta_3 v_n + \beta_4 v_n y_{n-1} + \beta_5 v_n y_{n-2} + \\
&\beta_6 C_n + \beta_7 C_n y_{n-1} + \beta_8 C_n y_{n-2} + \varepsilon_n
\end{aligned}
\tag{2}
$$

where

y_n = the lateral position coordinate at sample n

β_x = coefficients estimated in the modeling process

v_n = vehicle speed at sample n

C_n = road curvature at sample n

ε = white Gaussian noise whose variance (σ^2) is estimated

The order of the model was selected after considering the autocorrelation structure of the input data. The mean and variance of the distribution of coefficients, $\overline{\beta}$ and Σ_β, respectively, were estimated by maximum likelihood, as was σ^2.

During the 60 seconds or so that a vehicle simulation is carried out, the speed is not likely to vary. Similarly, the curves on freeways tend to be many hundreds if not thousands of feet long. Therefore, in the subsequent simulation step, the vehicle speed and road curvature are assumed to be constant. Thus, Equation (2) simplifies to

$$
y_n = \beta_0' + \beta_1' y_{n-1} + \beta_2' y_{n-2} + \varepsilon_n
\tag{3}
$$

where

$$
\begin{aligned}
\beta_0' &= \beta_0 + \beta_3 v + \beta_6 C \\
\beta_1' &= \beta_1 + \beta_4 v + \beta_7 C \\
\beta_2' &= \beta_2 + \beta_5 v + \beta_8 C
\end{aligned}
$$

This is a second-order autoregressive model whose coefficients depend on the speed of the vehicle and the road curvature.

The formula in Equation (3) has two uses. First, it can be used to generate paths for the simulated vehicle to follow. To do this, a random set of driver coefficients is drawn from the driver coefficient distribution. Then white Gaussian noise is passed through the filter

in Equation (3) to produce the desired path. These paths are the output of Step 2 of the block diagram in Figure 4-3. The second use of Equation (3) is to study the behavior of the drivers in different conditions.

Equation (1) for passenger cars or Equation (3), for trucks, with a random-number generator to select the noise term at each step, was used to generate paths that are representative of actual vehicle paths. The simulated car in RORSIM was then made to follow the path for a full minute on freeways and a half minute on county roads to measure nuisance alarm rates. To simulate potential run-off-road situations, the car was made to follow the path until a randomly-selected time, after which the steering wheel was held fixed to simulate failure of the driver to maintain steering control of the vehicle. This simulation is step 3 in Figures 4-3 and 4-8.

4.3   SIMULATION STUDIES

The models were exercised in thousands of slightly different cases to predict the effectiveness of different "tunings" of the countermeasures system at various possible shoulder widths. When a recovery maneuver on a few feet of shoulder adjoining the lane is permitted, it is possible to prevent a substantial number of run-off-road crashes while maintaining a reasonably low false alarm rate. As was expected, the ability of the countermeasure system to prevent run-off-road crashes of passenger cars is much better than its ability for heavy trucks because the passenger car is not as wide and therefore has more lane width available for warning. The passenger car is also more maneuverable. Performance in passenger cars on highways and county roads was similar, when the same shoulder width was considered.

4.3.1   PERFORMANCE MEASURES

The goal of any countermeasure system is to maximize the number of crashes prevented or mitigated while minimizing the number of nuisance alarms. In these experiments, a "nuisance alarm" is defined as a case where the countermeasure issued an alarm during a simulation, where the vehicle was following a representative path generated by Equation (1) or (3). The nuisance alarm rate is then calculated from the fraction of cases that experienced an alarm. For example, if a nuisance alarm occurred in three of the 195 minute-long simulations for a particular countermeasure, the nuisance alarm rate would be reported as 3/195 or 0.015 per minute, which is equivalent to 0.92 per hour. (We use the term "nuisance alarm" rather than "false alarm" to indicate that the alarm would be a nuisance to the driver but that the system is not malfunctioning.)

In the simulations to test crash protection, the driver relinquished steering control, simulated as a fixed steering wheel angle, at a predetermined point in the simulation. A "crash prevented" is defined as a case where the simulated driver responded to the alarm and steered the vehicle back to the lane, with no tire ever being beyond the predetermined distance (4 ft or 6 ft) from the lane edge. That is, the vehicle would have been safe had there been 4 (or 6) ft of clear shoulder on both sides of the original lane. The assumption

is that all inattentive drivers would have run off the road had no warning been issued. If all of the 195 recovery maneuvers for a given countermeasure are within the boundary, then the fraction of crashes prevented is 1.0 or 100%.

4.3.2   PARAMETER SELECTION

The analysis for passenger cars included conditions for both highway and rural road driving. The analysis for heavy trucks was limited to conditions representative of freeway driving.

The goal in selecting parameters for the simulations was to establish conditions that are representative of the conditions where ROR crashes typically occur, as outlined in Section 4.1, and where the lane-keeping experiments were performed, as noted in Section 4.2.5.3. Distributions for the parameters are listed in Table 4-7. Some values were fixed for the entire study; they are listed in Table 4-8. Where the distributions are the same for all three combinations of vehicle and roadway, exactly the same values were used for all three. That is, the sets of conditions were duplicated across vehicle and road type as much as possible.

The exact values for the parameters in the table were selected using the Latin hypercube approach. Latin hypercube sampling is similar to Monte Carlo in that the values in the study are randomly selected. Roughly speaking, Latin hypercube sampling spreads out each parameter as much as possible, but otherwise picks the vectors randomly [McKay et al., 1979]. It provides an appealing alternative to generating independent and identically distributed random vectors. Latin hypercube sampling generally produces estimates with a lower variance than simple random sampling of the input vectors [Stein 1987]. McMillan et al. [1997] have published the method by which Latin hypercube sampling and data modeling have been applied in an earlier phase of this program.

Table 4-7. Values of Parameters in the Latin Hypercube Study.

Parameter	Definition	Distribution	Values			Comments
			trucks on a freeway	cars on a freeway	cars on a county road	
Curvature	road curvature, 1/ft (Negative curvature indicates a left-hand curve.)	uniform, five fixed road designs	-0.0005 -0.00025 0.0 0.00025 0.0005	-0.0005 -0.00025 0.0 0.00025 0.0005	-0.001 -0.00035 0.0 0.00035 0.001	selected to be representative of highway conditions
Friction	coefficient of friction used in the tire model in the traveled way and the paved shoulder	mixture of normals 0.75N(0.8,sd=0.05) + 0.25N(0.3,sd=0.05), approximated by a beta with shape parameters 5 and 2	0.32 to 1.0	0.32 to 1.0	0.32 to 1.0	Very low values were excluded because road departure crashes where the driver relinquishes steering control in low-friction are rare.
Shoulder Rolling Resistance	rolling resistance used in the tire model for tires on the paved shoulder	lognormal with mean=0.0612, sd=.135, and offset=0.015	-0.015 to -0.753	-0.015 to -0.753	-0.015 to -0.753	Rolling resistance on the traveled way was fixed at -0.015.
Counter-measure Lane Width	lane width assumed by the system when calculating TLC, ft	Fixed	12	12	10	matches the actual lane width in the simulation
Speed	vehicle speed, fixed for the simulation, fps	Uniform	75, 88, 100	75, 88, 100	75, 88, 100	representative of highway conditions
Steering Reaction Time	time that elapses between the alarm and the driver's resuming steering, s	lognormal with mean = 0.82 and sd=0.24	0.43 to 1.59	0.43 to 1.59	0.43 to 1.59	Chosen to match the results of Malaterre and Lechner [1990]
Driver Model Properties			coefficients from the joint distribution	pre-calculated paths	pre-calculated paths	
Inattention Onset Time	time at which the steering wheel becomes fixed, s	Uniform	10-30	10-30	10-15	gives a variety of trajectories.

Table 4-8. Fixed values for the simulation study.

Parameter	Definition	Distribution	Values			Comments
			trucks	cars on a freeway	Cars on a county road	
Lane Width		fixed	12	12	10	typical highway design--close to the conditions where the driver model data was collected
Paved Shoulder Width	distance the pavement extends beyond the traveled way, ft	fixed	99	99	4	unlimited for freeways, limited to a typical width for county roads
Available Recovery Width	maximum permissible tire excursion for a "successful" recovery, ft	--	0, 6, 12, and 18	0, 3, 6, and 12	0, 2, 4, and 6	Every path was judged against every shoulder width, in post processing.

4.3.3 SIMULATION RESULTS

In any type of detection system, including a countermeasure for detecting an imminent roadway departure, there is a trade-off between the simultaneous desires for a high detection rate and a low false-alarm rate. Various scientific disciplines have various names for the situation--false positive versus false negative, Type I error versus Type II error, and others. A common way to study the performance of a detection system is to make a graph of its detection rate as a function of its false alarm rate. (In communication theory, this is called a receiver operating characteristic.)

Therefore, proposed countermeasure systems were evaluated by plotting the simulation results with the nuisance alarm rate on the horizontal axis and the crash prevention rate on the vertical axis. The parameter on each curve is the alarm threshold. Higher thresholds are toward the right, where nuisance alarms are more common and lower thresholds to the bottom, where the probability of prevention is less. The "good" corner of the graph is the upper left, where nuisance alarms are rare and prevented crashes are frequent. The goal is to devise a warning algorithm with appropriate settings so that the prevention countermeasure will be as close as possible to the upper left corner.

Figures 4-9 through 4-11 have assumed a shoulder width of 6 ft.similar to figure 4-2. If a part of a vehicle passes this physical location in a simulation, it is deemed to have "crashed." The separate curves in the graphs represent different virtual boundary locations. Remember from Figure 4-2 that the virtual boundary is a mathematical position to which TLC is calculated; it is merely a setting of the system and not necessarily a physical location.

The results of all groups of simulations are distributed as noted in Table 4-7. Therefore, some parameters may not be weighted in a way that is representative of the mix of traveled miles. For example, curved roads may be over-represented.

4.3.3.1   Influence of Vehicle Type

The freeway results were judged most critically at a hypothetical shoulder width of 6 ft. That is, a run-off-road crash was "prevented" if none of the vehicle's tires was ever more than 6 ft from the lane edge during the recovery maneuver. Figure 4-9 has the performance of the TLC countermeasure for passenger cars on freeways with a 6-ft success criterion. The four curves in the figure represent virtual boundaries that are 1.0, 2.0, 3.0, and 3.9 ft outside the actual lane boundary. (The nuisance alarm rate expected in actual use is lower than the rate given in the figure, partly because the mix of speeds and curvatures in the figure is different than that on highways.)

One possible selection for the optimum operating point is identified in the figure. With a nuisance alarm rate of about one per hour, 97 % of the potential run-off-road crashes would be avoided. This is achieved with a threshold of 1.0 seconds and a virtual boundary 3 feet outside the lane edge. (That is, a driver would be warned when the countermeasure system projects that, in 1 second, one of the front tires will be 3 feet beyond the lane edge.) Another possible selection would be an 80 % prevention rate at a nuisance alarm rate too low to estimate with the current data. That is achieved by triggering an alarm when the countermeasure system estimates that a front tire will be 3.9 ft outside the lane in 1.0 s.

Figure 4-10 shows the results for the heavy truck simulations. It represents an average over the same variety of highway conditions as in Figure 4-9 for passenger cars. Again, each separate curve in this figure represents a different "virtual boundary" location. The point identified in the figure had an alarm in only one of the 195 "normal driving simulations," which corresponds to one nuisance alarm in more than three hours of driving. Assuming a 6-ft shoulder, the countermeasure system would have prevented 57% of the run-off-road crashes caused by the driver's being inattentive or relinquishing steering control.

The results for the 3-ft virtual boundary for both vehicles are plotted together in Figure 4-11. The curve for the passenger cars is always above and to the left of the curve for heavy trucks. Therefore, the simulations have quantified the result that was expected-- preventing ROR crashes is easier for passenger cars than for heavy trucks. Remember

that the warning threshold is the parameter along the curve. The respective points on the two curves where the warning sounds at a TLC of 1.0 seconds are called out in the figure. The point for heavy trucks is well to the right of the corresponding point for passenger cars. This means that, when an identical warning system is deployed on the two types of vehicles, the nuisance alarm rate will be substantially higher on heavy trucks. The follows directly from the observation in Section 4.2.5.4 that trucks tend to leave the lane more often than cars. The 1.0-second point for cars is also slightly above the one for trucks, indicating that a higher crash prevention rate would be expected for cars from identical countermeasure systems. We attribute this to the better maneuverability of cars. Therefore, the better overall performance of countermeasure systems in cars is due to both the "normal" driving behavior and to the vehicle dynamics constraints.

The results clearly show the benefits of projecting TLC as the time to cross a line outside the actual lane line. The best prevention rate at the lowest nuisance alarm rates, for both types of vehicle on freeways, is achieved when the virtual boundary is 3.0 ft beyond the painted stripe. If the virtual boundary is set at the physical boundary (the lane edge), the nuisance alarm rate will be at least 6 per hour for cars and 40 per hour for trucks.
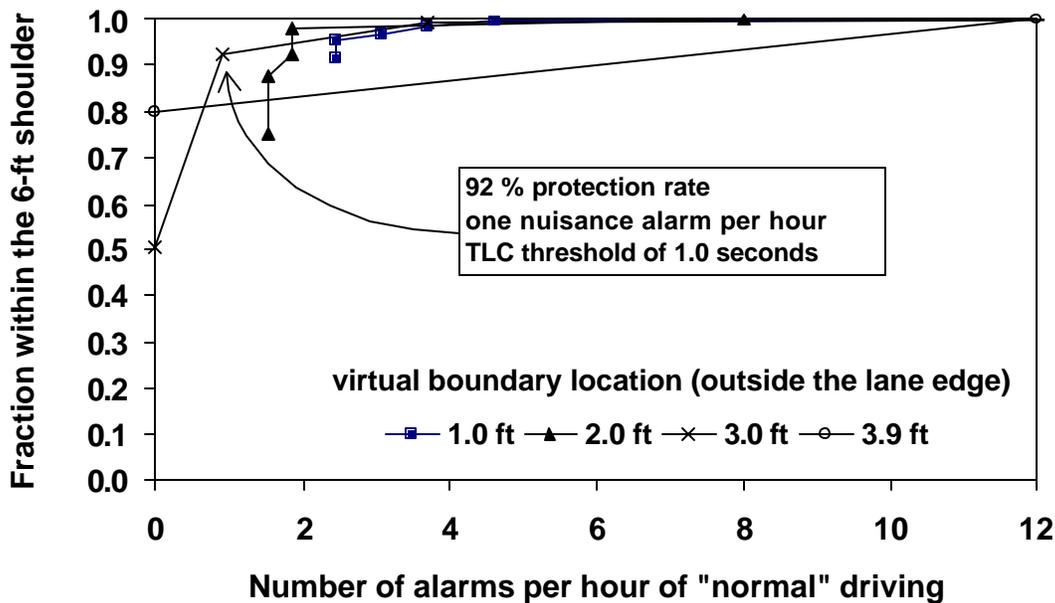
Figure 4-9. Performance of the run-off-road countermeasure system for passenger cars on freeways, assuming 6 ft of maneuvering room on both sides of the lane.
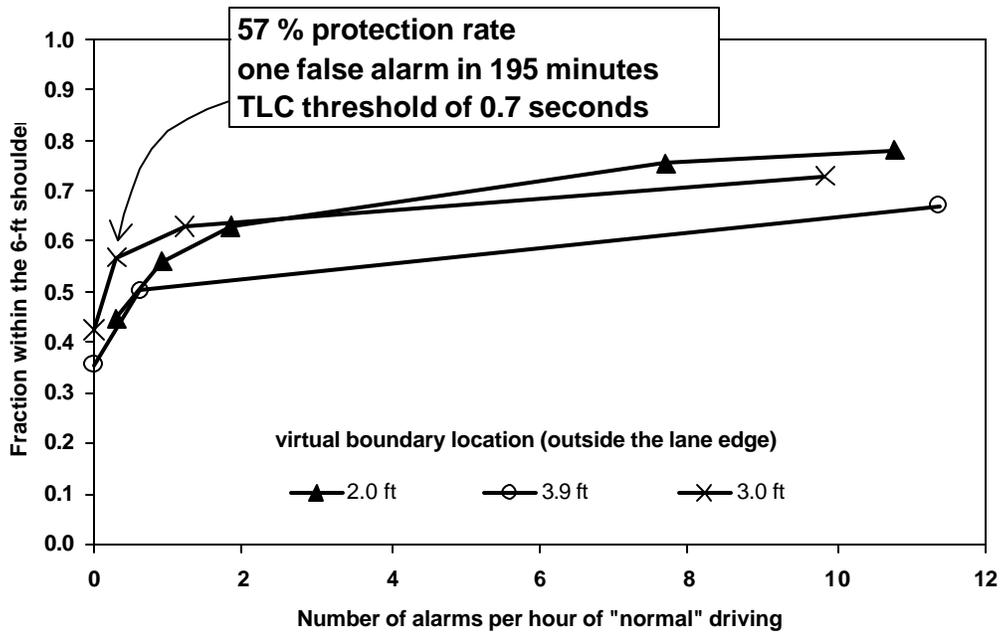
Figure 4-10. Performance of the run-off-road countermeasure system for <u>heavy trucks</u> on <u>freeways</u>.
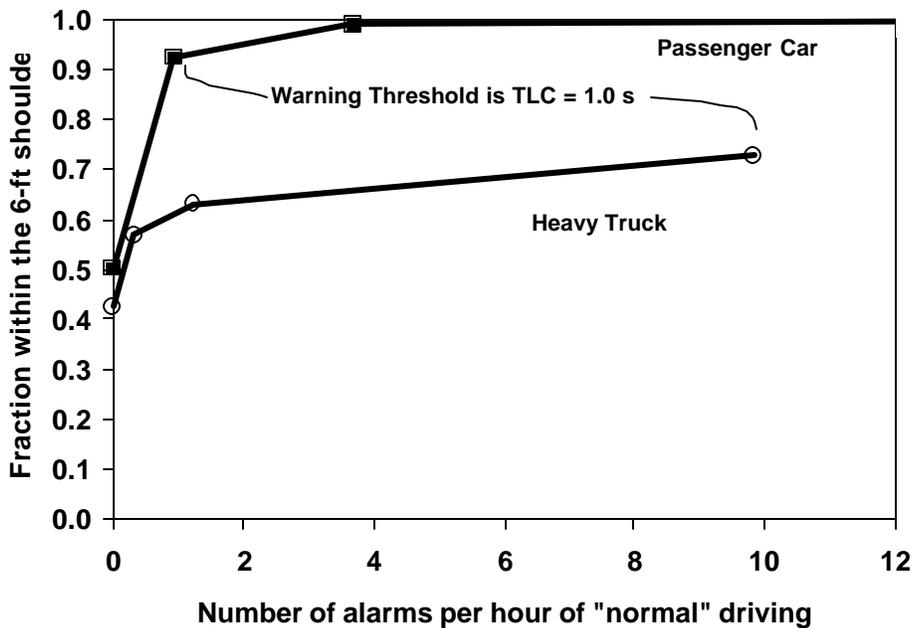

Figure 4-11. The predicted performance of the countermeasure system for passenger cars and trucks on freeways. The virtual boundary is 3.0 ft outside the lane in both cases. As was expected, the prevention rate is higher and the nuisance alarm rate is lower for passenger cars because passenger cars are smaller and more maneuverable.

4.3.3.2   Influence of Roadway Type

Figure 4-12 shows the predicted performance on county roads for passenger cars. On the road where the driving data was collected, the paved shoulder is 5 ft beyond the white stripe, so the criterion for success in this graph is 4 ft. The prevention rates are lower than for freeways, but a respectable prevention rate of nearly 60 % is achievable with only two nuisance alarms per hour. The conditions for this are a virtual boundary 2.0 ft outside the lane and a warning threshold of 0.5 s.
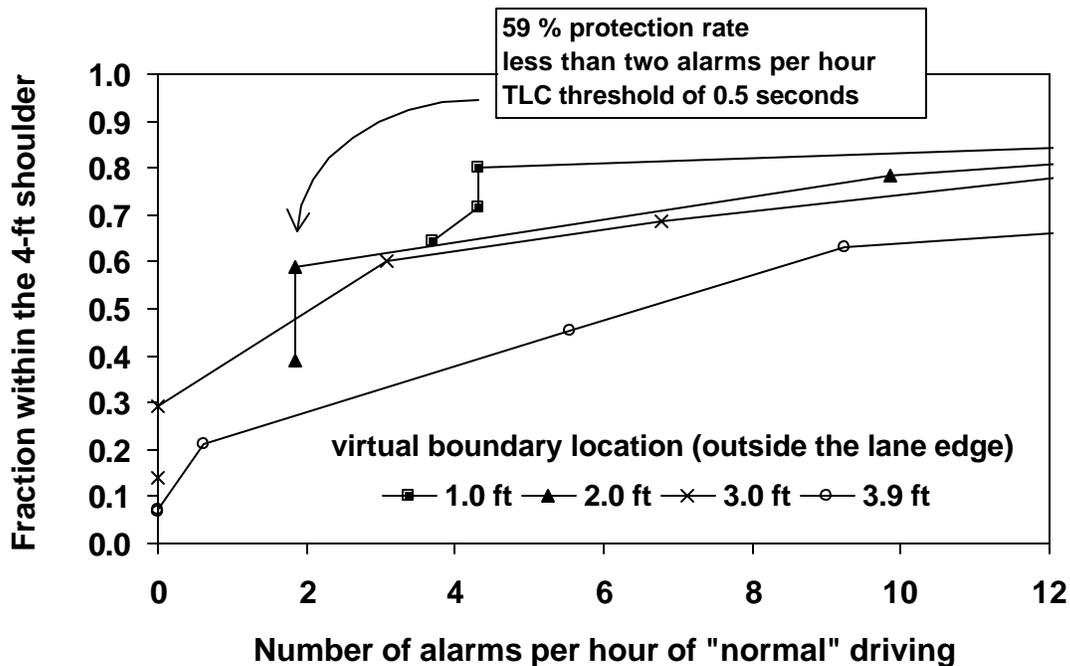
Figure 4-12.   Performance of the run-off-road countermeasure system for passenger cars on county roads, assuming 4 ft of maneuvering room on both sides of the lane.

