SAE TECHNICAL
PAPER SERIES

960517

Dynamic Vehicle Simulation to Evaluate Countermeasure Systems for Run-Off-Road Crashes

D. B. Pape, V. K. Narendran, M. J. Koenig, J. A. Hadden, and J. H. Everson
Battelle

D. A. Pomerleau
Carnegie Mellon University

The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL

International Congress & Exposition
Detroit, Michigan
February 26-29, 1996

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (412)776-4841 Fax:(412)776-5760

The appearance of the ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition however, that the copier pay a $7.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191

Copyright 1996 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA

96-0049

960517

Dynamic Vehicle Simulation to Evaluate Countermeasure Systems for Run-Off-Road Crashes

D. B. Pape, V. K. Narendran, M. J. Koenig, J. A. Hadden, and J. H. Everson
Battelle

D. A. Pomerleau
Camegie Mellon University

ABSTRACT

An important part of ITS (Intelligent Transportation Systems, formerly IVHS) is the development of collision avoidance systems. These systems continuously sense the dynamic state of the vehicle and the roadway situation, and they assess the potential for a collision. When the system determines that an emergency situation might be developing, it warns the driver to take evasive action. Such countermeasure systems must be subjected to rigorous testing to ensure reasonable performance in all foreseeable circumstances and effectiveness in reducing the incidence of collisions. The efficiency and safety of testing can be greatly enhanced by using a dynamic simulation of a vehicle in near-collision situations and "equipping" the vehicle with a proposed collision avoidance system. This paper discusses the development and application of a time-domain simulation code based on a dynamic model of the driver/vehicle/counter-measure system. Parameter studies were performed to evaluate the effectiveness of candidate countermeasure systems. The results of the parameter studies indicated that vehicle-based countermeasure systems are viable schemes for reducing the number of run-off-road accidents, with greater effectiveness than shoulder rumble strips.

INTRODUCTION

The overall goal of ITS (Intelligent Transportation Systems) is to help more traffic flow more smoothly and safely. A key component of ITS is collision avoidance. Reducing the incidence of collisions minimizes the personal injury and property damage losses caused directly by collisions, and it has the secondary benefit of lessening congestion by maintaining the availability of the lane or highway otherwise blocked by collisions. The Office of Collision Avoidance Research at the National Highway Traffic Safety Administration (NHTSA) has identified several classes of crashes, which are being studied separately: run-off-road, lane change and merge, rear-end, and signalized intersections. The focus of this paper is collision avoidance systems for run-off-road (ROR) crashes, which are also referred to as single vehicle roadway departure (SVRD) crashes.

Run-off-road crashes represent the most serious crash problem within the national crash population.

Analysis of the 1992 NASS GES (National Accident Sampling System, General Estimates System) file indicated that approximately 1.21 million police-reported crashes of this type occurred in the US in that year [Calspan Corporation, 19941. This number represented 20 percent of all crashes in the GES database. More than 520,000 vehicle occupants were injured in run-off-road crashes in 1992, which is 27 percent of the injuries in the GES database. Moreover, the 14,031 fatalities sustained in run-off-road crashes (*FARS*, Fatal Accident Reporting System) represented 42 percent of the 33,846 in-vehicle fatalities that occurred in 1992 in the U.S. In terms of injury frequency and severity, run-off-road crashes are an extremely serious problem.

Figure 1 indicates the fraction of ROR crashes on both straight and curved roads caused by the six major factors: driver inattention (e.g., retrieving a fallen object), driver relinquished steering control (i.e., heart attack or intoxication), excessive vehicle speed, evasive maneuver, loss of directional control on road surface (i.e., slippery surface due to rain or snow), and vehicle failure (e.g., tire blowout or loss of power steering). The driver's ability and willingness to perform the required task play a role in the majority of run-off-road crashes.

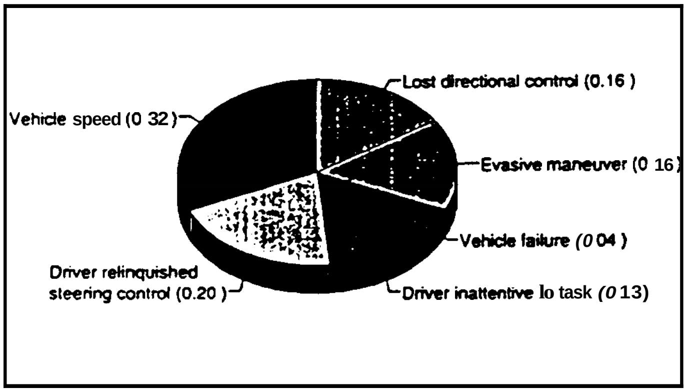

Figure 1: The primary causes of Run-Off-Road crashes fall into six major categories [Calspan Corporation, 1994]

The purpose of a collision countermeasure system is to increase the driver's awareness of the situation. For example, the conventional countermeasure system to inform drivers of an approaching curve is the familiar diamond-shaped yellow sign, which might be accompanied by a suggested safe speed for the curve. The ITS counterpart would also inform the driver of the presence of the curve, but it would recommend a safe speed based on the vehicle's own handling characteristics, the current surface conditions of the curve (the weather), and possibly even the driver's own skills and preferences. The ITS countermeasure would take the additional step of warning the driver when the vehicle is approaching the curve too fast for a comfortable deceleration to the safe curve entry speed. This is an example of a longitudinal countermeasure system, because it concerns acceleration along the vehicle's longitudinal axis.

Similarly, a lateral countermeasure system involves acceleration along the vehicle's lateral axis, and affects steering or lane-keeping. Drivers usually get information about their lane position by seeing road features such as the white and yellow stripes. An ITS countermeasure system would monitor the vehicle's position and heading within the lane. When it determines that the vehicle is in danger of departing the lane, it would warn the driver to pay more attention. Because a third of ROR crashes are due the driver's lack of vigilance toward the lane-keeping task, such a system could potentially save many lives.

Both lateral and longitudinal countermeasure systems for run-off-road crashes have been studied [Pape et al, 19951, but only the lateral countermeasure systems are discussed in this paper.

MODELING APPROACH

Vehicle dynamics and the requirements of countermeasure systems were analyzed by a time-domain simulation. The authors developed a package named RORSIM (Run-Off-Road SIMulation) to simulate a vehicle with a driver assisted by Run-Off-Road countermeasure systems. RORSIM is an enhancement to VDANL (Vehicle Dynamic Analysis, Non-Linear), which is a general-purpose rubber-tired vehicle simulation program [Allen et al 19921. VDANL provides the basic vehicle dynamics model for the simulation as well as the closed-loop driver model. Capabilities were added to VDANL to simulate some of the driver's actions (and inactions), model the performance of various proposed countermeasure systems, and provide representative roadways.

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 this, RORSIM is useful for demonstrating whether a countermeasure system can successfully prevent a run-off-road crash under the particular circumstances modeled.

The vehicle modeled in this study was a representative mid-size sedan. Selected important properties of the vehicle are listed in Table 1.

Table 1: Selected properties of the vehicle model used in this study

Total Mass	105.75	$lb\text{-}s^2/ft$
Sprung Mass	93.58	$lb\text{-}s^2/ft$
Front Trackwidth	5.125	ft
Wheelbase	8.83	ft
Distance from rear axle to center of gravity	5.82	ft
Height of the center of gravity above ground	1.94	ft

The basis of the driver model is a closed-loop steering control. Features were provided to model a human's tolerance of small errors, periods of inattention, and finite reaction times. As in the example of Carson and Wierwille [19781, adjustable thresholds were provided for errors in lane position and curvature error. Potential roadway departure situations were established by simulating a brief period of driver inattention to the driving task. Inattention was modeled by holding the driver's controls constant, independent of the vehicle's state.

DESCRIPTION OF THE COUNTERMEASURE SYSTEMS

Several countermeasure systems were modeled in RORSIM. Three systems designed to help the driver with lateral control (steering) are described in this paper.

The countermeasure systems have three basic components: (1) one or more sensors, (2) a decision making algorithm, and (3) an interface to the driver or vehicle. The sensor of each Countermeasure system is modeled explicitly in RORSIM. The program calculates what the output of the sensor would be, given the current dynamic state of the vehicle, the characteristics of the environment, and the properties of the sensor itself. The output of the sensor is then processed by a separate decision-making module, which performs whatever calculations or logic is specified by the system. When necessary, it will alert the driver to a potentially dangerous situation.

The first lateral countermeasure system uses a forward-looking vision sensor and a decision-making algorithm called Time to Trajectory Divergence (TTD)[Pomerleau et al, 1995]. This system notes the road position at a fixed distance ahead of the vehicle, calculates a trajectory to steer the vehicle to that position, and determines whether the driver's actual trajectory deviates significantly from the system's desired trajectory.