When freeways and county roads are compared at the same clear shoulder width, the system's performance on the two types of roads is remarkably similar, despite all the other differences. Figure 4-13 shows the predicted performance, using the best virtual boundaries, for both types of roads, assuming a 6-ft shoulder. Though the shoulder width is the same, the distance of the shoulder edge on the freeway is 1 ft farther from the lane centerline.

Figure 4-14 illustrates the trade-off of nuisance alarms and crashes averted when 12 ft of clear pavement are available on both sides of the traveled lane for the heavy truck. The assumption in this case is that an advanced countermeasure system would be cognizant of other vehicles that may be in the adjacent lane to the truck to avoid a possible crash with another vehicle.
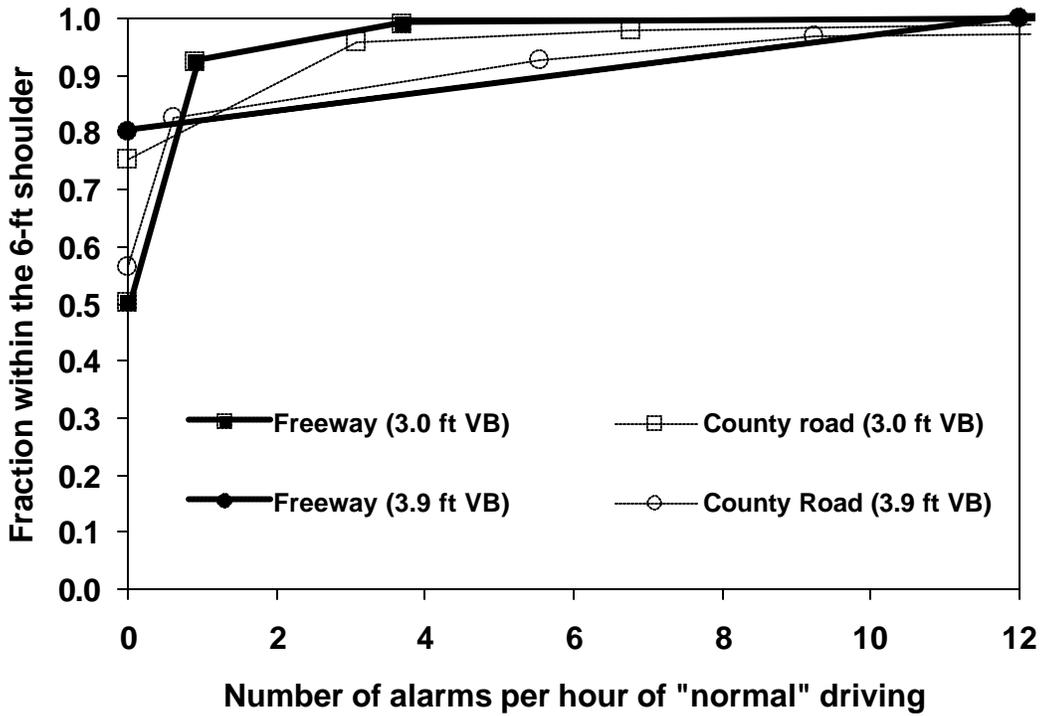
Figure 4-13. Comparison of the performance of the countermeasure system for passenger cars on freeways and county roads, assuming 6 ft of clear maneuvering room on each.
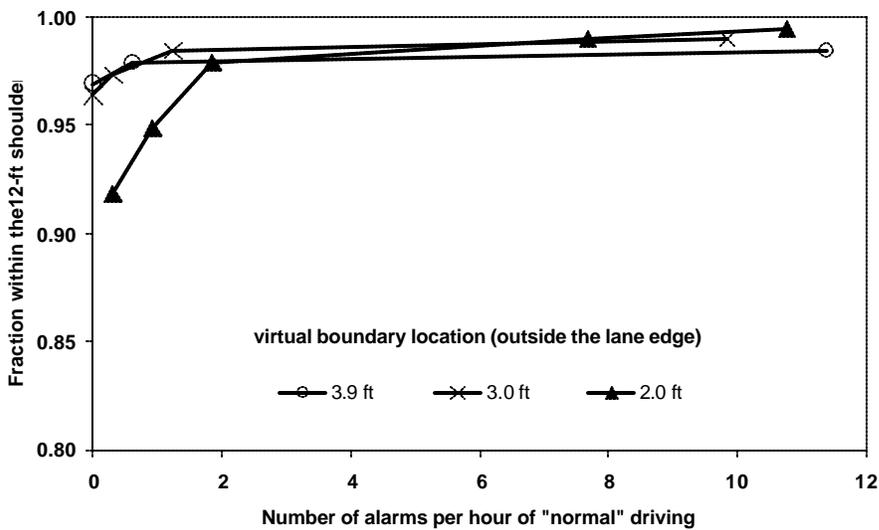

Figure 4-14. Trade-off of nuisance alarms and crashes averted when 12 ft of clear pavement are available on both sides of the traveled lane for the heavy truck

4.3.3.3   General Comments on Other Influences

The driving observations on the county road showed distinct differences between aggressive drivers who cut the curves and drivers who stayed mostly in the marked lane. Examples of both were included in the test parameters, and no distinction was made in the analysis. Therefore, aggressive drivers would tend to have an alarm rate higher than those reported here, while more cautious drivers may have a slightly lower alarm rate. Making more quantitative comments would require a special analysis focussing specifically on typical curve-cutting behaviors.

It is also probable that real drivers would change their behavior once they accumulated experience with a LDWS. It may be that the drivers who wander more across the lane would learn better lane keeping in order to reduce the number of nuisance alarms; this would improve the perceived value of the system.

4.3.4   SUMMARY OF SIMULATION RESULTS

The results of the RORSIM simulation studies work provided a comparison of LDWS performance for cars and trucks using driver lane-keeping models developed from extensive experimental studies. The simulation studies characterized the tradeoffs between ROR prevention and nuisance alarm rates, and suggest the importance of having available a maximum width roadway shoulder for safely maneuvering a vehicle back onto the road. When a shoulder width of 6ft or wider is available, these simulation results suggest that 92% of drift-off-road crashes could be prevented in passenger vehicles, and 57% could be prevented in heavy trucks, while maintaining an acceptably low nuisance alarm rate.

Among the significant findings of the simulation studies were:

- It may be feasible to develop an effective LDWS that provides a sufficiently early warning to prevent ROR accidents without excessive nuisance alarms.

- Driver lane-keeping behavior is substantially different on rural roads and freeways.

- Performance requirements for a LDWS are different for trucks and passenger vehicles, primarily because of the significantly different vehicle dynamic behavior and driver lane-keeping characteristics (which are related). Thus, it may be necessary to tailor warning criteria to different vehicle and driver types, to different roadway types (e.g., based on shoulder width and curvature), and different operating conditions (e.g., speed, and weather).

- The best time to deliver an early warning to the driver depends strongly on the roadway characteristics (lane and shoulder widths, curvature, etc.), driver lane-keeping behavior (degree of "meandering", curve-cutting behavior, etc.) and vehicle type.

- The strategy of using a "virtual boundary" can significantly improve the performance of a LDWS.

- The computer simulation package and Monte-Carlo technique used in the simulation studies are useful for evaluating the effectiveness of countermeasure systems for a wide range of realistic driving scenarios but are were found to require improvements in the future.

4.3.5   BENEFITS PROJECTIONS

If we assume the behavior of the LDWS, driver and vehicle were modeled correctly in the RORSIM simulations, we can begin to project these behaviors to determine the impact widespread deployment of a LDWS would have on the roadway departure crash problem. This section attempts to make such projections, through analysis of crash statistics generated in Phase I of this program. In order to estimate the potential effectiveness of a LDWS for a realistic distribution of road departure crashes, particular focus is placed on three aspects of the crash circumstances:

- Causal factors
- Available shoulder
- LDWS availability

4.3.5.1   Causal Factors

The factors causing a crash are important, because a LDWS can only be expected to prevent the subset of road departure crashes caused by driver inattention and driver relinquishing steering control. Other causes for road departure crashes, such as excessive speed, vehicle failure, and evasive maneuvers, could not be prevented by a system that only warns the driver when the vehicle is drifting off the road. Table 4-1 shows that 32.8% of road departure crashes in passenger vehicles are caused by driver inattention or driver relinquishing steering control. This 32.8% is almost certainly an overestimate of the pool of preventable crashes, since nearly 1/3rd of them involve the driver relinquishing steering control due to intoxication. So assume 75% of the crashes caused by intoxication are eliminated from the pool, on the assumption that only 25% of intoxicated drivers would respond to a warning quickly and appropriately enough to avoid a crash. The remaining approximately 24% of all road departure crashes in passenger vehicles have the potential to be prevented by a LDWS.

Based on our Phase I analysis of NTSB heavy truck crash data, the percentage of heavy truck related road departure crashes that could benefit from a LDWS is substantially higher than for passenger vehicles. This is primarily due to the increased frequency of drowsy related crashes, and the reduced frequency of intoxication related crashes. Of course this assumes that a drowsy driver will react more appropriately to a warning than an intoxicated driver – a hypothesis that remains to be tested. As Table 4-1 indicates, approximately 53% of road departure crashes involving heavy trucks are due to inattention or drowsiness, and therefore have the potential to benefit from a LDWS.

So with a potential pool of 24% of passenger vehicle road departure crashes and 53% of heavy vehicle road departure crashes, the next step is to determine what fraction of these could actually be prevented by a LDWS.

4.3.5.2   Available Shoulder

As Figures 4-12 through 4-14 show, shoulder width is an important factor determining the effectiveness of a LDWS. Without sufficient room to maneuver on the shoulder, the effectiveness of a LDWS drops substantially. Recall from Figure 4-1 that there is a large range of shoulder widths associated with lane departure crashes caused by driver inattention or relinquishing of steering control, ranging from 0ft to more than 12ft. By combining the shoulder width distributions in actual crashes from Figure 4-1 with the LDWS effectiveness estimates for various shoulder widths from Figures 4-12 through 4-14, we can estimate the percentage of actual road departure crashes that would likely be prevented by a LDWS. Tables 4-9 and 4-10 show these prevention estimates for various shoulder widths in passenger vehicles and heavy trucks

Table 4-9: Frequency of various shoulder widths for passenger vehicle lane departure crashes caused by inattention or driver relinquishing steering control, along with LDWS effectiveness and projected crash prevention rate.

Shoulder Width	% of Applicable ROR Crashes	LDWS Effectiveness	% of Applicable Crashes Prevented
0-3ft	40%	20%	8%
3-6ft	25%	60%	15%
6-12ft	20%	92%	18%
12+ ft	15%	97%	15%
Total	100%		56%

Table 4-10: Frequency of various shoulder widths for heavy truck lane departure crashes caused by inattention or driver relinquishing steering control, along with LDWS effectiveness and projected crash prevention rate.

Shoulder Width	% of Applicable ROR Crashes	LDWS Effectiveness	% of Applicable Crashes Prevented
0-3ft	18%	5%	1%
4-8ft	45%	57%	26%
10-14ft	28%	95%	27%
14+ ft	9%	97%	9%
Total	100%		63%

Interestingly, Tables 4-9 and 4-10 show similar crash prevention percentage estimates for lane departure crashes caused by inattention or driver relinquishes steering control in passenger cars and heavy trucks. While passenger cars are easier to maneuver and quicker to respond than heavy trucks, this is offset by an overall higher occurrence of lane departure crashes on roads with a narrow shoulder, reducing effectiveness in passenger cars. As a result, the overall effectiveness of a LDWS in the two vehicle types is similar, 56% for passenger cars and 63% for heavy trucks.

When we combine this data with the data from the previous section on the faction of all road departure crashes applicable for a LDWS, we get a more accurate estimate of the actual fraction of all ROR crashes that could be prevented by a LDWS. For passenger cars, that number is 14% (24% of all ROR crashes are that applicable * 56% of applicable crashes that could be prevented). For heavy trucks, that number is 33% (53% of all ROR crashes that are applicable * 63% of applicable crashes that could be prevented).

4.3.5.3 LDWS Availability

The above ROR crash prevention rates of 14% for passenger vehicles and 33% for heavy trucks assumes a LDWS that is functional at all times. As indicated in the formal system recommendations, there are several situations in which it is allowed or expected for a LDWS to not be able to operate effectively. The question is, what fraction of ROR crashes occur in circumstances where a LDWS may not be functioning effectively. This section enumerates conditions where a LDWS may not be operational based on the extensive road testing performed in Phase III of this program. We then attempt to infer from the ROR crash statistics from Phase I how frequently these conditions occur, to estimate the overall availability of a LDWS. This availability can then be used to scale the effectiveness estimates further.

4.3.5.3.1 Adverse Environmental Conditions

One situation likely to impact LDWS availability is adverse environmental conditions. In over 75,000 miles of on-road testing conducted for this program using a prototype LDWS provided by AssistWare technology, we have found the following conditions to be ones where existing, optical-based LDWS can sometimes have trouble.

- Nighttime rain with oncoming headlights or overhead streetlights. Reflections off the wet pavement in this situation make it very difficult for the vision system to find the road.
- Snow covered roadway. If the vision system can't see any features running parallel to the road (i.e. there aren't even any tracks in the snow), then it can't determine upcoming road geometry.
- Very low sun angles. The dynamic range of the camera we use sometimes isn't sufficient to handle the intense lighting when the sun is very low on the horizon, and the vehicle is driving towards it.

Note: the above conditions are those found to challenge a particular video camera-based LDWS. Other systems, particularly those implemented using different sensing technology, may produce

degraded performance under a different set of environmental conditions. However the system tested is representative of LDWS technology likely to be deployed in the relatively near future, so it is a good place to start.

The frequency of the above adverse conditions, and therefore their impact on LDWS effectiveness, depends heavily on the region of the country, direction of travel, and the prevailing weather conditions. Based on the statistics regarding the lighting and pavement conditions at the time of SVRD crashes from our Phase I database analysis, we estimate that 8% of inattention and relinquishes steering control fatal crashes occur in weather or lighting conditions which would potentially preclude effective operation of a LDWS. This 8% will be added to the other availability limiting factors listed below, and then used to scale the previous effectiveness estimates.

4.3.5.3.2 Missing Lane Boundaries

It was not possible to determine the presence or quality of the lane boundaries in each of the crashes investigated in Phase I of the program. What is known is that a significant fraction of US roads do not have painted lane markings on both sides of the lane (as is assumed by some vision-based LDWS). Such examples include rural roads with lane markings on only one side of the lane, and certain freeways, such as in California, that use small raised pavement markings to delineate the lane, instead of painted stripes. Because of the relative frequency of such road types, they are included in the list of recommendation for conditions a LDWS should be capable of handling (see recommendation [L-11]). There does exist LDWS technology, including the system tested as part of this program, that do not require painted lane markings on both sides of the lane to operate. Therefore the effectiveness of systems that meet the performance recommendations outlined in this document should not be substantially affected. Systems that do not follow the recommendations, but instead require explicit painted lane markings will likely exhibit significantly reduced availability, and therefore lower effectiveness.

4.3.5.3.3 Low Speed

The recommendations in this document and the draft ISO standard allow a LDWS to disable warnings when the vehicle is traveling below a certain speed, to minimize nuisance alarms when the vehicle is maneuvering in an unstructured environment or in stop-and-go traffic (see recommendation [L-29]). The recommended minimum operating speed is 35mph (60km/hr). The frequency of ROR crashes below this speed is important, since it is another pool of crashes that a LDWS might not prevent.

From the Phase I crash analysis, 66% of inattention road departure crashes in passenger vehicles occur on roads with a posted speed of 35mph or higher, and 76% of the severe road departure crashes (resulting in serious injury or death) occur on roads with a posted speed of 35mph or higher. For relinquishes steering control crashes, 77% occur on roads with posted speeds of 35mph or higher, and 81% of the severe relinquishes steering control crashes occur on roads with posted speeds of 35mph or higher. Since people frequently drive above the posted speed, since severe crashes should be counted more heavily, and since relinquishes steering control crashes are more common than inattention crashes, it seems conservative to use an average of 76%

across the two causal factor groups. In other words, we assume 76% of the combined group of inattention and relinquishes steering control crashes occur at 35mph or higher in passenger vehicles. This leaves 24% of passenger vehicle inattention or relinquishes steering control crashes that occur at less than 35mph, which might not be prevented by a LDWS.

Interestingly, in passenger vehicles 100% of the ``drowsy driver'' subclass of driver relinquishes steering control crashes (which is 7% of the whole roadway departure crash population in passenger vehicles) occurred on roads with a posted speed limit of 35mph or higher. This is encouraging, since one the main situations for which a LDWS could be useful is drowsy driver crashes.

In heavy trucks, according to the NTSB cases analyzed as part of Phase I, close to 100% of the inattention and drowsy driver crashes occur on roads with a posted speed of 35mph or faster. This reflects the fact that heavy trucks travel on interstate highways most of the time. So for heavy trucks, no significant additional reduction in availability should result from the low speed warning suppression condition.

So in total, reduced LDWS availability due to adverse environmental conditions and low speed warning suppression is projected to result in a 32% reduction in effectiveness for passenger vehicles, and an 8% reduction in effectiveness for heavy trucks. By discounting the previous crash prevention estimates of 14% for passenger vehicle ROR crashes and 33% of heavy truck run-off-road crashes by these availability estimates, the result is an estimated 10% for passenger vehicles and 30% for heavy trucks. In other words, taking all known factors into account, it is estimated that approximately 10% of all ROR crashes in passenger vehicles and 30% of all ROR crashes in heavy trucks could be prevented by a LDWS with the specific settings and limitations described here..

4.3.5.4   Numeric Projections

The next question to address in estimating benefits of a LDWS is to project the actual number of crashes and the associated costs that could be prevented through the use of a LDWS. As was noted in Section 1.3, according to GES data, there are approximately 1.6 million police reported road departure crashes each year in passenger vehicles. The FARS database indicates there are approximately 15,000 fatalities each year resulting from road departure crashes in passenger vehicles. Applying the 10% crash prevention rate for passenger vehicles, an estimated 160,000 crashes, and 1500 fatalities could potentially be prevented each year if every passenger vehicle were equipped with a LDWS.

According to another USDOT study (Wang, Knipling and Blincoe, 1999), the average monetary cost per road departure crash in a passenger vehicle is $18,840. The monetary cost included such costs property loss, economic losses due to reduced productivity, and medical expenses. A more comprehensive estimate of costs, which included the monetary costs plus less tangible costs like the derived valuations for life and "pain and suffering" put the cost at $60,870 per passenger vehicle ROR crash. Using the more conservative $18,840 cost, preventing 160,000 such crashes would save a total of over $3 billion dollars each year. Using the conservative estimate of cost, a LDWS could save an estimated $195 per passenger vehicle over its operational lifetime.

According to the same USDOT study, approximately 31,000 ROR crashes occur in combination-unit trucks each year, 320 of which involve a fatality. A LDWS that has the potential to prevent 30% of them would result in 9300 fewer crashes and 96 fewer fatalities. The direct monetary cost is estimated at $17,670 per heavy truck ROR crash, so preventing 9300 of them would result in a projected annual saving of approximately $164 million. A LDWS that prevents 30% of heavy truck ROR crashes would result in direct monetary savings of approximately $1335 over a truck's operational lifetime.