The geometry of the TTD algorithm is shown in Figure 2. The vehicle may be offset and rotated from the lane centerline. The sensor, as implemented in RORSIM, looks at distance L ahead of the vehicle. The sensor measures the perpendicular distance F from the vehicle's longitudinal axis to the lane center point. The processing algorithm calculates the "optimum" path to drive the vehicle through the lane center point identified by the sensor. That is, it calculates the radius of the arc, R_c, which is tangent to the vehicle's longitudinal axis and passes through the aim point. The radius of the countermeasure's desired arc is approximated by

$$R_c \approx \frac{L^2}{2F} \qquad (1)$$

The system also calculates the radius R_p of the vehicle's current curvature by measuring the yaw rate and forward speed of the vehicle V. The system then projects the time that will be required for the actual arc to diverge from the "optimum" arc by a predetermined distance D. This time is the time to Trajectory Divergence" or TTD. The formula for TTD is

$$TTD = \frac{\sqrt{\dfrac{2D}{\dfrac{1}{R_c} - \dfrac{1}{R_p}}}}{V} \qquad (2)$$

If the TTD value falls below a predetermined threshold, the system warns the driver.

The second lateral countermeasure system considered uses a downward- or sideways-looking vision system and a decision-making algorithm called Time to Line Crossing (TLC). The system measures the distance to the edge line of the vehicle's lane and projects how soon the vehicle will cross the line, assuming the vehicle continues its present curvature. The concept of TLC dates at least as far back as the early 1980's [Godthelp et al, 1984].

In RORSIM the sensor for the TLC system measures the distance from the vehicle's right front tire to the right edge of the lane. The distance from the left front tire to the left edge is calculated from the front track width of the vehicle and an assumed lane width.

The algorithm for calculating TLC is depicted in Figure 3. The arc in the figure is the tire's projected trajectory, if its current radius of curvature remains constant. The time before the tire crosses the line is the ratio of the arc length to the speed along the arc:

$$TLC = R\theta / V \qquad (3)$$

where

R = the current radius of curvature

θ = the angle swept by the radius before departure

V = the longitudinal speed of the vehicle.

The only measurement required is the distance d between the tire and the line. From this measurement (and its first two derivatives), the length of the arc can be calculated.

$$\theta = \cos^{-1}\left(\cos\gamma - \frac{d}{R}\right) - \gamma \quad \gamma = \frac{\dot{d}}{V} \quad R = \frac{V}{\dot{\gamma}} \qquad (4)$$

The algorithm implemented within RORSIM accounts for the fact that the vehicle may depart the lane to the left or right and its current curvature may be toward or away from the approached edge.

As a basis for comparison, an existing rumble strip system was modeled. The Sonic Nap Alert Pattern (SNAP) was developed and implemented by the Pennsylvania Turnpike Commission [Wood, 1994]. It consists of a series of grooves cut into the shoulder of the turnpike, about 3 inches outside the white edge line. If an inattentive (or napping) driver drifts outside the lane, the grooves make a loud (80 dB in a sedan at 60 mph) sound, which quickly restores the driver's attention. SNAP was initially deployed in 31 miles of roadway where the incidence of ROR crashes was relatively high—0.51 per month. During a trial period, the ROR crash rate was only 0.16 per month. Comments from drivers have been favorable, and the pattern is being deployed along the entire turnpike. Other states and authorities also are adopting variations of the idea.

SIMULATION EXAMPLE

The simulation scenario consists of a vehicle beginning to traverse a road segment at a specified velocity, following the path of a normal, attentive driver. The driver becomes inattentive at the predetermined moment and eventually begins to head towards the edge of the lane. The countermeasure system warns the driver, who, after a predetermined reaction time, resumes steering control and tries to bring the vehicle back to its proper position in the lane.

Figure 4 shows the trajectory of the vehicle controlled by the driver model as it travels at 88 fps (60 mph) on a straight, crowned road. The paths of the vehicle center as well as the left front and right front tires are shown. The vehicle does not follow a perfectly straight line but meanders or wanders somewhat, to mimic the behavior of a human driver. A roadway departure trajectory can be generated by