While preliminary and based on a number of assumptions, the potential benefits of deploying LDWS technology appear to be substantial, in terms of the number of crashes and fatalities prevented, as well as the costs saved. In large quantities, we believe that manufacturers should be able to reach the cost targets of $195 for passenger vehicles and $1335 for heavy trucks.

5 LDWS TEST PROCEDURES

The tests described in this section are designed to evaluate the performance of a LDWS. There are several benefits to having a consistent test procedure, including:

- providing unbiased information by which to compare the performance of alternative systems,

- ensuring that any systems that pass the tests achieve a minimum acceptable level of performance,

- fostering compatibility and common operating characteristics between systems sold by different companies.

These test procedures are based on experiments conducted with actual prototype systems, as well as preliminary drafts of ISO standard for lane departure warning systems, which addresses system testing. These test procedures are preliminary recommendations. More complete and definitive tests will require additional research.

In general, it is not anticipated that all possible combinations of conditions that could effect LDWS performance will be available for testing. The range of quality and type of road features and the range of environmental conditions that a deployed LDWS would encounter are impossible to reproduce consistently. As a result, the test procedures outlined in this section are designed to determine if a LDWS meets a minimum level of performance under relatively benign conditions. The tests are designed to be technology independent, although they do include provisions to ensure that likely candidate technologies for a LDWS can be evaluated. These test procedures are appropriate for evaluating the warning algorithm and driver interface aspects of LDWS operation under controlled circumstances. It is expected that the tests described here would be combined with longer term "in-situ" testing to validate system performance under a more realistic range of environmental conditions and road types. The exact form of the in-situ testing will require further research to determine.

5.1 ENVIRONMENTAL CONDITIONS

The environmental conditions for these controlled tests should be clear and dry. The one aspect of environmental conditions that should be varied in the testing is time of day. It is recommended that tests of vision-based systems be conducted in both daylight conditions and nighttime conditions (using only vehicle headlight illumination). This is to ensure that the LDWS being tested can operate both during the day (when most driving is done) and at night (when a large fraction of drowsiness-induced lane departure crashes occur). It may also be appropriate to test a LDWS based on optical sensing shortly after sunrise or shortly before sunset to ensure that low sun angle conditions do not substantially interfere with system operation. However the effectiveness of such a test would depend heavily on a number of factors which are difficult or impossible to control, including cloud cover, test road geometry, pavement type, etc. As a result, it may be most appropriate to leave the testing of such specific environmental conditions to the long-term in-situ test procedure.

5.2 ROADWAY CHARACTERISTICS

Tests should be performed on a road with an asphalt (bituminous) or concrete surface. The road surface should be dry. The road should have a paved shoulder on each side of at least 6-ft in width, to allow safe recovery from lane excursions during the testing. For purposes of evaluating system performance, the road should have at least one lane delineated by continuous painted lane markings of standard width and color on both sides. These lane markings define the travel lane and will be used by those conducting the test to determine when the vehicle has departed the lane. The vehicle will be defined to have departed the lane when the outside edge of the outermost tire crosses the center of the painted lane marking. The lane markings may optionally be used by the LDWS to measure the vehicle's position relative to the lane. The lane should be the standard 12ft (3.66m) width.

The test road should consist of a section of road with at least one straight section of several hundred meters, and at least one left and one right hand curve with radii of curvature between 125m and 150m. A section with a single curve can be used if the test vehicle can be used in both directions to simulate left and right curves. Unspecified road characteristics such as grade and superelevation should be within normal ranges recommended by AASHTO for US roadways.

5.3 TEST VEHICLE

It is possible that a LDWS will be sold as an integrated option on an OEM vehicle, or as an aftermarket option. For an integrated LDWS, tests should be conducted with an unmodified vehicle equipped with the LDWS at the factory. For an aftermarket LDWS, the system should be installed on a vehicle deemed appropriate by the manufacturer of the LDWS according to the manufacturer's instructions. Alternatively the manufacturer of an aftermarket LDWS could provide the system already installed on a vehicle for testing purposes.

The test vehicle may need to be equipped with special measurement equipment to allow for the measurement and evaluation of LDWS performance. An example of such measurement equipment is downward looking cameras on each side of the vehicle to image the vehicle tires as the vehicle departs the lane. The timing of warnings relative to the lane departure could be measured by correlating the onset of warnings from the LDWS with the video data recorded from these cameras. Installation of additional measurement equipment should not interfere with normal operation of the LDWS being tested.

5.4 TEST VEHICLE LOADING

To ensure that vehicle loading does not adversely effect the LDWS, the tests should be conducted with several variations in passenger weight distribution. At a minimum, tests should be conducted with only the driver and with the driver plus the equivalent of two average adults (300 lbs. total) in the rear passenger area.

5.5   LDWS CONFIGURATION

Configuration and calibration (if required) should be performed prior to the tests according to the manufacturer's specifications. For tests of a LDWS with an adjustable warning threshold, the threshold shall be set such that a warning is initiated as close as possible to the time when the first tire crosses the lane edge. No alterations to the system shall be made once the test procedure has begun.

5.6   TEST PROCEDURE

The test vehicles should enter and leave the section of test track at speeds in excess of 35 mph, maintaining speeds in excess of this throughout the test. On each lane departure, the outside tire of the test vehicle should depart the lane by at least 50cm and then return to the lane. Lane departures should be performed on the straight section (both to the left and to the right) and on the left and right hand curved sections (both to the left and to the right). The departures should occur at a variety of lateral velocities, ranging from 5cm/s to 100cm/s. A total of at least 50 lane departures should be conducted at various points along the test road and at various lateral velocities. The time between successive lane departures should be at least 5 seconds.

The outside edge of the vehicle's outside tire should also approach to a distance of between 10 and 20cm inside the lane boundary at low lateral velocity (less than 10cm/s) to test the ability of the LDWS to reject nuisance alarms. These events will be referred to as "near departures". A total of at least 50 near departures towards the left and right side of the lane should be conducted at various points along the test road, including the straight section and the curves.

5.7   EVALUATION

The LDWS should provide no false alarms when the vehicle's outside tire is more than 20cm inside the lane boundary during the test procedure, and at most one in 50 false alarms in the near departure situations (when the outside tire is between 10 and 20cm inside the lane boundary).

The LDWS should provide a warning for each lane departure during the test procedure. The warning should be initiated no later than the point at which the outside tire is more than 50cm past the lane edge.

6 CSWS PERFORMANCE GUIDELINES

This section presents guidelines for Curve Speed Warning Systems (CSWS). These guidelines are operating performance parameters that should be considered as part of the design of such systems.

These systems are designed to help prevent crashes resulting from excessive speed on the approach to a curve. A block diagram of a representative CSWS is shown in Figure 6-1. The CSWS uses sensors to determine the vehicle's state (position/velocity) relative to the upcoming curve, and the safe speed for traversing the upcoming curve. A collision warning algorithm interprets this information to determine if the vehicle is traveling too fast for the upcoming curve. If so, the system provides a warning to the driver to slow down.
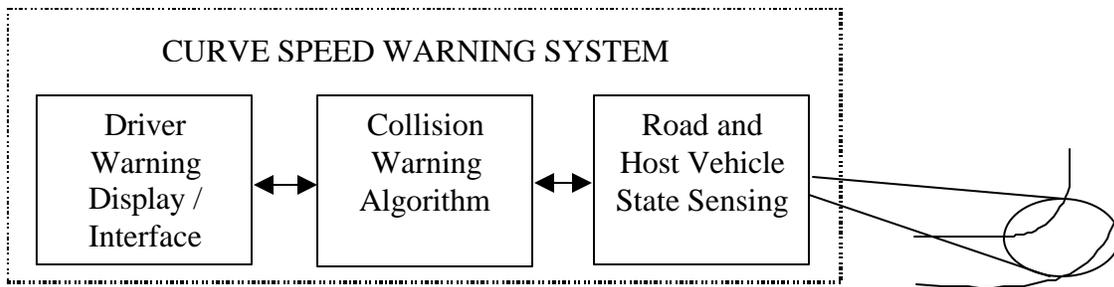
Figure 6-1: Curve Speed Warning System Block Diagram

6.1 SENSING FUNCTIONS AND GUIDELINES

The sensing functions that need to be performed by a CSWS include:
- Determine vehicle position and orientation relative to the upcoming curve
- Determine vehicle stability characteristics
- Determine vehicle dynamic state relative to the road
- Determine geometric characteristics of upcoming road segment
- Determine pavement conditions of upcoming road segment
- Determine driver intentions

6.1.1 DETERMINE VEHICLE POSITION AND ORIENTATION

In order to determine if the vehicle is approaching an upcoming curve too fast, a CSWS must accurately and reliably estimate the vehicle's position and orientation relative to the upcoming curve. In particular, a CSWS must determine if the vehicle is headed towards or away from a curve, and if headed towards it, how far from the curve it is. There are a number of potential methods by which the vehicle's position and heading relative to an upcoming curve could be measured. These could include:

- A GPS receiver and a digital map of the road network
- Beacons located at curves broadcasting the curve's position to approaching vehicles
- Upcoming road geometry information encoded in the roadway infrastructure (e.g. magnetic markers) and sensed by short-range sensors on the vehicle.

One candidate technology not mentioned is an optical sensor for visually detecting the upcoming curve, and estimating its distance. The reason it is not listed is that blind curves and reduced visibility conditions preclude the effective operation of optical sensors.

For any implementation of a CSWS, there are two main requirements associated with sensing the distance to the upcoming curve – positional accuracy and sensing range.

A certain level of positional accuracy is required to achieve acceptable performance. Experiments conducted for this program (described in Section 7) suggest that an error of 5m in the estimate of the distance to the upcoming curve leads to no significant degradation in perceived system performance on the part of the driver. At 35mph (or 16.4m/sec), a 5m error in the vehicle's position estimate will lead to a 1/3 second variation in the onset of a curve speed warning – an amount that experiments suggest is not significant to drivers.

[C-1]   A CSWS should be able to accurately determine the distance to the sharpest part of the upcoming curve. It is recommended that this distance be estimated to an accuracy of +-5m.

A CSWS must also be able to sense the distance to the upcoming curve far enough ahead of the curve so that a warning can be issued early enough to allow the driver to safely slow down prior to the curve. To calculate how far ahead the curve must be detected, assume the following:

- The vehicle is approaching a curve at 65mph,
- The maximum safe speed for traversing the curve is 25mph,
- The driver's reaction time to a warning is 1.5 seconds,
- The driver applies the brakes to decelerate the vehicle at 0.3g in response to the warning.

Under these assumptions, the CSWS must detect the curve and estimate its distance at least 160m before the vehicle reaches the curve. In order to account for slower driver reaction and/or less aggressive deceleration, it is recommended that a CSWS be able to detect an upcoming curve at least 200m prior to the curve's apex.

[C-2]   A CSWS should be able to detect and estimate the distance to an upcoming curve at least 200m prior to the curve's apex.
It is likely that there will be some conditions or locations in which the CSWS is unable to accurately determine the distance to the upcoming curve. For a GPS-based CSWS for example, this may be due to the unavailability at that time/location of an accurate vehicle position estimate from GPS or because the CSWS does not have an accurate map of the current road. For a CSWS that relies on infrastructure components, the required infrastructure may not be in place for the entire road, or for the upcoming curve. A CSWS should detect its inability to sense the upcoming curve, and reports its status to the driver.

[C-3]   A CSWS should be able to detect when it is unable to determine the vehicle position relative to an upcoming curve. In such a condition, it should make the driver aware of its degraded status through the driver interface.

6.1.2   DETERMINE VEHICLE STABILITY CHARACTERISTICS

In order to determine the safe speed for traversing an upcoming curve, it is important to know the roll stability of the vehicle. This is particularly important for commercial vehicles in which the load can vary substantially, changing the vehicle's center of gravity. The USDOT is currently investigating rollover warning systems what detect the roll stability of commercial vehicles using onboard sensors.

[C-4]   A CSWS should account for the roll stability of the vehicle when determining the safe speed for traversing an upcoming curve. The roll stability of commercial vehicles can change dramatically depending on the load, so in-vehicle load sensors should be incorporated into a CSWS intended for commercial vehicles.

6.1.3   DERTERMINE VEHICLE DYNAMIC STATE RELATIVE TO THE ROAD

The particular aspects of the vehicle's dynamic state that are important for a CSWS are the vehicle's forward velocity and acceleration. These are the primary factors determining the speed at which the vehicle will enter the upcoming curve. An error in the vehicle's forward velocity or acceleration will propagate directly through the CSWS warning algorithm and result in errors in the warning onset time. The sensitivity analysis in Section 8 indicates that errors in vehicle speed of greater than 4 feet per second (1.2m/s) will lead to unacceptable errors in warning onset. The forward velocity could potentially be measured in a number of ways, including wheel speed sensors or the Doppler-based velocity estimates provided by a GPS system.

[C-5]   A CSWS should measure the vehicle's forward velocity to an accuracy of 4 fps (1.2m/s).

By a similar argument, a CSWS should estimate vehicle acceleration or deceleration to an accuracy of approximately 1 foot per second^2 (0.3m/s^2) to keep the projected velocity error at the point of curve entry below 4 fps (1.2m/s) when projecting ahead 4 seconds prior to the curve. Vehicle acceleration is typically measured using an accelerometer, although short term changes in vehicle velocity may also be used to determine acceleration if an accurate and frequently updated source of vehicle velocity is available.

[C-6]   A CSWS should measure the vehicle's forward acceleration (or deceleration) to an accuracy of 1 foot per second^2 (0.3m/s^2).

6.1.4   DETERMINE GEOMETRY OF UPCOMING ROAD SEGMENT

Several aspects of the upcoming road geometry are crucial for effective countermeasure operation. First, the countermeasure should be able to determine whether the vehicle is on a road.

[C-7]   A CSWS should be capable of detecting when the vehicle is traveling on a road, as opposed to a parking lot or other unstructured environment.

[C-8]   When traveling in an unstructured environment, the CSWS should suppress warnings to avoid nuisance alarms.

A challenge for a CSWS is to determine how to respond when there are several choices for vehicle direction of travel. This is particularly important at exit ramps, where many speed related road departure crashes occur. In the typical scenario, the vehicle is traveling down a road at a high velocity then exits to follow a sharply curving off-ramp without slowing down, resulting in a rollover and/or road departure crash. To warn about such a danger in time for the driver to react appropriately, a CSWS must detect the presence of cross streets, forks in the road and exit ramps. The range at which it should detect such alternative travel directions is the same as the range it must detect upcoming curves.

[C-9]   A CSWS should be able to detect the presence of cross streets, forks in the road and exit ramps at least 200m ahead.

The two other aspects of upcoming road geometry that are important for a CSWS are road curvature and superelevation (banking). First, the CSWS should operate on the range of curvatures and superelevations encountered on US roads. AASHTO standards for curvature and superelevation are sometimes ignored or were not in place at the time some roads were built. But data from the FHWA Highway Performance Monitoring System and AASHTO suggest that the following maximums will cover nearly all US roads.

[C-10] A CSWS should operate effectively on roads with a radius of curvatures as low as 200ft (60m).

[C-11] A CSWS should operate effectively on roads with a maximum superelevation of 12 percent.

The values for acceptable errors in the estimation of road curvature and superelevation in the next two specifications are both half of the "tolerable" errors calculated in Section 7 to allow for an added cushion of safety.

[C-12] A CSWS should determine the curvature of the upcoming roadway segment to an accuracy of 10 percent of the actual curvature. The determination could be made by direct measurement, a roadside transponder or a reliable map database.

[C-13] A CSWS should determine the superelevation of the upcoming roadway segment to an accuracy of 3% (e.g. 0.03ft/ft). The determination could be made by direct measurement, a roadside transponder or a reliable map database.

[C-14] A CSWS should be able to detect when it is unable to determine the geometry of the upcoming road segment. In such a condition, it should make the driver aware of its degraded status through the driver interface.

6.1.5   DETERMINE PAVEMENT CONDITIONS OF UPCOMING ROAD SEGMENT

Perhaps the most challenging but important aspect of a curve speed warning system is detection of the upcoming pavement conditions. The safe speed in a curve depends strongly on the condition of the roadway, particular the coefficient of friction. Friction affects both the vehicle's ability to negotiate a curve and its ability to slow down prior to the curve. The recommended accuracy of the friction estimate is based on the sensitivity analysis provided in Section 7.3.3. The source of the friction estimate is left to the developer of the system, but it is likely that the estimate will have to come from an infrastructure based measurement system. This is because no in-vehicle technology we are aware of can measure the road's coefficient of friction several hundred meters ahead, as required.

[C-15] A CSWS should determine the available side friction coefficient on the upcoming road segment to an accuracy of 0.05, to a distance ahead of the vehicle of at least 200m.

[C-16] A CSWS should determine the available longitudinal friction coefficient on the upcoming road segment to an accuracy of 0.05, to a distance of at least 200m ahead of the vehicle.

[C-17] A CSWS should be able to detect when it is unable to determine the condition of the pavement for the upcoming road segment. In such a condition, it should make the driver aware of its degraded status through the driver interface.

6.1.6   DETERMINE DRIVER INTENTION

In order to minimize nuisance alarms and detect dangerous situations as soon as possible, a CSWS should attempt to determine the driver's intentions related to curve negotiation. This may include simple measures, like monitoring the vehicle's turn signals to determine when the driver is intending to follow an upcoming exit ramp. It may also include more sophisticated measures like modeling a particular driver's typical curve negotiation pattern, such as brake onset time, deceleration rate, tolerance for lateral acceleration, etc.

[C-18] A CSWS should monitor the vehicle's turn signals to determine the driver's intended path of travel, so it can effectively determine the upcoming road geometry.

[C-19] A sophisticated CSWS may model a particular driver's curve negotiation behavior, such as brake onset time, deceleration rate, tolerance for lateral acceleration, etc. Deviations from this model may be used to determine when the driver is unaware of the severity of an upcoming curve.

Tests with a prototype curve speed warning system indicate that a relatively frequent source of nuisance alarms occurs when a warning is triggered just after the driver has released the accelerator pedal and has just begun to press the brake pedal. At this point, deceleration of the vehicle may be negligible, but the driver has started to react to the curve and may be annoyed by a warning telling him what he already knows. To prevent this form of nuisance alarm, a CSWS should monitor the brake pedal, and perhaps look for accelerator releases as well, as an early sign of driver awareness of the upcoming curve. A CSWS should not suppress warnings entirely when accelerator release or brake activation is detection, since these actions themselves may not slow the vehicle sufficiently to safely negotiate the curve.

[C-20] A CSWS should monitor for brake pedal activation and, if practical, accelerator pedal release, as a means of detecting the driver's awareness of the upcoming curve. If one or both of these events is detected, the CSWS should delay triggering a curve speed warning for up to 0.5 seconds to determine if the driver's response is aggressive enough to slow the vehicle to a safe speed for the upcoming curve.

6.2   WARNING ALGORITHM GUIDELINES

The job of a CSWS warning algorithm is to process the data from sensors characterizing the vehicle's stability characteristics, and its position/trajectory relative to an upcoming curve, the geometry of the upcoming curve, the road condition and the driver's intentions to assess the danger of a road departure crash.

6.2.1   DETERMINE SAFE SPEED FOR APPROACHING CURVE

The most important aspect of the CSWS warning algorithm is determining the maximum safe speed for negotiating the upcoming curve. The maximum safe speed is the maximum speed at which the vehicle can negotiate the curve without loosing control.

[C-21] The maximum safe speed for the approaching segment should be determined from the equation:

$$V = \sqrt{R\,g\,\frac{e+f}{1-ef}}$$

where:
      R = the minimum curvature of the vehicle's path through the road segment
      g = the acceleration due to gravity
      f = the planned side friction factor
      e = the estimated superelevation of the road segment.

The values for R, e, and f may be measured directly by the vehicle, retrieved from a reliable database, or acquired from the infrastructure, subject to the accuracy constraints imposed by other specifications.

The above formula is derived from the AASHTO recommendation for computing the maximum safe design speed of a curve [AASHTO 1994, p. 141]. The side friction factor, f in the equations, is the ratio of actual side friction force on an object to the normal force. This ratio must be less than or equal to the quantity commonly called the coefficient of friction, which is the ratio of maximum possible friction force to normal force. The side friction factor assumed for highway **design** (as opposed to highway use) is generally less than 0.1 or 0.2. Under most conditions, a road surface can provide a significantly higher side friction factor, and aggressive motorists routinely drive curves much faster than the design speed. The low value is used for design to allow for the possibility of ice on the surface.

When the value of f is the maximum friction available, the above equation represents the speed at which it would just barely be possible to negotiate the curve without losing control, neglecting dynamic considerations. A CSWS should not use this absolute maximum speed when calculating whether to trigger a warning, since measurement errors and variability in driver skill (reaction time, deceleration rate, and steering vagaries) could mean that the true safe speed is somewhat lower. Instead, there should be a speed cushion (i.e., the speed at which the countermeasure permits the vehicle to enter the curve should be somewhat lower than its estimate of the maximum speed at which the curve could possibly be negotiated). The cushion or margin, of course, should not be too large, or the driver would perceive that the system generates too many false alarms.

In addition to the road-related influences on the maximum safe speed, the vehicle's characteristics influence how fast a curve can be negotiated. These need to be reflected in the maximum acceptable speed.

[C-22] A CSWS should adjust the maximum safe speed according to vehicle-specific parameters such as rollover susceptibility, roll stiffness, mass distribution, and tire condition.

Some of the vehicle specific characteristics, like roll stiffness are fixed and need not be calculated dynamically. Others, like mass distribution, can change frequently, depending on the type of vehicle and its loading. The sensitivity of a CSWS to errors in various estimates is analyzed in Section 7. These potential variations should be accounted for when computing the maximum safe speed for negotiating the upcoming curve to ensure a "cushion of safety" in the estimates.

[C-23] The combined errors in all the above measurements should be such that the CSWS has a TBD% confidence that the actual maximum safe speed is equal to or less than the estimated maximum safe speed for the upcoming road segment.

It is important to distinguish the maximum safe speed for negotiating a curve from the posted speed limit, or recommended safe speed. A passenger vehicle can typically negotiate a curve with dry pavement faster than the posted speed. A CSWS that warned when the driver was

exceeding the posted speed for a curve would provide far too many warnings to be acceptable. On the other hand, a system should not permit the driver to drive too close to the maximum safe speed since small errors in estimating the maximum safe speed or small errors in vehicle control, could result in a road departure crash. Therefore the maximum acceptable speed, the speed beyond which a warning should be triggered, should be set below the maximum safe speed.

How to determine the maximum acceptable speed, both when in the curve and on the approach to the curve, is the subject of the next section.

6.2.2   DETECT POTENTIAL FOR ROADWAY DEPARTURE

Given sensor data about the upcoming road and vehicle speed, a CSWS needs to determine if the vehicle is in danger of departing the road due to excessive speed for the upcoming curve. In general the goal of the system is to reduce the number of road departure crashes due to excessive speed on curves while keeping the nuisance alarm rate as low as possible.

Preventing nuisance alarms – conditions when the CSWS and the driver disagree about the danger, is likely to be more difficult for a CSWS than for a LDWS addressed earlier. The reason is that there is no commonly accepted benchmark for "correctly" negotiating a curve. Individual drivers vary substantially in their speed profile when negotiating a curve. Some drivers slow down gradually starting long before the vehicle reaches the curve, while other, more aggressive drivers brake very close to the curve entrance, if at all. This variation in driver behavior will likely make it difficult to find a warning algorithm that will be acceptable to all drivers, and may necessitate an adjustable or adaptive threshold to cope with driver differences. This contrasts with the task of lane keeping, which a LDWS must monitor. For lane keeping, there is a commonly accepted performance benchmark that is easily discerned by drivers – the driver is expected to keep the vehicle in the lane. Of course drivers, particularly heavy truck drivers, do not keep all of the vehicle inside the lane at all times, which may necessitate a more lenient threshold than one tire crossing the lane boundary, as discussed earlier. Nevertheless, from our testing experience, it seems relatively easy for a driver to directly sense and comprehend the behavior of a LDWS that always warns when the vehicle is 1-ft outside the lane (for example). In contrast, it is more difficult for a driver to understand the behavior of a CSWS, because of the more abstract nature of the warning criterion - traveling too fast for the upcoming curve.

Despite the difficulty, a CSWS must attempt to maximize detection of crash hazard, and keeping false and nuisance alarms to a minimum.

[C-24] A CSWS should attempt to maximize detection of crash hazard due to excessive speed for an upcoming curve, while minimizing false and nuisance alarms.

In general, the CSWS should compute the danger of a road departure crash by determining how much the vehicle must decelerate from its current speed to reach the safe speed for negotiating the upcoming curve before actually reaching the curve. The CSWS should determine whether a warning is necessary based on the magnitude of this required deceleration.

[C-25] A CSWS should compute the danger of a road departure crash by determining how much the vehicle must decelerate from its current speed to reach the maximum acceptable speed for negotiating the upcoming curve before actually reaching the curve. A warning should be triggered if the deceleration required exceeds a threshold.

The above recommendation leaves three quantities to be determined:

- The maximum acceptable speed for the upcoming curve
- The deceleration required to reach the maximum acceptable speed
- The threshold deceleration above which a warning should be triggered.

As mentioned above, the maximum acceptable speed for negotiating the curve should be set below the maximum safe speed for negotiating the curve to allow for small errors in estimating the maximum safe speed or small errors in vehicle control. The maximum allowable speed should also reflect a driver's preference. An aggressive and/or experienced driver with a quick reaction time may want to set the maximum acceptable speed closer to the maximum safe speed than would a more conservative driver. The maximum acceptable speed might be computed in a number of ways including as:

- A velocity below the maximum safe speed (e.g. 10mph below the maximum safe speed)
- A percentage of the maximum safe speed (e.g. 90% of the maximum safe speed)
- A maximum acceptable lateral acceleration, which is converted into the maximum acceptable speed for the upcoming curve using the curve's geometry information.

In each of the above cases, the maximum acceptable speed should be significantly below the maximum safe speed, to allow for sensor and/or driver error. From the results of sensitivity analysis in Section 7, it is recommended that this speed "cushion" be 10%.

[C-26] The maximum acceptable speed for negotiating a curve should be set to at most 90% of the maximum safe speed. The driver may be given the option to adjust the maximum acceptable speed to be less than 90% of the maximum safe speed to give an earlier warning if desired.

Referring back to [C-25], a CSWS should trigger a warning if the deceleration needed to slow the vehicle to the maximum acceptable speed for the upcoming curve exceeds a threshold. The deceleration required to slow the vehicle to the maximum acceptable speed at any point prior to a curve is governed by the following simple kinematic equation.

[C-27] A CSWS should use the following equation to determine the deceleration required to slow the vehicle to the maximum acceptable speed at any point prior to a curve:

$$a = \frac{V^2 - V_c^2}{2(d - t_r V)}$$

Where:
- a = the required deceleration
- V = the vehicle's current speed
- V_c = the maximum acceptable speed for negotiating the curve
- d = the distance between the current vehicle position and apex of the curve
- t_r = the estimated reaction time of the driver

[C-28] A CSWS should assume a driver reaction time of no less than 1.5 seconds.

The reaction time of 1.5 seconds is derived from the work of Malaterre and Lechner [1990] indicating that 98% of the population should react to a warning in 1.5 seconds or less.

If the required longitudinal deceleration **a** in the above equation exceeds a threshold, the CSWS should trigger a warning. This longitudinal deceleration threshold is dependent on a number of factors, including:

- Vehicle characteristics (braking efficiency, tire condition)
- Pavement condition (wet, icy, dry)
- Driver tolerance of deceleration

In short, the CSWS should not anticipate longitudinal acceleration that will exceed the capability of the vehicle in the current conditions or cause undue discomfort to the driver or passengers.

[C-29] A CSWS should trigger a warning if the longitudinal deceleration required to slow the vehicle to the maximum acceptable speed prior to the curve exceeds 50% of the estimated deceleration limit of the vehicle in the current conditions.

The 50% in the above equation provides a safety cushion, in case the maximum deceleration capability of the vehicle in the current conditions is overestimated, or in likely case that the driver chooses to delay serious braking. Through in-vehicle experiments with a prototype CSWS described in Section 7, it was found that 0.15g (1.5 m/s^2) deceleration was a good nominal value. When the CSWS was configured to trigger a warning when a longitudinal deceleration of more than 0.15g would be required to reach the maximum acceptable speed prior to the curve, subjects reported that the trigger point for the warning was "about right". Although we did find subjects who reported a preference for a slightly earlier warning and other subjects who reported a preference for a slightly later warning, suggesting an adjustable longitudinal deceleration threshold would be desirable. Note that the 0.15g nominal braking is far below the 50% of available deceleration limit under normal conditions, where 0.5-0.75g braking is typically possible.

[C-30] The recommended nominal longitudinal deceleration threshold for a CSWS is 0.15g (1.5 m/s^2). Either automatic or manual adjustment of the longitudinal deceleration threshold should be included to help minimize nuisance alarms. But in no case should the longitudinal deceleration threshold exceed 50% of the estimated maximum deceleration achievable by the vehicle in the current conditions.

6.3 DRIVER INTERFACE

The third and final key aspect of CSWS performance is the driver interface. Like the driver interface for the LDWS, the driver interface for the CSWS is the means by which the driver:

4) Receives warnings of potential road departure danger
5) Adjusts the operating characteristics of a CSWS
6) Is informed of the operating status of a CSWS

As might be expected, the driver interface recommendations for a LDWS and a CSWS have much in common. Some duplicate recommendations are included in this section for completeness, particularly in light of the fact that the CSWS recommendations may be read by developers of such systems independently of the LDWS.

First and foremost, the purpose of the driver interface is to provide the driver with alerts or warnings about impending crash danger. Such a warning might communicate to the driver through visual (e.g. a light), auditory (e.g. a buzzer) or haptic (e.g. a shaking steering wheel or a vibrating seat). The communication should convey an appropriate sense of urgency. As far as possible, the warning should be quickly interpretable, even by drivers not familiar with the system. Thresholds for when to warn should be determined in accordance with the warning algorithm recommendations. Unlike the case for a LDWS, there may be sufficient time prior to the curve for CSWS to allow for a graded series of warnings - several warnings of increasing urgency. Even if a warning cannot be issued in time to prevent a crash, the system should warn the driver in hopes of reducing the severity of the unavoidable crash.

[C-31] The system should provide one or more signals to alert the driver to the crash hazard. To the extent feasible, the signal onset should be such that the driver has sufficient time to become aware of the alert and execute an appropriate crash avoidance maneuver.

[C-32] The system may signal the driver through visual, audible or haptic means. Due to the importance of visual attention in highway safety, the visual demand on the driver away from the driving scene should be minimized.

[C-33] To the extent possible, the signals should convey the urgency of the danger. Urgency may be conveyed through the choice of modality (e.g. visual for low urgency, audible or haptic for higher urgency) or through the characteristics of the signal itself (e.g. louder or higher pitch audible tones for higher urgency). If sufficient time is available, several signals of increasing urgency may be provided to the driver.

[C-34] The signal should be easily interpretable, and distinct enough so as not to be confused with other in-cab signals. If graded urgency signals are provided, the signal for an imminent crash should be distinct from other warning signals.

Selecting the actual signal for the warning is a challenge, involving many design decisions on many signal attributes such as intensity (e.g., luminance, contrast, polarity, hue, saturation), duration (e.g., rise time, on-off duty cycle, presentation rate), tonality (e.g., pitch, volume, timbre), etc. Also, the stimuli in the cab may come from outside the cab (e.g. glare on a visual

display from direct sun, road noise drowning out audible stimuli, etc.). Finally, in-cab masking stimuli may be situation-specific (e.g., only if the radio is on, need it be turned down).

[C-35] The signal should be designed such that they are not masked by other signals or stimuli normally present in the cab. This may necessitate suppression of other in-cab distractions (e.g. radio) during countermeasure signaling.

[C-36] The signal should not be so intense or complex as to overload the driver's sensing and processing capabilities, or startle the driver into an inappropriate response.

[C-37] The countermeasure signal intensity may be adjustable by the driver. However if such an adjustment is provided, there should be a minimum signal intensity, below which it cannot be adjusted. This minimum intensity level will depend on the modality and other characteristics of the signal, but will be no lower than the intensity detectable by 95 percent of the population under typical in-cab conditions. Feedback on the results of driver adjustment of signal intensity should be provided to the driver during the adjustment process.

Results of driving simulator experiments suggest that warnings that help a driver know how to respond are slightly preferable to non-directional warnings. For example, a CSWS might provide a directional signal through an active accelerator pedal, that pushes back on the driver's foot when approaching a curve too fast, to signal him to slow down.

[C-38] When practical, the CSWS signal should in some way indicate the appropriate driver response, as long as this information can be conveyed without reducing the signal's interpretability or increasing the driver's confusion.

Through in-vehicle experiments with a prototype CSWS described in Section 7, we determined that drivers have different preferences for warning onset, irrespective of the vehicle characteristics and road conditions. Therefore it is recommended that the warning threshold for a CSWS be made adjustable. These adjustments could be made automatically based on analysis of a particular driver's style, or manually by the driver through the driver interface. As discussed earlier, adjustments to the warning threshold of a CSWS could take the form of changes to the maximum lateral acceleration the driver is comfortable with when negotiating a curve, and/or how much braking force (longitudinal deceleration) the driver is willing to input when slowing for the curve. Since drivers will likely have no means by which the judge the appropriateness of particular numeric values for these parameters, it is recommended that any manual adjustments be associated with intuitive labels. These labels might reference different driving styles, such as "aggressive" or "conservative", or they might reference intuitive notions about warning onset time, such as "early" and "late" warnings.

[C-39] When practical, a CSWS should provide for adjustment of the warning threshold to cope with variations in driver behavior and vehicle characteristics. These adjustments may be made manually by the driver, or automatically by the CSWS. Manual adjustment of the warning threshold should be accompanied by feedback to the driver as to the current setting.

[C-40] Manual adjustment of CSWS operation should not result in a significant distraction of driver attention from the driving task. Any manual adjustments should be easy to make and understand. Complex interaction with the system should be reserved for times when the vehicle is stopped.

To avoid compromising safety, manual or automatic adjustments to the warning threshold of a CSWS should be limited in their magnitude. As implied in recommendations [C-26] adjustments to the warning threshold should not allow the CSWS to use a maximum acceptable speed for negotiating the curve of more than 90% of the estimated maximum safe speed for negotiating the curve. Similarly, as implied in recommendations [C-29], adjustments to the warning threshold should not allow the CSWS to use an estimate of deceleration prior to the curve of more than 50% of the estimated maximum deceleration achievable by the vehicle in the current circumstances.

[C-41] The allowable range of warning threshold adjustment should be limited to avoid unintentional compromising of system effectiveness. If adjustable, the maximum allowable speed for negotiating a curve should be no more than 90% of the estimated maximum safe speed. If adjustable, the estimate of deceleration prior to the curve should be no more than 50% of the estimated maximum deceleration achievable by the vehicle in the current circumstances.

Through observations of a prototype CSWS in the hands of a several naïve drivers, several important aspects of the driver interface became apparent. As described earlier in association with recommendation [C-20], we found drivers were annoyed when the CSWS triggered a warning after they had begun to react to the upcoming curve on their own accord. Specifically, there were several occasions where the driver had released the accelerator pedal and was either moving his foot to the brake, or actually braking when the warning system triggered. The drivers indicated that they expected the system to detect the onset of their response, and not warn. As stated in [C-20], a CSWS should monitor for brake pedal activation and/or accelerator pedal release. If one or both of these events is detected, the CSWS should delay triggering a warning for up to 0.5 seconds to determine if the driver is reacting aggressively enough to slow the vehicle without a warning.

Another situation that disturbed subject drivers was a warning triggered when the vehicle was actually in the curve. At that point, drivers judged the warnings to be too late, and a distraction to their driving. Through experimentation, we found that the drivers judged warnings triggered less than 1.5-2.0 seconds prior to the apex of a curve to be too late. This is supported by the kinematics of the situation. It takes a driver approximately 1.0 seconds to react to a warning and begin decelerating, leaving only 0.5 to 1.0 seconds to actually decelerate the vehicle. At a typical, aggressive rate of deceleration of 0.2g (2.0 m/s^2), this would allow the vehicle to slow only by 1-2 m/sec (2-4mph) before the vehicle reaches the apex of the curve. This rather limited deceleration is unlikely to significantly reduce the risk of a road departure crash. In fact, the onset of braking when already in the curve, as is likely to occur in this scenario, may even destabilize the vehicle, increasing rather than decreasing the likelihood of a road departure crash.

[C-42] A CSWS should not triggering a warning less than 1.5-2.0 seconds prior to the apex of a curve to avoid distracting the driver with warnings that are too late to prevent or significantly mitigate the severity of a crash.

In addition to controlling warning intensity and warning threshold, a third control drivers are likely to desire is an on/off switch, to allow the driver to selectively enable or disable the CSWS. There is some controversy over whether an on/off switch should be provided on collision avoidance system. For example, the guidelines for forward collision warning systems recommend not providing an on/off switch for forward collision warning systems. The reasoning goes that with an on/off switch, people are likely to turn the system off and forget to turn it back on, preventing its benefits from being realized. Because of the likelihood of false alarms under certain circumstances with these systems, we believe drivers will strongly desire an on/off switch to disable it operation.

[C-43] A CSWS should be equipped with a clearly marked on/off switch, to allow the driver to disable warnings.

As mentioned earlier, the developer of a CSWS should attempt to minimize false alarms, to avoid the risk the user will have it turned off at the time of a crash. This would include provisions for the system to temporarily disable itself when external conditions preclude effective operation.

To further reduce the risk that the driver will turn the CSWS off and forget to turn it back on, particularly at vehicle ignition start, the CSWS should power-on with application of ignition power if the on/off switch is in the on position.

[C-44] A CSWS should power-on with application of ignition power if the on/off switch is in the on position.

The final function the driver interface needs to perform is to provide the driver with system status information. The driver must be kept apprised of the system's operating status, to avoid relying on the system when it is not operating effectively.

[C-45] A CSWS should be capable of providing status information to the driver under the following conditions:
  - **The system fails its power-on self test**
  - **The system is not working due to component failure or other cause during operation**
  - **The system detects conditions having rendered it ineffective (e.g., loosing GPS lock, or not having a digital map of the upcoming road segment).**

[C-46] A CSWS should provide a continuous visual indication to the driver that the system is on and operating properly.

A continuous visual indication is important to allow the driver to check system status with a quick glance. However with extended use, the driver may stop conducting consistent visual checks of the system status. Therefore it may be necessary to supplement the continuous visual

status indicator with a more easily detected audible or haptic indicator to inform the driver of status transitions, such as when the system goes off-line because conditions have rendered it ineffective.

[C-47] As a supplement the continuous visual status indicator, a CSWS should employ an audible or haptic signal to indicate system status transitions, as long as the signal does not distract or disturb the driver.

[C-48] If the system goes off-line for one of the above reasons, all warning displays should remain inactive.

Once off-line due to a temporary condition (e.g. loosing GPS lock), the driver should not be required to explicitly reactivate the CSWS, since it is likely that driver will either forget about or be confused about this extra step to activate the system. This could result in the system not being available to warn the driver when a crash is imminent.

[C-49] When off-line due to a temporary condition (e.g. loosing GPS lock), a CSWS should continuously monitor for disappearance of the condition preventing effective operation. If the condition disappears and proper operation is again possible, a CSWS should automatically transition back to the enabled state, without requiring explicit input from the driver. This transition should be accompanied by an audible or haptic signal, as long as the signal does not distract or disturb the driver.

There are many other general principles of human factors that should be considered when designing a CSWS. These principles and guidelines are covered in other DOT reports, and are mentioned here for reference.

[C-50] Detailed system design features shall incorporate human factors design guidelines and principles as contained in COMSIS, MIL-STD-1472D, and other human factors documents as appropriate.

As with any new technology, initial user education will be important to insure proper use of the system.

[C-51] User orientation to the system should be provided via documentation, video, demonstration or hands-on training.

Finally, curve speed warning is just one collision warning service. In the future, vehicles will likely be equipped with more than one such collision warning service. In addition to making systems that do not interfere with each other's operation, developers should be encouraged to look for and exploit potential synergies between collision warning technologies. For example, the sensing technology required by a CSWS to determine the upcoming road geometry could be used to improve "threat assessment" in a forward collision warning system. By merging information about how far ahead and how sharp the upcoming curve is with information about where obstacles are, the CSWS could help the forward collision warning system determine if an obstacle is in the travel lane, or just a harmless object on the side of the road. The technology required for CSWS could also be used as an unsignalized intersection collision warning system.

If the system determines the vehicle is approaching an intersection where stopping is mandatory, but the vehicle does not appear to be slowing down, a warning very similar to the curve speed warnings described above could be triggered.

Integrating the LDWS functions with other collision warning services will help to bring costs down, improve overall performance, and reduce driver confusion. In addition to other collision warning services, the technology for a CSWS could also be shared by other services, such route guidance, vehicle location, and collision notification.

[C-52] When practical, CSWS functions and/or sensing results should be integrated with other services to reduce costs, improve overall performance and reduce driver confusion.

7   CSWS PERFORMANCE ANALYSIS

It is important to estimate the potential benefits of collision avoidance systems as soon as possible, to help federal regulators, manufacturers and the driving public to determine if the technology is worth pursing. The true benefits of a technology are impossible to estimate prior to actual deployment, and even then they are sometimes difficult to quantify due to confounding factors such as changes in driving behavior, and the presence of other technology that may have influenced crash frequency or severity.