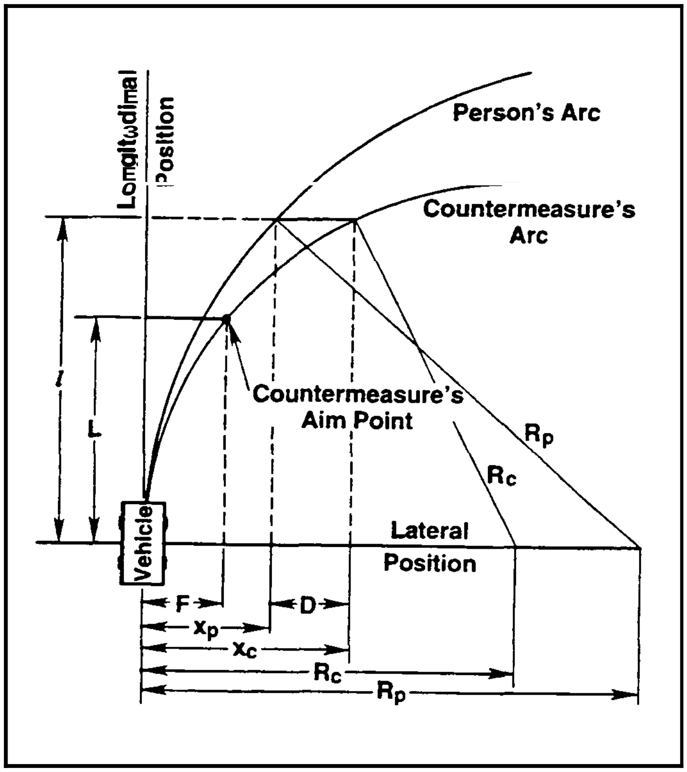

Figure 2: Method for calculating the time to trajectory divergence (TTD)

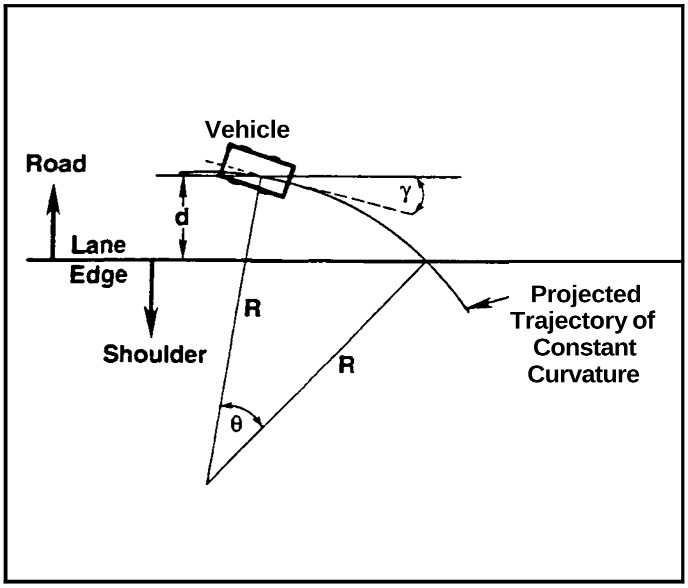

Figure 3: Method for calculating time to line crossing (TLC)

causing the driver to become inattentive to steering at a chosen point along the path.

As an example of countermeasure system performance, Figure 5 shows the path of the vehicle center of gravity for the normal case and one crash recovery case. The heavy lines in the figure indicate the paths of the center of gravity and the right front tire when a departure-bound driver is warned by a countermeasure system and then resumes steering control.

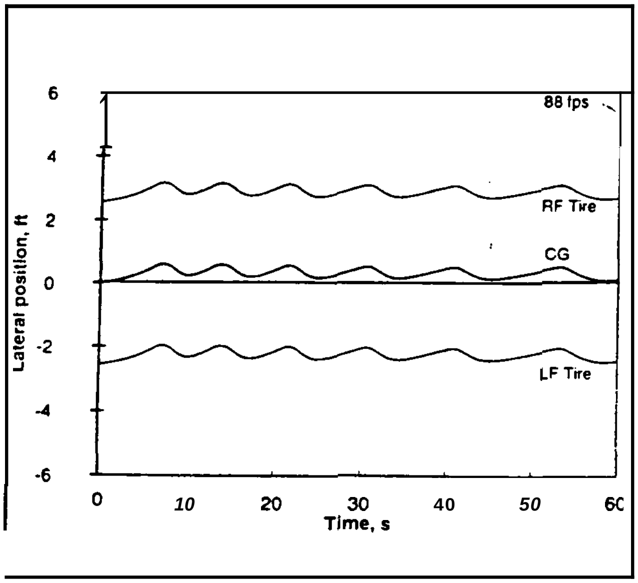

Figure 4: Path followed by a normal, alert driver on a straight, crowned road, in the **RORSIM** computer simulation