Prior to deployment, the only way to estimate potential benefits is through mathematical modeling and computer simulation. To estimate the potential benefits and performance requirements of a CSWS we chose a combination of physics-based analysis and limited field testing. The results of these experiments are described in this section.

The first step in the analysis is to elucidate the equation that governs the deceleration of a vehicle approaching a curve. Then the procedure for estimating the maximum safe speed for a curve is discussed. The crucial part of the analysis is the investigation of the effects of various CSWS errors on the speed at which a vehicle enters a curve. This methodology formed the basis for the preliminary specifications on the measurement accuracy necessary for an effective CSWS.

The following analysis is based on the understanding that the CSWS system is for safety and not for enforcement. For example, curves in two-lane rural highways and freeway ramps are frequently marked with a recommended safe speed. A passenger car can typically negotiate a curve with dry pavement faster than the posted speed. A CSWS system for enforcement would warn the driver or perhaps intervene if the driver attempted to enter the curve faster than the posted speed. Drivers would be annoyed by a system that forced them to drive through a curve significantly slower than they "know" they safely could. On the other hand, a system that permits vehicles to drive at or near the limits of safety could cause a roadway departure when the safety margin is only slightly less than believed.

7.1   WARNING DISTANCE AND TIME REQUIREMENTS

The permissible speed for a vehicle approaching a curve is calculated using basic kinematics:

$$V^2 = V_c^2 + 2\,a\,d \qquad\qquad \textbf{Eq. 7-1}$$

    V = the maximum permissible speed at distance d from the curve entry
    V_c = the maximum safe speed of the curve
    a = the assumed constant deceleration to reach the curve, and
    d = the distance between the current vehicle position and the curve entry.

For a comfortable, natural approach to a curve, the deceleration, a, may have a value of 0.2 g or 6.4 ft/s^2. The maximum speeds for these two deceleration rates are plotted in Figure 7-1.
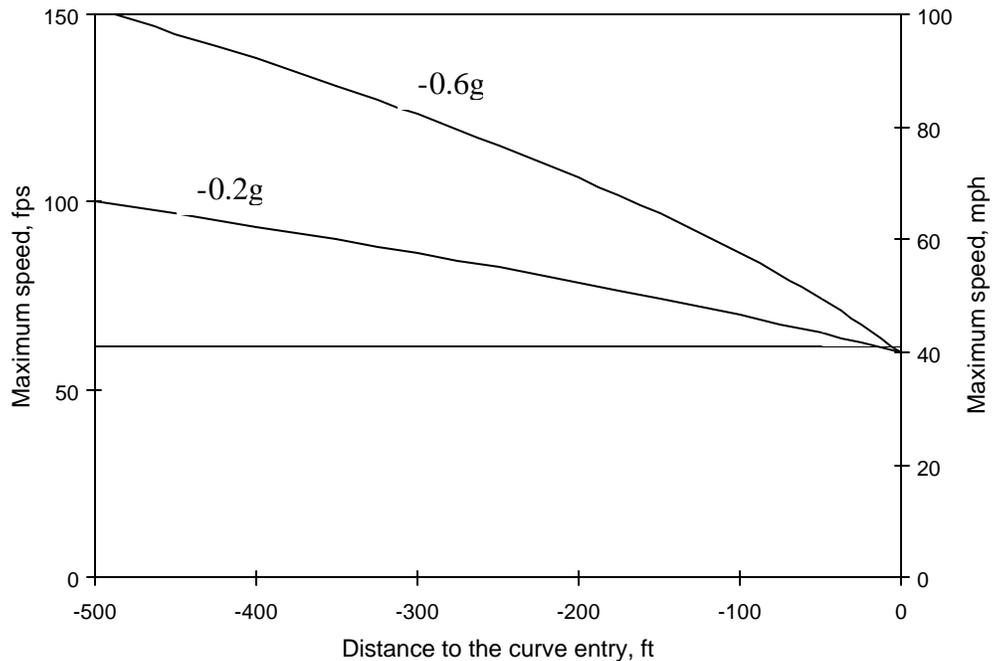
Figure 7-1: Maximum permissible speeds on approach to a 40mph (67km/h), assuming fixed deceleration rates.

A CSWS would continuously compare the vehicle's current speed to the maximum permissible speed for an upcoming curve. A warning would be issued when the vehicle's speed is above the lower curve in the figure, and a system with active intervention capabilities would brake the vehicle when the speed is above the upper curve. In practice, the system must allow for a human's finite reaction time, so the warning might begin when the distance to the curve entry is:

$$d = \frac{V^2 - V_c^2}{2\,a} + t_r V \qquad\qquad \textbf{Eq. 7-2}$$

Where:

    t_r = the reaction time due to CSWS and driver reaction delays.

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Alternatively, the above equation can be expressed as a function of required deceleration instead of distance (as is done in recommendation [C-27]):

$$a = \frac{V^2 - V_c^2}{2(d - t_r V)} \qquad \textbf{Eq. 7-3}$$

The two equations above are equivalent, and could be used interchangeably by a CSWS to determine the point prior to a curve at which a warning should be issued.

7.2   CURRENT PRACTICE FOR SAFETY IN CURVES

The maximum safe speed in a curve depends on the geometry of the roadway, the surface conditions, the skill (or tolerance for discomfort) of the driver, and the rollover stability of the vehicle. The geometric factors of a curve that are always fixed are its radius of curvature and its superelevation or banking. The other road-dependent factor is the maximum side friction factor that can be generated by the road surface. The friction factor can vary from vehicle to vehicle, and from hour to hour; it varies with the temperature of the surface, precipitation on the surface, the tires and speed of the vehicle.

The formula for the maximum safe design speed of a curve is [AASHTO 1994, p. 141]

$$V_c = \sqrt{g\,R\,\frac{e+f}{1 - e\,f}} \qquad \textbf{Eq. 7-4}$$

where:

V_c = the maximum safe speed in a curve
g = the gravitational acceleration constant
R = the radius of the curve
e = the superelevation of the curve
f = the side friction factor of the pavement and tires

This full formula can be derived from the force balance of a mass on a banked segment of a constant-radius curve. A simpler version of this formula is usually used for design calculations, but the following analysis requires the complete formula.

The side friction factor, f in the equations, is the ratio of actual side friction force on an object to the normal force. This ratio must be less than or equal to the quantity commonly called the coefficient of friction, which is the ratio of maximum possible friction force to normal force. The side friction factor assumed for highway **design** (as opposed to highway use) is generally less than 0.1 or 0.2. Under most conditions, a road surface can provide a significantly higher side friction factor, and aggressive motorists routinely drive curves much faster than the design speed. The low value is used for design to allow for the possibility of ice on the surface. Even if the road is capable of providing a higher side friction factor, persons in the vehicle may experience the discomfort associated with high side forces, and a vehicle with a high center of

gravity may be subject to roll over. The maximum safe side force should be fixed for a given vehicle, though it might vary with the manner by which the vehicle is loaded or maneuvered. The desired maximum side force could be an adjustable parameter set to the driver's preference. It could vary from one driver to the next, but it would probably be established before a trip. The maximum side force selected by the driver would be an upper limit; the actual force permitted by the CSWS might be further limited by its estimate of the available side friction and roll over stability of the vehicle.

When the value of f is the maximum friction available, Equation 7-4 represents the speed at which it would just barely be possible to negotiate the curve without loosing control, neglecting dynamic considerations. The CSWS must not use this absolute maximum speed when calculating whether to trigger a warning, since measurement errors and variability in driver skill (reaction time, deceleration rate, and steering vagaries) could mean that the true safe speed is somewhat lower. Instead, there should be a speed cushion (i.e., the speed at which the CSWS permits the vehicle to enter the curve should be somewhat lower than its estimate of the maximum speed at which the curve could possibly be negotiated). The cushion or margin, of course, should not be too large, or the driver would perceive that the system generates too many false alarms. The effect on the speed cushion of incorrect measurements or assumptions on the part of the CSWS is the next subject of discussion.

7.3   MEASUREMENT SENSITIVITY ANALYSIS

A vehicle may enter a curve at a speed higher than desired for reasons that fall in two broad categories: the driver may not have noticed the curve, or the driver may have misjudged the maximum safe speed for the curve. A CSWS will help the driver avoid these mistakes, but it, too, is subject to measurement error. We, assume that the CSWS will be aware of the presence of a curve, but it may misjudge the distance to the curve entry, the safe speed for negotiating the curve, or the driver's ability to maneuver as expected.

The system will miscalculate the proper speed to enter the curve if the radius, superelevation, or friction coefficient is measured incorrectly. These variables will influence the safe speed estimate through the relationship in equation 7-4. Even if the proper speed is calculated, the vehicle may not enter the curve at the desired speed. The entry speed might be too high if the distance to the curve or one of the other variables in Equation 7-2 is incorrect. In Equations 7-2 and 7-4, there are a total of eight parameters that can influence the speed at which the vehicle enters a curve. They are:

- radius of the curve
- superelevation of the road in the curve
- available side friction force
- distance from the vehicle to the curve entry
- current speed of the vehicle
- driver steering performance
- driver reaction time
- deceleration rate.

The effects on CSWS performance of each of these miscalculations will be analyzed separately.

For the purpose of plotting trends in the following analysis, a speed error of 10 percent is assumed to be tolerable. If a system is designed where the combined errors of all parameters cannot control the entry speed this well, the speed cushion will have to be adjusted accordingly.

7.3.1 RADIUS OF CURVATURE ERROR

The countermeasure system's estimate of the safe speed for an upcoming curve depends in part on its measurement of the radius of curvature. A smaller radius corresponds to a sharper curve and a slower safe speed.

The error (V_{err_R}) in the estimate of the maximum safe speed for a curve due to an error of R_{err} in the radius measurement depends on the partial derivative of V_c with respect to R through the following equation:

$$V_{err\_R} = \frac{\partial V_c}{\partial R} \, R_{err} \qquad \textbf{Eq. 7-5}$$

The fractional error in safe speed measurement due to an error in radius measurement is:

$$\frac{V_{err\_R}}{V_c} = \frac{\frac{\partial V_c}{\partial R} R_{err}}{V_c} = \frac{\frac{1}{2}\sqrt{\frac{g}{R}}\sqrt{\frac{e+f}{1-ef}} R_{err}}{\sqrt{gR\frac{e+f}{1-ef}}} = \frac{1}{2R} R_{err} \qquad \textbf{Eq. 7-6}$$

The sensitivity to error in radius measurement depends on the actual value of the radius, but not on the actual values of the superelevation or side friction. If we define a "tolerable" error in safe speed measurement to be, say, 10 percent, then the tolerable error in radius measurement, R_{err}, can be expressed as a function of the actual radius R.

$$\frac{V_{err\_R}}{V_c} = 0.1 R_{err} = 2R(0.1) = 0.2R \qquad \textbf{Eq. 7-7}$$

This equation is plotted in Figure 7-2. For example, if the actual radius is 1000 ft, the error in maximum safe speed estimate will be less than 10 percent of the actual safe speed if the error in radius measurement is 200 ft. In other words, the radius must be known to an accuracy of 20 percent to provide a safe speed estimate with an accuracy of 10 percent. However, as will be discussed in Section 8.3.6, human driving practices will affect the effective minimum radius.
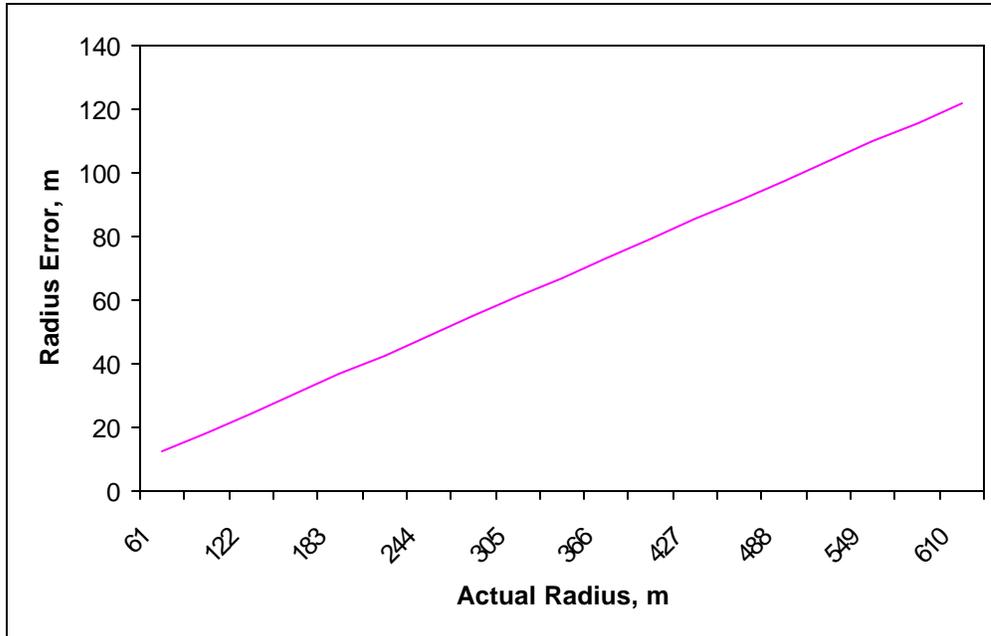
Figure 7-2: Absolute error in measurement of the radius of a curve that results in a "tolerable" 10-percent error in the estimated maximum safe speed for negotiating the curve, as a function of actual curve radius.

Figures 7-3 and 7-4 are graphs of the accuracy of road curvature estimates generated using a Navtech map vs. ground truth generated using an onboard yaw rate gyro. Figure 7-3 shows results on an extended stretch of interstate highway, and Figure 7-4 shows results on a shorter stretch of rural road. Curvature estimates were generated from the Navtech map by fitting a b-spline to the map data points. Overall, the mean error in curvature estimate was 24%, which is in the range required to achieve a "tolerable" 10-percent error in safe speed for the curve.

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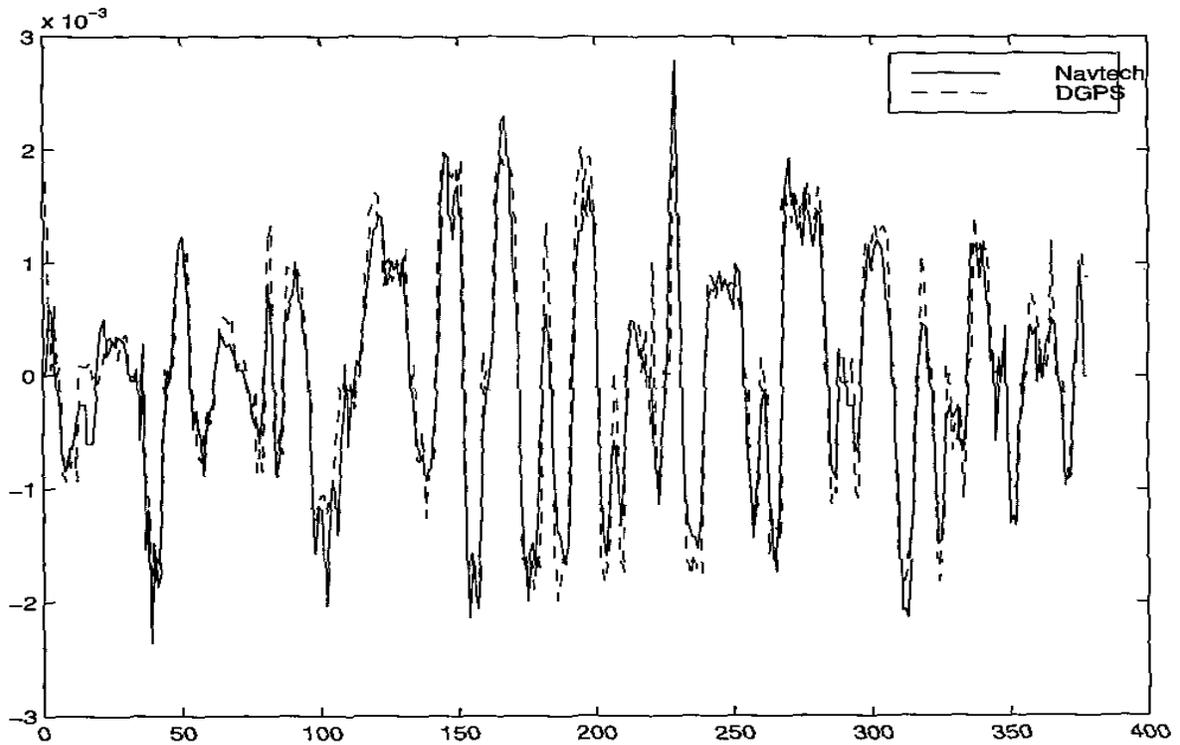
Figure 7-3: Curvature estimates (m^{-1}) for a stretch of interstate highway from the Navtech map database and measured value using DGPS and a yaw rate gyro.
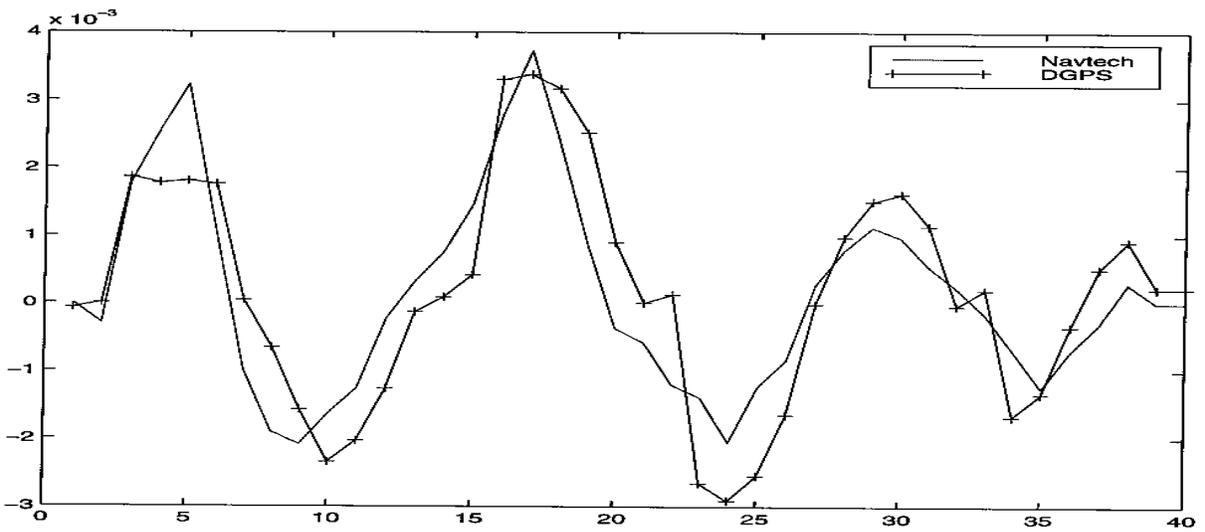
Figure 7-4: Curvature estimates (m^{-1}) for a stretch of interstate highway from the Navtech map database and measured value using DGPS and a yaw rate gyro.

7.3.2 ERROR IN SUPERELEVATION

Of the physical and geometrical properties of a curve, the superelevation is the one over which the driver has the least control; even the radius of curvature can be changed by curve cutting, but the superelevation in inexorably fixed by the road geometry. The side friction force demanded of the road depends on the speed and steering, but the cross slope built into the highway is constant.

Following the same procedure as for the analysis of errors in radius measurement, the effects of errors in superelevation measurement are analyzed by taking the partial derivative of the speed function (Eq. 7-4) with respect to the superelevation:

$$V_{err\_e} = \frac{\partial V_c}{\partial e} \; e_{err} = \frac{1}{2}\sqrt{g\,R}\left(\frac{1}{\sqrt{e+f}\,\sqrt{1-ef}} + \frac{\sqrt{e+f}}{(1-ef)^{\frac{3}{2}}}\,f\right) e_{err} \qquad \textbf{Eq. 7-8}$$

The fractional error in safe speed estimate, due to an error in superelevation measurement, is:

$$\frac{V_{err\_e}}{V_c} = \frac{1}{2}\,\frac{1+f^2}{(1-ef)(e+f)}\,e_{err} \qquad \textbf{Eq. 7-9}$$

The error depends on the actual values of the superelevation and side friction factor, but not on the actual value of the radius. This superelevation measurement error that corresponds to a "tolerable" 10 percent error in safe speed measurement is plotted in Figure 7-5. Whereas the ratio in Equation 7-6 depends on the actual value of only a single quantity, R, the ratio in Equation 7-9 depends on the actual values of two parameters (i.e., e and f). The contour plot and surface plot in Figure 7-5 show the same relationship in two formats.
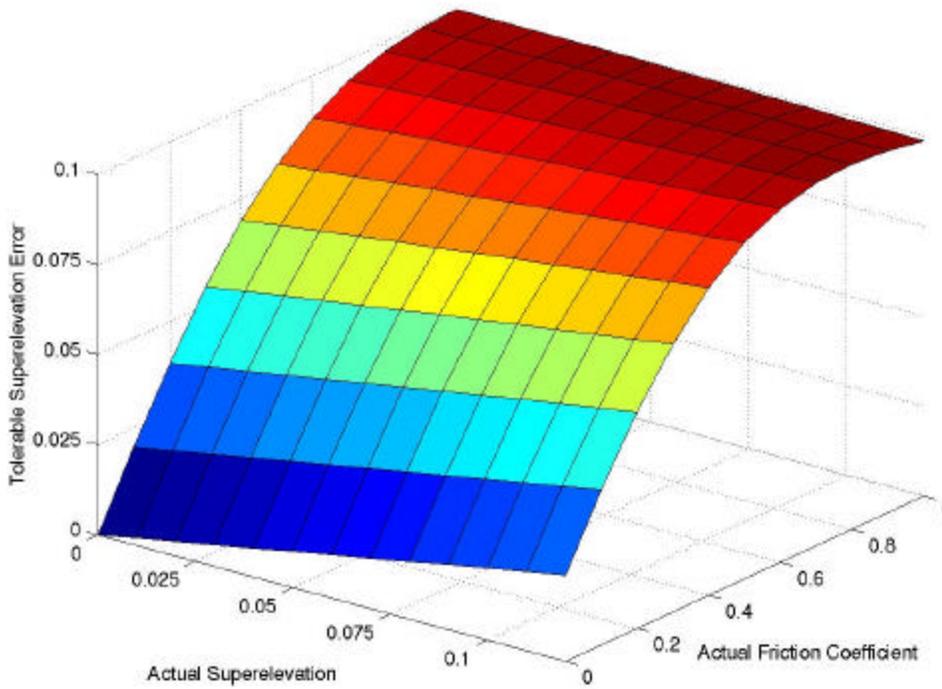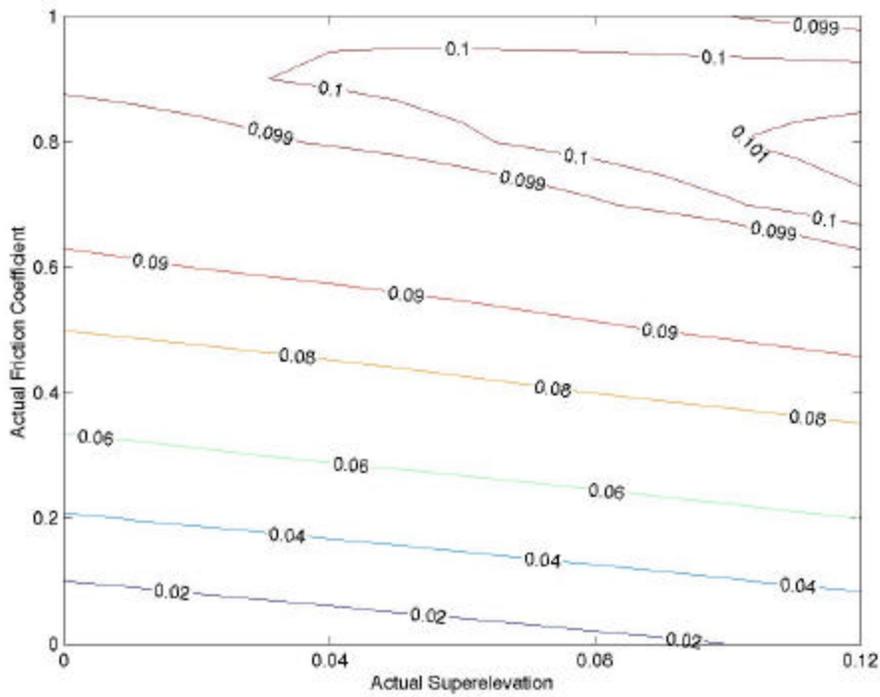
Figure 7-5: Absolute error in measurement of the superelevation of a curve that yields a "tolerable" 10-percent error in the estimate of the maximum safe speed for the curve. This is shown as a function of the actual side friction coefficient and the actual superelevation of the curve. The same relationship is shown as a contour plot and a surface plot.

Note that common highway design admits a maximum superelevation of 12 percent, and that only rarely (AASHTO 1994, p. 151). Therefore, if any curve were assumed to have a superelevation of 6 percent, the maximum conceivable error (aside from the possibility of adverse superelevation) would be 6 percent. In Figure 7-5, an error in superelevation estimate of 6 percent (0.06) is "tolerable" when the actual friction is above about 0.3 (at no superelevation) or 0.2 (at 12 percent superelevation). The friction is above these values in most surface conditions. Furthermore, the safe speed estimate is more sensitive to superelevation error at higher actual superelevations, when the fixed value of 6 percent is conservative. Therefore, measurement precision of superelevation is not a major issue. Because error due to superelevation inaccuracy will combine with other errors, however, a rough estimate of superelevation might be advisable.

7.3.3   ERROR IN SIDE FRICTION FACTOR

No reasonable driver would attempt to negotiate a curve at a speed requiring the very maximum available side friction force. Instead an estimated side friction capability (with a safety factor) is used to determining what speed to negotiate a curve. The following analysis determines how an error in the estimated side friction capability of a curved roadway segment might affect the planned speed for the segment.

The equations for the analysis of error in side friction factor measurement have a form quite similar to those for error in superelevation.

$$V_{err\_f} \ = \ \frac{\partial V_c}{\partial f} \ \ f_{err} = \ \frac{1}{2} \ \sqrt{g\,R} \ \left(\frac{1}{\sqrt{e\,+\,f}\ \sqrt{1\,-\,ef}} \ + \ \frac{\sqrt{e+f}}{(1\,-\,ef\,)^{\frac{3}{2}}} \ e \right) f_{err} \qquad \textbf{Eq. 7-10}$$

The fractional error in safe speed estimate, due to an error in measurement of the available side friction, is:

$$\frac{V_{err\_f}}{V_c} \ = \ \frac{1}{2} \frac{1\,+\,e^2}{(1\,-\,ef)\ (e\,+\,f)} \ f_{err} \qquad \textbf{Eq. 7-11}$$

The error depends on the actual values of the superelevation and side friction factor, but not on the actual value of the radius. The error in measurement of available side friction that corresponds to a "tolerable" 10 percent error in safe speed estimate is plotted in Figure 7-6. The tolerable error depends only slightly on the actual superelevation, since it is primarily a function of the actual friction. As might have been expected, the friction must be known most precisely

when the actual value is quite low; when the when friction is high, its value need not be known as precisely.

Estimating the coefficient of friction of the upcoming roadway may be the most difficult sensing function a CSWS must perform. Ray [1995] has shown through simulations that the coefficient of friction can be determined in real time using sensors that could reasonably be mounted on a vehicle. Under most conditions, if the vehicle is maneuvering, the coefficient of friction can be estimated to +/- 0.05 of the actual value. Briefly, the procedure is to measure tire angles and vehicle accelerations and use a simplified vehicle model to infer the tire forces. Then the most likely coefficient of friction is estimated. While this procedure appears to work in simulation, we are unaware of a real world system able to estimate the coefficient of friction this accurately. In addition, this proposed method estimates the friction coefficient at the tires' current location, and it is not necessarily a good indic ator of the friction in upcoming road segments.

According to Figure 7-7, a friction error of 0.05 is "tolerable" for all but the most slippery of conditions (i.e., when the friction coefficient is below about 0.2). Usually, only under conditions of ice or water with shallow tire tread is the friction coefficient below 0.2. Under these conditions, the mere fact that the coefficient of friction is unusually low is sufficient reason for a driver to be advised to exercise extra vigilance. For common surface conditions of dry or modest moisture (friction coefficient above 0.6 or so), a friction estimate within 0.05 would be adequate. Of course, in the case of sudden friction coefficient changes, such as ice patches or oil spills, a friction measurement under the tires' current position is inadequate. To function under these circumstances, a CSWS would have to either sense friction a distance ahead of the vehicle, communicate with the infrastructure in some way or perhaps with another vehicle some appropriate distance ahead.
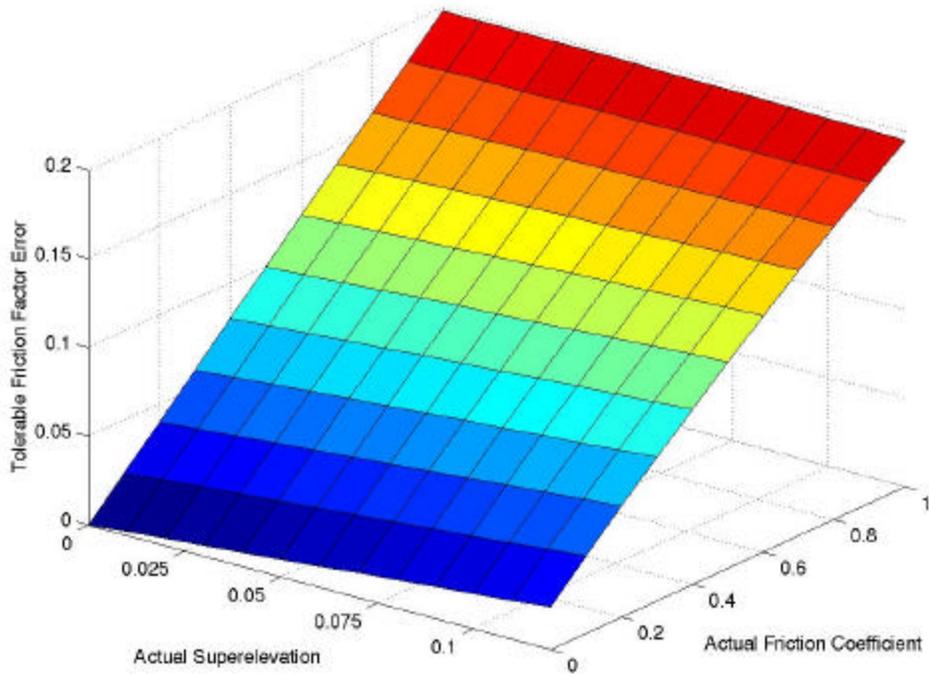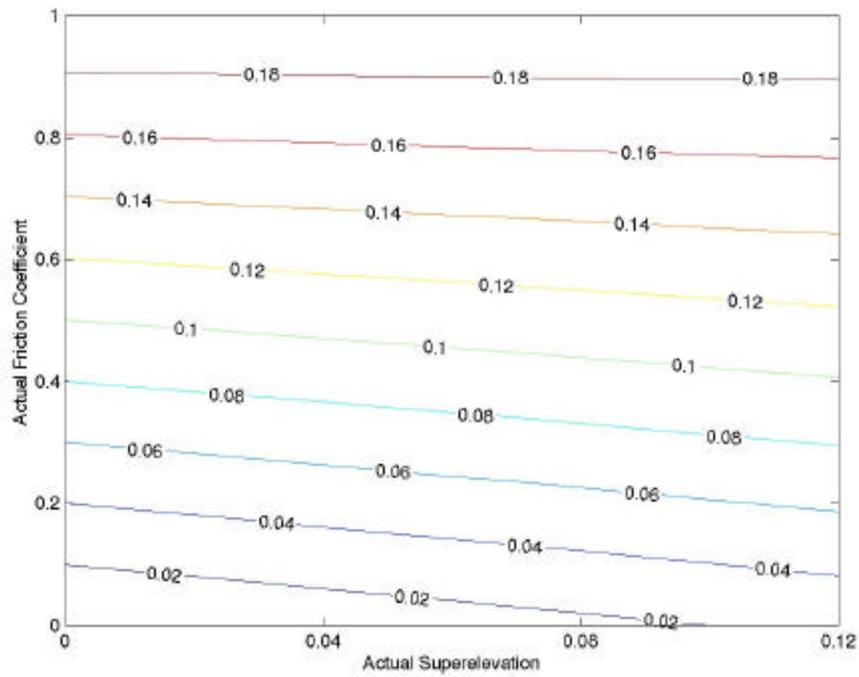
Figure 7-6: Absolute error in measurement of the side friction coefficient of a curve that yields a "tolerable" 10-percent error in the estimated maximum safe speed for a curve. This is shown as a function of the actual side friction coefficient and the actual superelevation of the curve. The same relationship is shown as both a contour plot and a surface plot.

7.3.4   ERROR IN DISTANCE

If the CSWS misjudges the distance to the curve entry point, the vehicle might enter the curve too fast, even when the maximum safe speed of the curve has been properly estimated. A position measurement error may be in the vehicle's position or in the location of the curve in the system's database. If there is a constant bias error in position, the vehicle will enter the curve when the system believes it is still a distance d_{err} away, and the speed of the vehicle will be:

$$V_a = \sqrt{V_c^2 + 2\, a\; d_{err}} \qquad\qquad \textbf{Eq. 7-42}$$

Where:

V_a = the actual entry speed
V_c = the desired entry speed
a   = the planned constant deceleration
d_{err} = the error in position measurement

The relative error in speed is:

$$\frac{V_a}{V_c} = \frac{\sqrt{V_c^2 + 2\, a\; d_{err}}}{V_c} \qquad\qquad \textbf{Eq. 7-13}$$

and the "tolerable" error in distance measurement is:

$$d_{err} = 0.105\, \frac{V_c^2}{a} \qquad\qquad \textbf{Eq. 7-14}$$

For a fixed deceleration, the relative error depends only on the desired entry speed. Figure 7-7 shows the distance measurement error that yields a 10 percent error in entry speed for a fixed deceleration of $a = 2.0$ m/s^2 (0.2 g). When the actual speed of the curve is less than about 30 mph (50 km/h), an error in position of only 12m (40ft) can lead to a significant entry speed error. Global Positioning System (GPS) may be adequate for advising a driver that a curve lies ahead, when the driver still has time to assess the situation and react accordingly.   However, differential correction to the GPS position estimate (and a good map) will be essential if the countermeasure is to provide an accurate and timely warning of excessive speed during the approach to a curve.
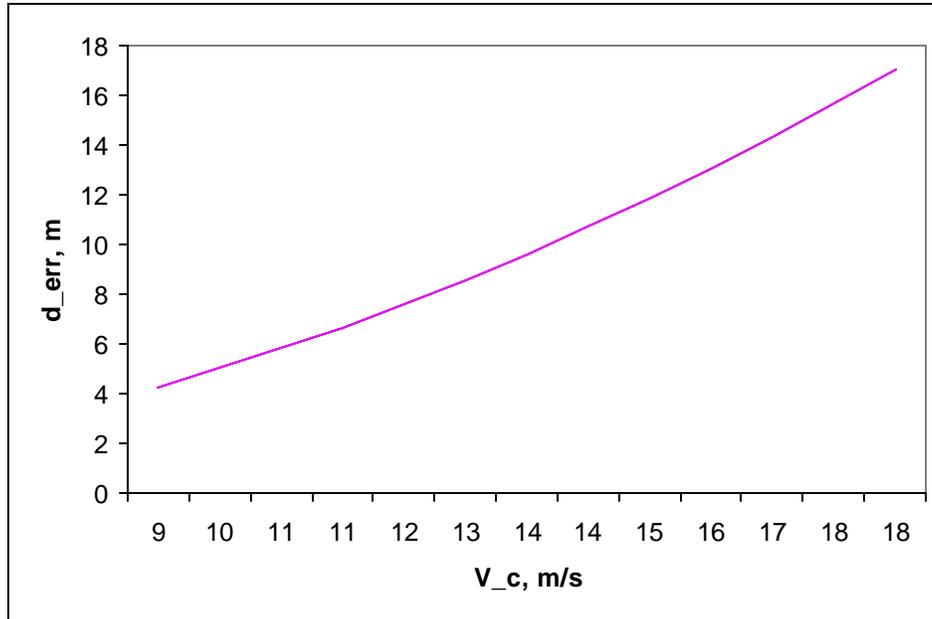
Figure 7-7: Absolute error in measurement of distance to the curve that yields a "tolerable" 10-percent error in actual curve entry speed, assuming constant deceleration at a rate of $2m/s^2$ (0.2g). This is shown as a function of the maximum safe speed for the curve.

7.3.4.1 GPS Accuracy Tests

In order to estimate the distance to an upcoming curve, a CSWS must know the position of the vehicle. A likely candidate for sensing vehicle position is GPS. To determine if existing GPS technology is suited for sensing vehicle position for a CSWS we conducted tests of several combinations of GPS receivers (Trimble SV-6, Ashtech G-12) and differential receivers (Omnistar, CSI, Accupoint, cellular modem). Overall, the results of these tests clearly show that achieving reliable vehicle position accuracy within 3-10m (10-33ft) is relatively straightforward with existing technology.

In one of these experiments, we drove our experimental vehicle several times over a 60 mile (100km) route around Pittsburgh. The vehicle was equipped with an inexpensive Trimble SV-6 six-channel GPS receiver, with differential corrections provided by a Novatel RT-10 base station via cellular modem. The route included downtown driving with tall buildings on both sides of the road, interstate highway driving with frequent overpasses and rural driving with thick overhanging trees. During each traversal of this route, we logged GPS data, including the number of satellites the GPS was tracking, as well as the latitude and longitude reported by the GPS.

The percentage of the time various numbers of satellites were being successfully tracked by the GPS during the two traversals is provided in Table 7-1. As can be seen from this table, satellite tracking was quite reliable. During the two traversals, the GPS was unable to track 3 or more satellites less than 0.2% of the time. Some of this ``dropout'' occurred when driving through downtown Pittsburgh and some of it occurred when traveling along rural roads with extremely dense overhanging trees. For more than 99.8% of two trips, the GPS maintained lock on a sufficient number of satellites to allow it to estimate the vehicle's position.

Table 7-1: Differential GPS Satellite Tracking Results

# Satellites Tracked	6	5	4	3	<3
Run1	45.8%	31.9%	18.6%	3.4%	0.2%
Run2	14.5%	55.3%	23.8%	6.3%	0.1%

The accuracy of the position estimates provided by the DGPS was measured by comparing the distance between each point recorded during the second traversal (Run2) and the closest point on the path recorded during the first traversal (Run1). Note that the first path certainly did not form a perfectly accurate map, but for the purposes of a curve warning system, perfect accuracy is not particularly important. What is important is the repeatability of the position estimates over time, and for this propose comparing two recorded paths is appropriate. The position estimate from one traversal to the next as reported by the GPS varied by an average of 6.24 meters, with a standard deviation of 11.05 meters.

A histogram of the actual errors is presented in Figure 7-8. It shows that for an overwhelming majority of the two runs, the two vehicle paths reported by the GPS were within 10-15m of each other. Note that there were a few outliers, represented by the spike at 80m (the maximum error allowed). These were primarily caused by large jumps in the GPS position estimate when driving in downtown Pittsburgh. The problem GPS has in these so called ``urban canyons'' is depicted in the Figure 7-9. It shows a close-up of the two recorded paths while the vehicle traveled through downtown Pittsburgh (also shown in the bottom center of the color map of Appendix A). There were several large jumps in the position reported by the GPS, corresponding to times when there were not enough satellites visible to get an accurate estimate. Fortunately, our analysis of crash statistics indicates that few roadway departure crashes occur in this type of extremely built up environment.