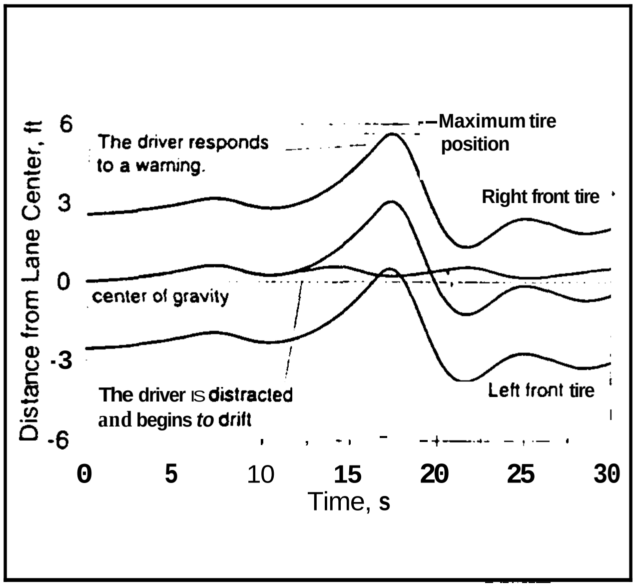

Figure 5: Path followed by a vehicle when its driver begins to drift off the road and recovers after being warned by a countermeasure system. (The thin line is the path of the center of gravity for an alert driver, as in Figure 4.)

The maximum front tire deviation (either to the left or to the right) is the basis for judging the success of a simulation. The maximum tolerable lane violation, of course, depends strongly on the situation (i.e., whether there is a wide, paved shoulder, a guardrail, roadside obstructions, oncoming traffic, etc.). If the maximum fiont tire position in a simulation **is 6.5 ft** and the lane halfwidth is **6 ft,** success is qualified. However, in many cases, this outcome **is** more desirable than a simulation where an unwamed, inattentive driver led the tire to 10 or more ft fiom the lane center.

RESULTS

The value of a countermeasure system is judged by its effectiveness in reducing the rate of run-off-road crashes. The potential effectiveness of the two proposed countermeasure systems was estimated by comparing their performance to that of an existing countermeasure system.

The analysis was carried out by simulating a variety of potential runsff-road scenarios. **As** indicated in Table **2,** there was a range **of** speeds **on** a 1000-ft-radius curve and a single speed (88 fps or **60** mph) **on** road segments of different curvature. The test suite comprised four crash-bound trajectories for each case identified in Table **2.** On each curved segment, the driver moved two feet toward the inside of the curve to simulate typical “curve cutting” behavior.

The warning thresholds for the TTD and TLC functions were selected after simulating representative scenarios with pre-selected periods of driver inattention. The goal **is** to set the warning thresholds high enough to **minimize** the number of crashes but not so high that false alarms become a nuisance. In the simulations reported below, the warning thresholds were set to avoid false alarms during ''**normal**"driving, **as** determined by the **RORSIM** driver model and a human driver in an instrumented vehicle **on** a fieeway. The driver reaction time was set at **0.82** s, which **is** the approximate median value for healthy adults [Malaterre and Lecher, ***19901.***

Table 2: Cases used to study the performance of the lateral countermeasure systems

Road Parameters		Vehicle Speeds		
Curvature	**Superelevation**	**44 fps**	**66 fps**	**88 fps**
Straight road	2.08% (crown)			X
4000 ft curve	4.0%			X
1000 ft curve	4.0%	X	X	X
800 ft curve	*9.5%*			X

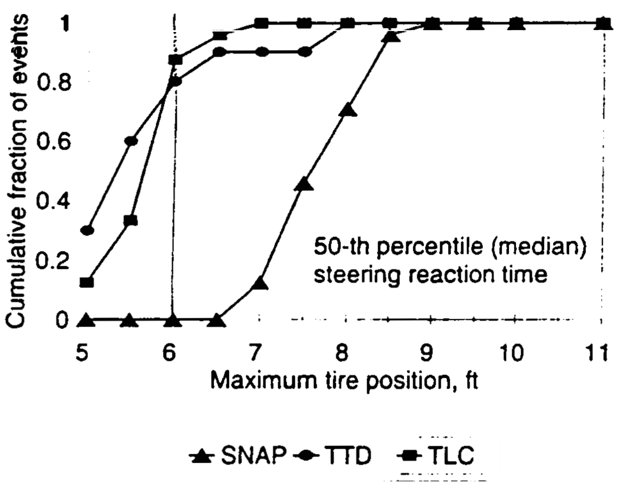

Figure 6: Cumulative distribution of maximum tire position for drivers **warned** by the three countermeasure systems, over the test suite of potential run-off-road crash **scenarios**