Overall, the results of these experiments are fairly encouraging. Using inexpensive GPS technology a CSWS could estimate the position of the vehicle typically to within approximately 6m, which is accurate enough to achieve the "tolerable" 10% error in curve speed. We did find outliers that were farther than the required 12m accuracy, but recent rapid improvements in GPS technology should ensure than nearly all measures are within tolerance.
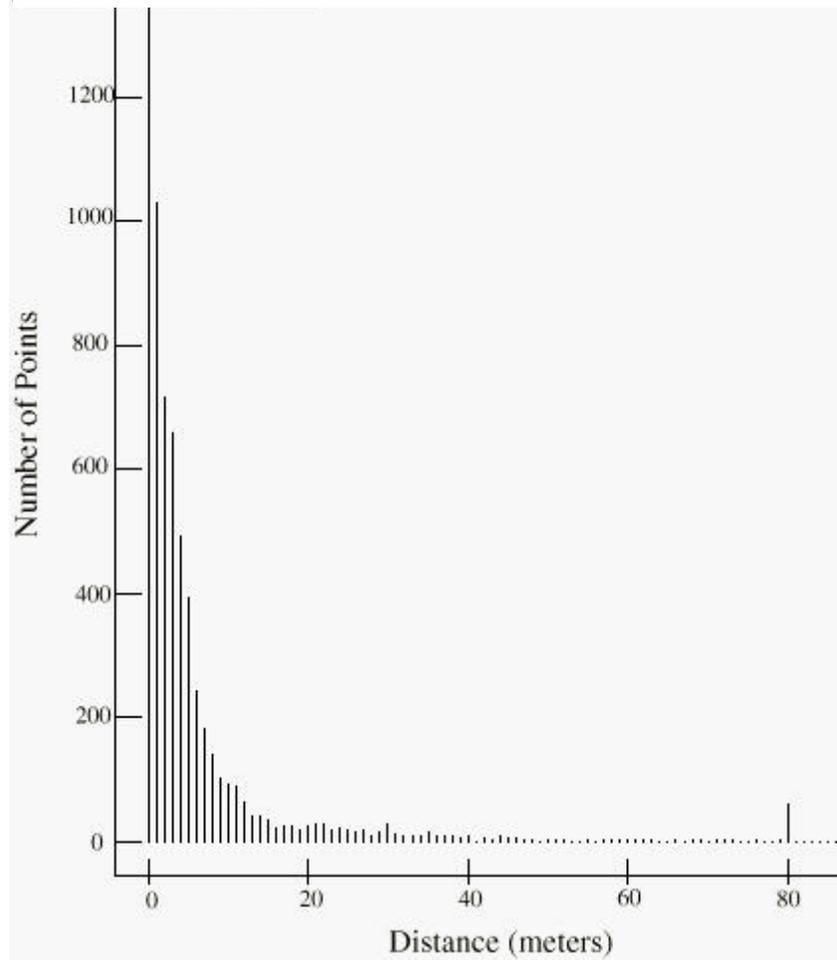
Figure 7-8: Histogram of distance between closest points on two recorded paths as reported by the GPS.
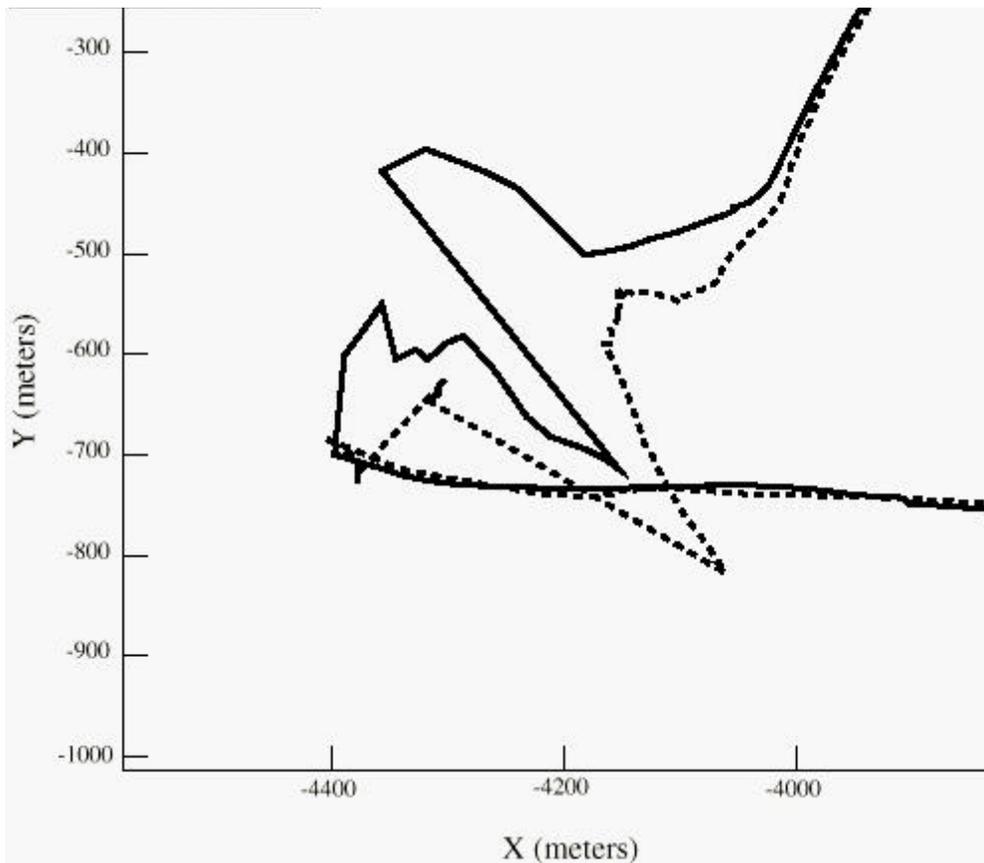
Figure 7-9: Position estimates from GPS as vehicle traveled through downtown Pittsburgh.

7.3.4.2   Commercial Map Database Accuracy Tests

Unfortunately, existing map databases (Etak and Navtech maps in particular) do not appear to be sufficiently accurate to estimate the distance to an upcoming curve to within 12m. The accuracy numbers provided by Navtech for their most accurate databases are that 97% of the road data points will be within 15m of the true road position. Results of tests conducted with the Navtech map database of the Pittsburgh area (including interstate highways and rural secondary roads) are shown in Figures 7-10 and 7-11. They show a histogram (7-10) and a time plot (7-11) of the difference between the Navtech maps estimate of the road's location and the nearest road point as reported by DGPS as the vehicle was driven over the road. The position error cannot be definitively attributed to the Navtech map or the DGPS, but the disagreement between them is substantial. Nearly 25% of the points disagreed by more than 15m.

These findings suggest it may be difficult to achieve the required 12m accuracy in vehicle position estimation relative to the upcoming curve using inexpensive DGPS technology and existing commercial map databases.
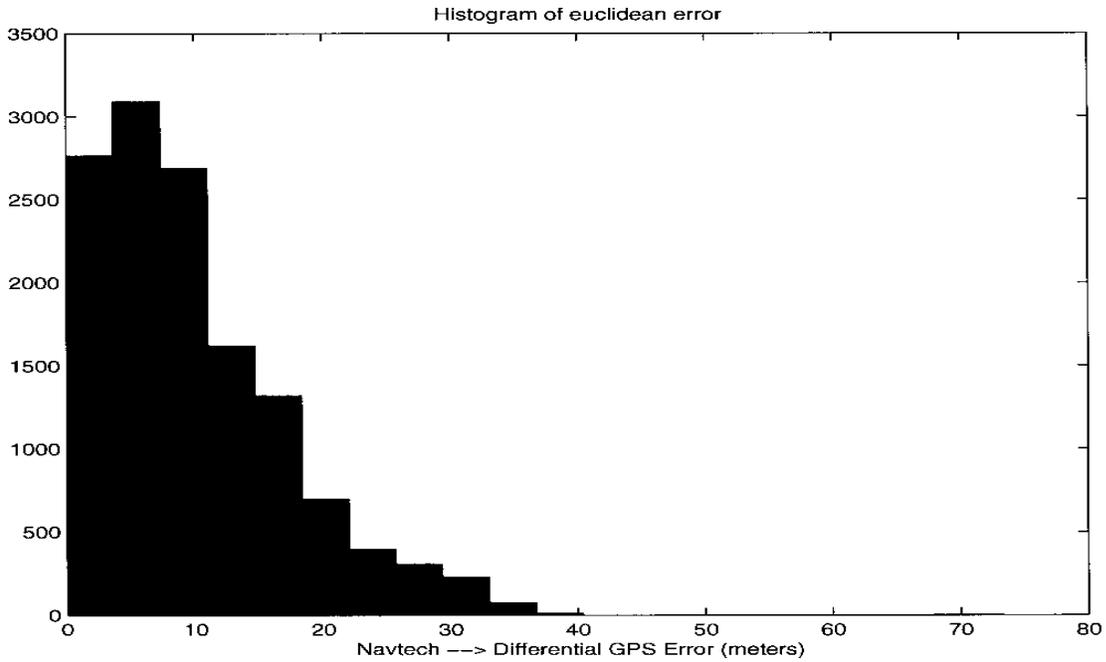
Figure 7-10: Histogram of difference between road position estimates from a Navtech map and the nearest road point as measured using DGPS while driving over the road.
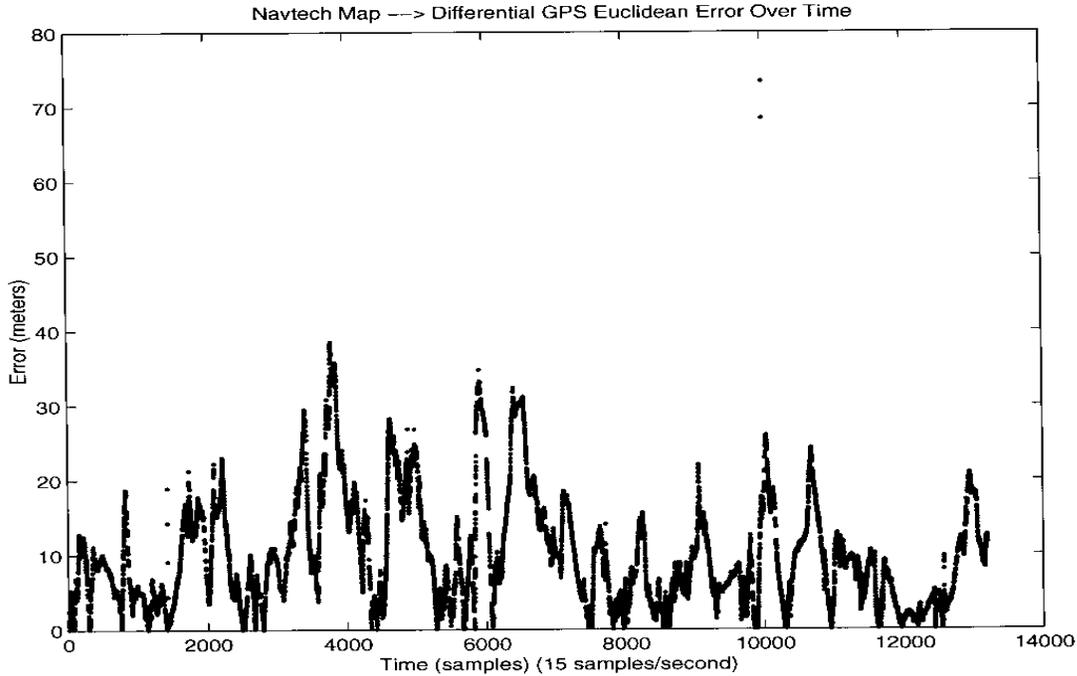

Figure 7-11: Graph of difference between road position estimates from a Navtech map and the nearest road point as measured using DGPS while driving over the road.

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7.3.5   ERROR IN VEHICLE SPEED MEASUREMENT

The calculations of required warning time and deceleration rate depend on the current speed of the vehicle. If the speedometer is not calibrated properly, the vehicle may enter the curve too fast even if the curve itself has been properly assessed. If the driver has been apprised of the curve by the CSWS, the driver may adjust the speed according to the feel of the vehicle and the curve. Thus a modest speedometer error would be inconsequential. In the case where a CSWS continuously monitors the vehicle's speed as it decelerates toward a road segment, an error in vehicle speed measurement would cause an equal error in entry speed.

The effect of an error in vehicle speed measurement at the time when the system decides whether to warn the driver is more subtle. Because vehicle speed occurs as a squared term in Equation 7-2, a speedometer error of only 5 percent at the time when the warning decision is made can lead to a curve entry speed error of approximately 10 percent, if after the warning either the driver or the countermeasure decelerates the vehicle at the assumed, fixed deceleration rate. Automobile speedometers are typically accurate to +/- 3 mph (5 km/h). At 60 mph (100 km/h), this is 5 percent of the true value. An alternative solution would be to use a more accurate means of estimating vehicle velocity, such as GPS. Inexpensive GPS receivers can estimate velocity using doppler shift to an accuracy of better than 1 mph (1.66km/h).

7.3.6   ERROR IN DRIVER STEERING PERFORMANCE

If the driver exactly follows the lane center throughout the curve, then the analysis of Section 7.3.1 would be sufficient to describe the effect of radius. A skilled, alert driver may not exactly follow the lane centerline in a curve. The driver may "cut" to the inside of a long, high-speed curve to lessen the travel distance, or may move "outside-inside-outside" to increase the effective radius of the curve so it can be driven at a higher speed. An unskilled or modestly inattentive driver might not maintain a constant curvature but meander. In this case, the minimum radius actually driven by the driver would govern the maximum safe or comfortable speed. The dynamic effects of load transfer between the left and right tires could play a role, beyond the strictly kinematic considerations, when the curve is tight and the driving is erratic. Therefore, when estimating the radius of curvature, an allowance for driver skill should be made.

7.3.7   ERROR IN ALLOWED DRIVER REACTION TIME

The countermeasure system must assume a nominal driver reaction time in deciding when to warn the driver. If the driver takes too long to react before beginning to decelerate, the vehicle will travel farther than anticipated at the original speed. The effect will be that the deceleration will need to be more severe than anticipated to slow the vehicle in time, or the curve entry speed will be too fast. Over a reasonable range of curve safe speeds and initial approach speeds, the "tolerable" reaction time error is 0.4 s or more. The difference between the 50-th percentile and 90-th percentile braking reaction times (in response to a surprise) is roughly 0.4 s. Little accuracy would be lost in most circumstances if a conservative choice of the 90-th percentile braking reaction time were assumed. If more accuracy is needed, the reaction time could be combined with the desired deceleration level on a "driver preference" knob, or a more

sophisticated system could adapt to the perceived reaction time of the present driver. Also, an alerted driver should be able to compensate for a delayed braking onset.

7.3.8   ERROR IN ASSUMED DECELERATION RATE

The thresholds for a longitudinal countermeasure system will likely be cast in terms of required deceleration rates, because the acceleration is a measure of the urgency of response needed from the driver. When a curve or other reduced-speed road segment lies ahead, the countermeasure system will use Equation 7-3 to determine the deceleration required to slow the vehicle in time. When the required deceleration exceeds a pre-established limit, the warning will be issued. Of course, different drivers have different "normal" practices for slowing down [Wortmann and Matthias 1983]. Some drivers decelerate gently, beginning well ahead of the need, while others maintain their cruising speed as long as possible, slowing down, as it were, at the last second. A warning given when the required deceleration is 0.15 g, comfortable for a conservative driver might be perceived as too early for an aggressive driver, accustomed to braking at 0.3 g. A longitudinal countermeasure system, therefore, might have an adjustable threshold. The adjustment might be a knob set by the driver to personal preference, or a more sophisticated system could sense the driver's usual braking practice and adjust accordingly.

The eventual curve entry speed is only moderately sensitive to the actual deceleration rate. An alerted driver can apply extra braking if necessary. Difficulties might arise when the pavement is slippery and extra deceleration is not possible, or when an inexperienced driver is faced with the necessity to brake more than usual and then panics. Another possibility is that the driver does not perceive the hazard signaled by the warning and chooses to ignore it. This might occur when there is "black ice" ahead, or when the view of the upcoming curve is occluded. Perhaps the CSWS should specifically advise the driver when it detects a hazard that the driver might not. A voice from the dashboard would say, "Caution! Ice Patches". This would be the electronic equivalent of the familiar "Bridges Freeze Before Roadway" or "Hidden Curve" signs.

7.4   EXPERIMENTS ON THE VIABIILITY OF A CSWS

A CSWS is conceptually easy to model based on the physics and kinematics of curve negotiation. As was shown above, modest errors in nearly any of the measured parameters cause only a minor error in the curve entry speed. However the biggest potential danger is that the combined errors in the eight relevant input parameters could potentially be substantial, resulting in a large error in curve entry speed.

In order to measure the combined effects of estimation errors both on quantitative performance and driver's acceptance of a CSWS system, we conducted two experiments with a prototype CSWS. Before describing the experiments, we first present the details of the prototype CSWS tested.

7.4.1   PROTOTYPE CSWS DESCRIPTION

The prototype CSWS consisted of the following sensor components:

- GPS receiver (Trimble SV-6)
- Differential receiver (Omnistar)
- Map database (custom – see below)
- Longitudinal accelerometer (Crossbow)
- Yaw rate gyro (Systron Donner)

The map database was generated by driving the test vehicle repeatedly over a stretch of road, estimating the position and radius of curves using position and velocity estimates from the GPS and vehicle yaw rate information from the yaw rate gyro. Note we did not use a commercial map because it was determined that the existing commercial map databases aren't accurate enough (see section 7.3.4.2).

When operating, the prototype CSWS constantly estimated the distance to and the radius of the upcoming curve. Assuming a dry pavement coefficient of friction (0.70) and a moderate superelevation (0.05m/m), the CSWS would estimate the maximum safe speed for negotiating the upcoming curve according to Equation 7-4. Next it calculated the maximum "comfortable" speed for this particular driver based on the driver adjustable maximum lateral acceleration as well as the upcoming roads curvature. It then used the minimum of 90% of the maximum safe speed and the maximum "comfortable" speed to determine the maximum acceptable speed – the speed that the vehicle should decelerate to before reaching the apex of the curve.

Using the maximum acceptable speed and the distance to the curve, it computed the deceleration required to slow the vehicle to the maximum acceptable speed prior to reaching the apex of the curve. If the required deceleration exceeds a driver adjustable threshold, the CSWS would trigger a single audible warning (in the form of a 0.5 second tone alternating between 2000 and 3000 Hz) to slow the vehicle down.

7.4.2 COMBINED ACCURACY EXPERIMENT

The first experiment conducted with the prototype CSWS was to measure its overall accuracy and consistency in triggering a warning for an upcoming curve. The protocol the experiment is described below:

1. A video camera was mounted facing sideways out the passenger window of the test vehicle, and configured to capture an image at the moment the curve speed warning system triggered.

2. A long straight stretch followed by a sharp curve, with a large open area to one side was selected from a mapped stretch of road for the experiment.

3. A marker was placed adjacent to the road prior to a sharp (70m radius) curve so that it would be in view on the approach to the curve. The marker was offset from the road by approximately 30m, so that it would be in view of the side looking camera for a substantial period during the approach to the curve. The horizontal position of the marker in the image

at the moment the image triggered could be used to calculate the distance from the apex of the curve at which the warning was triggered.

4. A fixed test speed and warning threshold were chosen so that warnings would, on average, trigger when the marker was centered in the side looking camera's field of view. This ended up being a distance of 75m (4 sec) prior to the curve. This is earlier alarm than would be selected normally, but it was convenient for testing purposes. The absolute warning onset distance was not important for this experiment, since it is designed to determine the warning system's consistency.

5. The test vehicle was driven towards the curve at a fixed speed ten separate times (10 runs). A consistent speed was ensured by setting the cruise control for the target speed at the start of the experiment, and then pressing "resume" 1/2 mile prior to the curve on each run. Pressing "resume" gave the cruise control the same target speed on each run, and pressing it 1/2 mile prior to the curve ensured that any differences in speed at the time the cruise control was engaged would be eliminated by the time the vehicle reached the approach to the curve. The vehicle speedometer consistently read 44mph at the time of the approach to the curve on each run. However, the velocity estimate from GPS was consistently in the range 40-42mph during the approach, suggesting there may be some offset in the vehicle's speedometer (or in the GPS velocity estimate, which is less likely). Again this was not a problem, since consistency, rather than absolute accuracy, was important for this experiment anyway, since the goal was to measure the consistency of the warning onset.

6. The position of the warning onset was recording using the video, and measurement of the horizontal position of the marker in the image was used to estimate the distance (and time) prior to the curve at which the warning was triggered.

The results show that over the 10 runs, the warning onset was triggered a mean distance of 75m (4 sec) prior to the apex of the curve. The warnings were evenly distributed within a range of +-15m (+-0.8 sec). The contributions to the error from various sources were as follows.

Tests of the differential GPS at the same spot indicate that vehicle position estimation errors account for approximately +-5m of error of the +-15m or error in the warning onset. The same map was used for each run, so errors in the map did not contribute to variations in the warning onset time in this experiment. Errors in velocity probably did contribute to errors in the warning onset. According to the GPS, the vehicle velocity at the time warnings were triggered ranged from a low of 40.5mph to a high of 42.2mph over the 10 runs. It is difficult to determine how much of this velocity error was due to errors in the GPS velocity estimate, or in the cruise controls ability to exactly reproduce the same vehicle speed over the 10 runs. It appeared visually from the speedometer that the velocity range time of the warning onsets was less than the 1.7mph reported by GPS, but the speedometer may have had errors as well. A 0.85mph error in velocity (1/2 the measured range) would result in a 6.8m error in warning onset location, when alarms are set up to trigger 4 seconds prior to the curve.

Subjectively, the driver could easily detect the variation in the warning onset time over the 10 runs. The difference in distance between the earliest and the latest warnings was approximately 30m. This variation was judged to be on the borderline of what could be tolerated in a deployed

system. It should be noted that for ease of measurement, the experimental protocol was set up to trigger a warning 4 seconds prior to the curve. This is significantly earlier than a CSWS normally would trigger a warning. This very early warning had the effect of amplifying any errors in sensor data. So in one sense, this experiment could be considered a "worst case" scenario. Subjective assessment of more realistic scenarios by a variety of drivers is addressed in the next section.

7.4.3   SUBJECTIVE ASSESSMENT EXPERIMENT

In next experiment, we conducted a limited in-vehicle field test of the prototype CSWS. The primary goals of the experiment were to get subjective assessment of the overall viability of a CSWS, and to determine reasonable values for tolerable lateral and longitudinal accelerations during curve negotiation.

7.4.3.1   Experiment Protocol

In the experiment, we had six male subjects (ranging in age from 25 to 45) drive the testbed vehicle (a 1997 Oldsmobile Silhouette minivan) over a 2 mile section of winding country road. Prior to the test subjects were told they would be testing a "prototype curve speed warning system", and that the system would "beep at them when it believed the vehicle was traveling too fast for an upcoming curve". Subjects were instructed to drive "safely, but as if they were late for an important meeting". They were told the CSWS was being tested to determine if the timing of its warnings are appropriate, and therefore the subjects should make a mental note about whether warnings came too early, too late or just right.

Subjects then drove the vehicle several miles with the CSWS disabled to familiarize themselves with its handling. Then they were allowed to drive over a 2-mile stretch of test road as many times as they wished at whatever speed they wished to experience the behavior of the CSWS. Each subject drove each direction on the test road between 3 and 5 times. All the test runs were conducted under fair weather conditions and dry pavement. There was an experimenter in the vehicle along with the driver at all times.

The prototype CSWS was the same one used in the previous experiment. The map was again generated by driving the vehicle over the test stretch of road numerous times, collecting data with the differential GPS each time, and merging the data from multiple traversals together into a single accurate map. The 2 mile stretch of rural test road contained 6 significant curves to the left and right, ranging in radius from 70m (230ft) to 190m (627ft).

The CSWS was tuned prior to the experiment to trigger a warning at what was judged to be a reasonable onset time for a typical driver. The two parameters that were adjusted to achieve reasonable performance were the maximum acceptable lateral acceleration in the curves and the estimated longitudinal deceleration rate on the approach to the curve. The maximum lateral acceleration in the curves was set to 3.25 m/sec^2 (0.33g) and the estimated longitudinal deceleration rate on the approach to the curve was set to 1.45 m/sec^2 (0.15g).

7.4.3.2   Results

Each of the six subjects rated the overall system performance as quite reasonable. Four of the six subjects judged the warning onset time to be "about right". The remaining two drivers were split, one judged the warnings a little too early and the other judged them a little too late. So the lateral acceleration threshold of 0.33g and the assumed longitudinal deceleration of 0.15g seem like quite reasonable defaults that will satisfy a typical driver. However even in the small sample of subjects we did see some variation in warning onset preference, so an adjustable threshold is a desirable feature. Such an adjustment should probably consist of a single "sensitivity" setting that simultaneously adjusts both the lateral acceleration threshold and the assumed longitudinal deceleration, since drivers are unlikely to understand the meaning of these individual variables.

Anecdotal remarks and experiences from the experiment provide some additional insight into the performance of the prototype CSWS. One of the subjects was particularly convinced of the potential of this technology after approaching a blind curve at clearly too high a speed during the experiment. The CSWS triggered a warning substantially before the curve, but the driver ignored the warning and waited several seconds before initiating braking. He was able to negotiate the curve, but not without screeching the tires and frightening both himself and the experimenter. The subject later reported that he thought the warning was a "false alarm" since the upcoming curve (which was blind) did not appear dangerous to him. He then reported emphatically that he "should have listened to it". This points out an important fact – with a CSWS, as with any collision countermeasure, there is always a person in the loop and it is the person who makes the final judgement about how to act. A level of trust must be established between the driver and the countermeasure. Without it, drivers will react slowly if at all to a warning, with obvious potential for negative consequences. This issue of trust is particularly important for a CSWS, where the danger may not be readily apparent.

Another driver remarked that the system seemed promising, but what would really be required to make it useful was the ability to sense road conditions (which the prototype did not do). He judged that such a system would only be worth purchasing on a new vehicle if it could account for the speed reduction required to safely negotiate curves when they are wet or icy. Unfortunately, sensing the upcoming pavement condition is very difficult and will probably require cooperative infrastructure.

7.5   OVERALL VIABILITY OF A CSWS

Quantitative and subjective tests suggest that a simple CSWS holds promise. Performance appeared to be repeatable using existing sensor technology, and drivers judged the performance of the prototype CSWS to be reasonable. However it should be noted that the experiments described above represented a "best case" scenario for a CSWS along several important dimensions. The quantitative experiment demonstrated the repeatability of the CSWS, but not the accuracy of the warning onset time. If the conditions had been different, the prototype CSWS might not adjust its warning onset time appropriately. In fact, there are several important variables that the prototype CSWS made significant assumptions about – assumptions that would significantly reduce performance and that could not be made by a deployed CSWS. The available friction under the vehicle or on the upcoming curve was not measured, but instead was

assumed to be high and constant (which was true in the limited tests conducted). Vehicle roll stability was not sensed, but instead was ignored entirely in determining the warning onset point. The superelevation of the curves was assumed to be a typical intermediate value. Finally, the map employed for these experiments was very accurate, having been made using differential GPS by actually driving the vehicle through the curve several times. A less accurate map (like those commercially available now) would results in less accurate and more varied warning onset times under actual operating conditions.

Probably the most critical of the above assumptions is the one made about friction. Sudden, but quite possible, changes in the surface friction can be disastrous. The analysis of Section 7.3.3 showed that an error in side friction capability of less than 0.05 leads to a 10 percent error in the estimated safe speed of a curve. Changes in precipitation, tire condition, and road roughness can easily lead to a significant friction discrepancy. An infrastructure-based system may give good information about the weather or even the precipitation present on a particular roadway segment, but the infrastructure certainly does not know the current tire condition. Conversely, a friction-measuring system contained within a vehicle can probably account for the condition of the tires, but it would be completely unaware of ice patches that lie ahead. Even so, measuring the tires' ability to avoid hydroplaning may be difficult until a puddle of water presents the opportunity...too late for safety. Perhaps the countermeasure system should be combined with a vehicle maintenance program, reminding the owner to rotate the tires or check their tread depth at the proper time. To be sure, as development of a CSWS system continues, getting a reliable, accurate friction measurement will be an important issue.

The key assumption in the sensitivity analysis in this section is that a 10 percent error in curve entry speed is tolerable. If the excess speed is small, the difference will likely result in a slightly increased lateral force. For example, if a vehicle plans to enter a 300m radius curve with a 4 percent superelevation at 60mph but has a 10 percent speed error, the side friction required will be 0.25 rather than the planned 0.20. This is within the capability of most non-icy surfaces and probably tolerable for the passengers. If the excess speed is too high, the driver will need to maneuver more carefully and perhaps increase the radius slightly (i.e., depart the lane). Should the driver panic because of an unexpectedly high side force or squealing tires and apply the brakes, control of the vehicle may be lost. Therefore, as with the lateral countermeasure systems, the question of stability ultimately becomes a matter of human factors. The analysis above is suitable for planning a countermeasure system, but more information on human drivers' practices is needed before final performance specifications can be written.

If a 10 percent error in curve entry speed is shown to cause instability in too many cases, the safety margin will have to be increased. Similarly, if the minimum achievable errors in parameter estimates combine to produce an error of more than 10 percent, the cushion will again have to be increased, by lowering the estimated safe speed of the curve. The drawback of this additional safety margin is the greater likelihood of false alarms, when the conservative countermeasure warns a driver who was well aware of the situation and was planning to slow down anyway.

7.6   PROJECTED BENEFITS OF A CSWS

Under the assumption that technology is/will be available to achieve performance that meets the recommendations and tolerances described above, the next question is what benefits would such a system provide? This section attempts to make such projections, through analysis of crash statistics generated in Phase I of this program. The two most important factors determining the effectiveness of a CSWS are the casual factors associated with a crash and the driver's response to the CSWS.

7.6.1.1   Causal Factors

The factors causing a crash are important, because a CSWS can only be expected to prevent the subset of road departure crashes caused by excessive speed when approaching a curve. Theoretically, a countermeasure that can sense upcoming road friction could warn of low friction conditions on straight sections as well as curves, and as a result benefit crashes caused by loss of directional control due to wet or icy roadways. However the difficulty of sensing upcoming pavement conditions from on-board a vehicle makes it unlikely that such benefits will be achieved, so they are not included as part of these estimates.

Table 4-1 shows that 32.1% of road departure crashes in passenger vehicles are caused by excessive vehicle speed. However data from the clinical analysis conducted in Phase I of the program indicates that only 58% of passenger vehicle crashes caused by excessive speed occur on curves, where a CSWS has the potential to prevent the crash. As a result, the pool of crashes potentially preventable with a CSWS is reduced to 18.6% of all road departure crashes in passenger vehicles.

Table 4-1 shows that 22.5% of road departure crashes in heavy trucks are caused by excessive vehicle speed. Analysis of NTSB heavy truck crash data in Phase I indicates that approximately 45% of the speed related crashes were due to speeds that were too fast for the curve the truck was negotiating. This leaves a pool of 10.1% of heavy truck road departure crashes potentially preventable by a CSWS.

7.6.1.2   Human Factors

Human factors issues will play a dominant role in determining the ultimate effectiveness of a CSWS. For example, 40 percent of the speed-related curve departures in the Task 1 clinical database of passenger vehicle crashes involved drivers impaired by alcohol. The likely response of these drivers to a longitudinal warning system needs to be further investigated before true benefits of a CSWS can be estimated. If we assume (as we did for the LDWS) that only 25% of impaired drivers will respond appropriately to a CSWS and avoid a crash, this reduces the pool of preventable crashes in passenger vehicles to 13% of all road departure crashes.

As with the inattention and driver relinquishes steering control causal factors, there are few excessive speed crashes involving alcohol or other controlled substances in heavy trucks. Therefore the pool of crashes potentially preventable with a CSWS remains approximately 10% of all heavy truck road departure crashes.

There are undoubtedly other situations/conditions where the driver will not react appropriately to the warnings provided by a CSWS, but the frequency of these circumstances will require further field tests with naïve subjects to determine.

7.6.1.3   Numeric Projections

The next question to address in estimating benefits of a CSWS is to project the actual number of crashes and the associated costs that could be prevented through the use of a CSWS. As was noted in Section 1.3, according to GES data, there are approximately 1.6 million police reported road departure crashes each year in passenger vehicles.   The FARS database indicates there are approximately 15,000 fatalities each year resulting from road departure crashes in passenger vehicles. Applying the 13% crash prevention rate for passenger vehicles, an estimated 208,000 crashes, and 1950 fatalities could potentially be prevented each year if every passenger vehicle were equipped with a CSWS.

According to another USDOT study (Wang, Knipling and Blincoe, 1999), the average monetary cost per road departure crash in a passenger vehicle is $18,840. The monetary cost included such costs property loss, economic losses due to reduced productivity, and medical expenses. A more comprehensive estimate of costs, which included the monetary costs plus less tangible costs like the derived valuations for life and "pain and suffering" put the cost at $60,870 per passenger vehicle ROR crash. Using the more conservative $18,840 cost, preventing 208,000 such crashes would save a total of over $3.9 billion dollars each year. Using the conservative estimate of cost, a CSWS could save an estimated $254 per passenger vehicle over its operational lifetime.

According to the same USDOT study, approximately 31,000 ROR crashes occur in combination-unit trucks each year, 320 of which involve a fatality. A CSWS that has the potential to prevent 10% of them would result in 3100 fewer crashes and 32 fewer fatalities. The direct monetary cost is estimated at $17,670 per heavy truck ROR crash, so preventing 3100 of them would result in a projected annual saving of approximately $55 million. A CSWS that prevents 10% of heavy truck ROR crashes would result in direct monetary savings of approximately $445 over a truck's operational lifetime.

While preliminary and based on a number of assumptions, the potential benefits of deploying CSWS technology appear to be substantial, in terms of the number of crashes and fatalities prevented, as well as the costs saved. Since the cost of much of the technology required for a CSWS could be amortized over a number of other useful services (route guidance, vehicle location, collision notification) we believe that manufacturers should be able to reach the incremental cost targets of $254 for passenger vehicles and $445 for heavy trucks. Of course this assumes solutions become available to the technology hurdles facing a CSWS, such as reliable road condition sensing and more accurate maps.

8   CSWS TEST PROCEDURES

The tests described in this section are designed to evaluate the performance of a CSWS. There are several benefits to having a consistent test procedure, including:

- providing unbiased information by which to compare the performance of alternative systems,

- ensuring that any systems that pass the tests achieve a minimum acceptable level of performance,

- fostering compatibility and common operating characteristics between systems sold by different companies.

These test procedures based on experiments conducted with actual prototype systems. These test procedures are preliminary recommendations. More complete and definitive tests will require additional research.

In general, it is not anticipated that all possible combinations of conditions that could effect CSWS performance will be available for testing. The range of road geometry and the range of environmental conditions that a deployed CSWS would encounter are impossible to reproduce consistently. As a result, the test procedures outlined in this section are designed to determine if a CSWS meets a minimum level of performance under a limited set of reproducible conditions. The tests are designed to be technology independent, although they do include provisions to ensure that likely candidate technologies for a CSWS can be evaluated. These test procedures are appropriate for evaluating the sensing, warning algorithm and driver interface aspects of CSWS operation under controlled circumstances. It is expected that the tests described here would be combined with longer term "in-situ" testing to validate system performance under a more realistic range of environmental conditions and road types. The exact form of the in-situ testing will require further research to determine.

8.1   ENVIRONMENTAL CONDITIONS

Since environmental and pavement conditions, are important factors in the operation of a CSWS, tests should be conducted in a range of such conditions. At a minimum, tests should be conducted under both dry and wet pavement conditions. Ideally, tests should also be conducted under low friction conditions (i.e. ice or snow covered pavement). Since a CSWS must be able to detect local patches of reduced friction pavement, care should be taken to insure that only the test curves have the degraded pavement condition, and not the approach to them. This will probably require artificially creating localized wet or icy patches of road surface by introducing water on the roadway.

It is important to know the coefficient of friction of the pavement in the test curves. Skid resistance measurements should be made with a calibrated locked-wheel skid tester using

the ASTM E 274 method and supplemental procedure described in [FHWA, 1980]. Due to the sharp curves on which these tests will be conducted, it is unlikely that the locked-wheel skid tests will be safe at the standard speed of 40 miles per hour. Therefore a convenient lower speed should be used for testing. Alternative methods of measuring pavement friction properties may be used provided they correlate well with the locked-wheel skid tester.

8.2   ROADWAY CHARACTERISTICS

Tests should be performed on a stretch of road with an asphalt (bituminous) or concrete surface.   The test road should have at least one curve with a radius of 100m or sharper, and a nearly straight section of at least 150m prior to the sharp curve. The test curve should have a paved shoulder of at least 1m on the outside of the travel lanes, and no roadside obstructions that could provide dangerous in the event of an unintended road departure during testing. During the testing, access to the test road must be restricted to only the test vehicle. The vertical grade of the road should be nearly flat, and superelevation should be within normal ranges recommended by AASHTO for US roadways.

Important geometric characteristics of the test curve should be measured, including its minimum radius of curvature, length of entry spiral, and superelevation. These geometric characteristics, along with the pavement condition and vehicle parameters will be used to compute "ground truth" for the safe speed for negotiating the curve.

If the particular CSWS being tested requires infrastructure modifications, the infrastructure should installed on the test curve according to the manufacturer's instructions.

8.3   TEST VEHICLE

It is possible that a CSWS will be sold as an integrated option on an OEM vehicle, or as an aftermarket option. For an integrated CSWS, tests should be conducted with an unmodified vehicle equipped with the CSWS at the factory. For an aftermarket CSWS, the system should be installed on a vehicle deemed appropriate by the manufacturer of the CSWS according to the manufacturer's instructions. Alternatively the manufacturer of an aftermarket CSWS could provide the system already installed on a vehicle for testing purposes. If the CSWS is design to accommodate passenger vehicles as well as commercial vehicles, the tests should be conducted separately with both vehicle types.

The test vehicle may need to be equipped with special measurement equipment to allow for the measurement and evaluation of CSWS performance. Examples of such measurement equipment are technology to localize the vehicle relative to the curve, an accurate ground speed sensor, and accelerometers to measure lateral and longitudinal

forces. These measurement devices should be independent of the CSWS sensors, and should not interfere with the operation of the CSWS in any way.

8.4   TEST VEHICLE LOADING

A CSWS, particularly one designed for commercial vehicles, must account for the roll stability of the vehicle, which is strongly influenced by its load distribution and center of gravity (CG). Therefore tests with commercial vehicles should be conducted with a variety of load distributions ranging from an empty trailer to a maximally loaded trailer (as defined by state and federal weight limits). If the CSWS is also designed for commercial tanker trucks, tests should be conducted using a tanker truck with loads that include empty, 25% full, 50% full, 75% full and 100% full.

8.5   CSWS CONFIGURATION

Configuration and calibration (if required) should be performed prior to the tests according to the manufacturer's specifications. For tests of a CSWS with an adjustable warning threshold, the threshold shall be set at the default. No alterations to the system shall be made once the test procedure has begun.

8.6   TEST PROCEDURE

Static measurement of the test curve's radius and superelevation should be made prior to the testing. Shortly before, as well as periodically during testing, the coefficient of friction for the curve itself and the approach to the curve should be measured. These measurements should then be used to determine the maximum safe speed for negotiating the curve according to the equation in [C-21]. This maximum safe speed should be adjusted according to vehicle-specific parameters such as rollover susceptibility, mass distribution and tire condition, as indicated in [C-22].

During testing, the vehicle should repeatedly approach the curve at the same constant speed. The constant approach speed should be chosen to be between 10 and 20mph above the maximum safe speed. The constant speed may be maintained by using the vehicle's cruise control, if the test vehicle is so equipped. The CSWS should trigger a warning on each approach to the curve, and the precision location of the vehicle relative to the curve at the moment of warning onset should be recorded. At least 20 approaches to the test curve should be conducted at a single speed and under identical vehicle loading and pavement conditions.

8.7   EVALUATION

Post analysis of the warning onset locations for identical test conditions should verify the following:

1. The "spread" of the warning onset locations, from earliest to latest, should be less that one second in time, at the vehicle's approach speed during the tests. This is to ensure consistent enough warning onset to be acceptable to drivers.

2. The mean distance of the warning onset prior to the curve should be at least:

$$d \; = \; \frac{V^2 \; - \; V_c^{\,2}}{2\,a} \; + \; t_r V$$

where:

V = the vehicle's approach speed to the curve,
V_c = the maximum safe speed of the curve,
a = the assumed constant deceleration to reach the curve, not to exceed 50% of
    estimate deceleration achievable by the vehicle, given the road condition, and
t_r = driver reaction delay to the CSWS, assumed to be 1.5s.

9   SUMMARY AND CONCLUSION

Road departure crashes are caused by a wide range of factors. In this program, we have focused on technology that has the potential to prevent two classes of road departure crashes: those caused by driver inattention or relinquishing of steering control, and those caused by excessive speed when approaching a curve.

A Lane Drift Warning System (LDWS) is designed to warn drivers when they begin to unintentionally drift off the road due to inattention or relinquishing of steering control due to drowsiness, intoxication or some other impairment. In-vehicle tests and Monte Carlo simulations of a LDWS suggest that approximately 10% of road departure crashes in passenger vehicles and 30% of road departure crashes in heavy trucks could be prevented by a LDWS. These reductions would potentially result in 160,000 fewer crashes and 1500 fewer fatalities in passenger vehicles per year. In heavy trucks, a 30% reduction in ROR crashes would result in 9300 fewer crashes and 96 fewer fatalities.

A Curve Speed Warning System (CSWS) is designed to warn drivers when they are approaching a curve at too high a speed for the current conditions. In-vehicle tests and mathematical analysis of a CSWS suggest that approximately 11% of road departure crashes in passenger vehicles and 10% of road departure crashes in heavy trucks could be prevented by a CSWS. These reductions would potentially result in 176,000 fewer crashes and 1650 fewer fatalities in passenger vehicles per year. In heavy trucks, a 10% reduction in ROR crashes would result in 3100 fewer crashes and 32 fewer fatalities.

This document provides performance guidelines for how a LDWS and CSWS should operate in order to be effective and acceptable to drivers. As with all collision warning systems, the key to driver acceptance of these systems may not be when to warn the driver, but when not to warn the driver. Reducing false and nuisance alarms without significantly sacrificing the protection these systems provide is a challenge developers must face.

The technology to implement an acceptable LDWS appears to be available in the form of camera-based systems for sensing the position of the vehicle in the lane. Some of the technology necessary to implement a CSWS, such as accurate vehicle position estimation based on GPS, is readily available. Other key components, like accurate digital maps and upcoming pavement condition sensing, require further improvements before an acceptable and effective CSWS will be possible.

There are still open issues in the area of driver reaction to these collision warning systems. Preliminary tests suggest that drivers will react positively and appropriately to this technology, but more extensive in-vehicle testing with drivers are required to answer many of the open human factors questions.