The overall effectiveness of a system is indicated by the distribution of maximum *tire* positions in the **situations** in which the **system was** simulated. Figure *6* shows that the sensor-based systems are potentially more effective than **SNAP** because they keep vehicles, on average, closer to the travel **lane** than **SNAP.** Since the lane marker **is** *6* ft from **the lane** center, and the **SNAP** grooves are outside the lane marker, the driver is not wamed until a lane departure **has** occurred. Therefore, none of the **SNAP** simulations had a recovery within *6* ft. In all of the simulations, drivers alerted by **SNAP** kept both fiont tires within ***9* ft** of the lane center **(3** ft **of** the lane edge). Drivers assisted by TTD recovered and kept the **tire** 1 ft inside the edge line in **30** percent of the cases. More than **75** percent of the drivers assisted by TTD were able to keep both fiont tires within the 12-ft lane. Since the TTD and TLC curves are well above the SNAP curve across the figure, the TTD and TLC algorithms are potentially considerably more effective than SNAP in preventing run-off-road crashes.

CONCLUSIONS

Analytical studies were performed to compare the performance of two proposed lateral Countermeasure systems to shoulder rumble **strips,** a passive countermeasure system that **has** been proven to be quite effective in actual use.

Shoulder rumble strips contributed to a significant reduction in run-off-road crashes during a test period. These strips, which are cut into the shoulder a few inches outside the edge line, provide an audible and compelling notice to the driver that a lane departure **has** occurred. Electronic Countermeasures, with the potential to warn a driver **before** a lane departure occurs, offer yet greater ability to help the driver with the lane-keeping task. This feature is especially important on narrow rural highways. On **a** two-lane road with little or no shoulder and a truck in the oncoming lane, the consequences of even a small lane departure are particularly adverse.

However, this benefit may be offset by the difference in availability between SNAP and the electronic countermeasures. Once deployed, SNAP is always functional; it applies to nearly all vehicles, and the grooves make their noise even when filled with ice or snow. The performance of the electronic countermeasures is subject to degradation by environmental conditions, adverse sun angle, or other factors. Work currently in progress is showing that these issues can be addressed.

ACKNOWLEDGMENT

This work was funded by the Office of Collision Avoidance Research, National Highway Traffic Safety Administration as part of Contract DTNH22-93-C-07023.

REFERENCES

Allen, R.W., et al, (1975) “Alcohol effects on driving behavior and performance in a car simulator.” IEEE Transactions on Systems, Man, and Cybernetics Vol SMC-5.

Camegie Mellon University and Calspan Corporation, “Run-off-road collision avoidance using IVHS countermeasures: Task 1 report.” (Contract No. DTNH22-93-C-07023). Pittsburgh, PA: Carnegie-Mellon University Robotics Institute.

Carson, J. M. **and** Wierwille, W.W., (1978) “Development of a strategy model of the driver in lane keeping,” Vehicle System Dynamics, Volume 7, Number **4,** International Journal of Vehicle Mechanics and Mobility.

Godthelp, H., Milgram, P., and Blaauw, G., (1984) “The Development of a time-related measure to describe driving strategy.” Human Factors Vol 26, No 3, pp 257-268.

Malaterre, G., & Lecher, D., (1990) “Emergency maneuver at junctions using a driving simulator.” Transportation and Traffic Theory: Proceedings of the 11th International Symposium on Transportation & Traffic Theory, pp 213-232.

Pape, D., Narendran, V., Hadden, J., Everson, J, Koenig, M., and Pomerleau, D., (1995), “Run-off-road collision avoidance using **IVHS** countermeasures: Task 3--Volume I.” (Contract No. DTNH22-93-C-07023). Pittsburgh, PA: Camegie-Mellon University Robotics Institute.

Pomerleau, D., Kumar, B., Everson, **J.**, Kopala, E., & Lazofson, **L.** (1995, August). “Run-off-road collision avoidance using IVHS countermeasures: Task 3 report - Volume 1.” (Contract No. DTNH22-93-C-07023). Pittsburgh, PA: Carnegie-Mellon University Robotics Institute.

Wood, N.E., (1994), January “Shoulder rumble strips: a method to alert ‘drifting’ drivers.” Transportation Research Board 73rd Annual Meeting. Paper No. 94-0312.