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MODELING AND ANALYSIS OF DRIVER/VEHICLE DYNAMICS WITH "RUN-OFF-ROAD" CRASH AVOIDANCE SYSTEMS

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ABSTRACT

An analytical study was performed to assess the safety-related performance of a class of vehicle crash avoidance (CA) systems. The simulation software package RORSIM was developed and used to predict the dynamic behavior of a driver in a vehicle equipped with a CA system under Run-Off-Road (ROR) accident conditions. Simulation studies were performed to characterize the conflicting performance requirements for a CA system, i.e., that it warns of every incipient ROR event with a minimal false alarm rate. The results indicate that 1) CA systems are viable for preventing ROR accidents; 2) ROR warning criteria depend on parameters such as speed, roadway curvature, shoulder width and driver reaction time; and 3) RORSIM is an effective analytical tool for evaluating the safety-related dynamic performance of vehicles equipped with CA systems under a wide range of driving and road conditions.

INTRODUCTION

Single Vehicle Roadway Departures – also known as Run-Off-Road (ROR) events - are one of the most serious safety problems on U.S. highways. In 1992, there were about 1.2 million reported ROR events in the U.S., which accounted for 20 percent of all crashes, 27 percent of all crash-related injuries and 42 percent of all crash-related fatalities [1][1]. The principal causal factors for ROR events are excessive vehicle speed, driver incapacitation, loss of directional control on the road surface, evasive maneuvers, and driver inattention.

A significant amount of research in the United States has focused on the development of in-vehicle crash avoidance (CA) systems for preventing accidents such as ROR crashes [2]. These systems can potentially reduce the frequency and severity of highway accidents by providing an early warning to the driver of an unsafe condition. Several prototype systems exist and have been demonstrated to provide early warnings under certain conditions. Examples in the U.S. include the RALPH system developed at Carnegie Mellon University [3] and the CAPC system developed at the University of Michigan Transportation Research Institute (UMTRI) [4].

As part of a U.S. DOT-funded research program to develop performance specifications for CA systems, an analytical study was undertaken to investigate key driver, vehicle, and CA system characteristics that influence the ability to effectively warn of an incipient ROR event [5]. A major focus of this study was the development of the computer simulation tool RORSIM (Run-Off-Road SIMulation), which predicts the dynamic behavior of a vehicle equipped with a CA system under

[1] Numbers in brackets designate references listed at the end of this **paper.**

ROR accident conditions. Subsequent sections of this paper describe the modeling approach, the statistical design of the parameter studies, and the results of simulations.

MODELING APPROACH

A schematic illustrating the software package RORSIM is shown in Figure 1. RORSIM is a menu-driven time-domain simulation program based on dynamic models of three basic components: the vehicle/driver system, the roadway, the CA system.

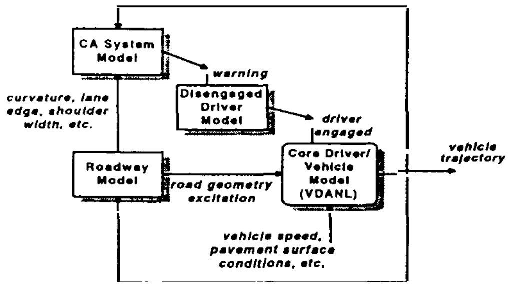


Figure 1. Schematic of program RORSIM

The framework for the *vehicle/driver component* is the commercial code VDANL (Vehicle Dynamic Analysis, Non-Linear), a dynamic simulation code based on a seventeen degree-of-freedom model of a rubber-tired vehicle. VDANL was developed for NHTSA by Systems Technology, Inc. [6]. VDANL was selected as the Vehicle/Driver Module because 1) it has been validated against experimental data, 2) it has a database of parameters representing many vehicles, **3)** it runs quickly on a desktop computer, and **4)** it can be augmented easily with other simulation modules. We modeled a mid-size American-made sedan for our simulation studies. We expanded the features of VDANL to allow realistic driver weaving behavior and delayed response to steering, braking and throttle commands. We also added the ability of the driver to have different response characteristics before and after being warned by the **CA** system (e.g., an inattentive driver may be startled by the warning, resulting in more "panicky" driving characteristics).

The *roadway component* can be configured to represent virtually any set of road design characteristics (width, superelevation, crowns, curvature, etc.). For the purposes of this study, the roadway was modeled as a straight road segment, followed by a spiral segment leading to a constant radius curve, an exit spiral and, finally, another straight roadway segment. Shoulder characteristics (width, friction, rolling resistance, etc.) also were modeled in detail.

The **CA** *system component* represents the dynamics of the sensor system, signal conditioning and decision algorithm for operating on the sensor signals and issuing a warning. Several types of CA system models were developed. These included longitudinal position-based (curve warning) systems, and lateral position-based systems. The subject of this paper is a lateral position-based system based on a Time-to-Line Crossing (TLC) algorithm [7].

TLC is a estimate of the time remaining before the driver leaves the lane. The TLC method involves using data on the position and velocity of the vehicle and the roadway geometry to continuously estimate the remaining time until the vehicle crosses the lane edge. For example, TLC > 0 whenever the vehicle is in the roadway lane. If the vehicle is travelling perfectly parallel to the lane edge, then TLC $\rightarrow \infty$. If a front tire of the vehicle is touching the lane edge, then TLC $= 0$. If the vehicle is across the lane edge (e.g., on the shoulder), then TLC < 0.

A critical issue associated with CA system performance is where to set a threshold level of TLC for issuance of a warning. An excessively large value will always warn of an incipient ROR event, but also will issue warnings for potential non-ROR events (i.e., false alarms). Conversely, an excessively small threshold value of TLC would minimize false alarms but would provide insufficient time for the driver to maneuver to avoid an ROR event.

For the purposes of this study, RORSIM was used to evaluate the following sequence of events:

- A driver is "meandering" down a road (i.e., following the road in a normal manner with some weaving).
- At some point, the driver becomes disengaged (e.g., inattentive or unconscious) from his driving task (the steering, throttle and braking commands to the vehicle remain fixed during this period of disengagement).
- The vehicle approaches the edge of the road, and at some point a warning is issued to the driver.
- After some delay associated with the driver's reaction time, the driver is re-engaged (e.g., regains attentiveness or awakens), and resumes control of the vehicle with some change in his response characteristics (his reaction may be either faster or slower than before he became inattentive).
- The path of the vehicle is monitored, based on which the performance of the CA system is judged (e.g., ROR was prevented, a false alarm was issued, a ROR was not prevented).

PARAMETER STUDIES

The following methodology was used to conduct the parameter studies:

1. *A set of driving scenarios was developed:*
   - Thirteen key parameters were selected for evaluation of their influence on CA System performance. These were:
     - Roadway curvature
     - Lane width
     - Road friction
     - Shoulder friction
     - Shoulder rolling resistance
     - Vehicle speed
     - CA system accuracy
     - Driver lane-keeping performance
     - Driver reaction time
     - Driver aggressiveness of response
     - Initial time of driver inattentiveness
     - Duration of driver inattentiveness
     - TLC threshold
   - Realistic ranges and distribution functions were established for each parameter, based reviews of available data.
   - A baseline set of 591 driving scenarios (each about 30-seconds long) was developed using Latin hypercube sampling [8], with each scenario described by a unique combination of the key parameter values.

2. *The driving scenarios were simulated with RORSIM for three situations:*
   - Normal driving scenarios without a CA system for typical, attentive driving characteristics – this was done to verify that each scenario represents a realistic driving event.
   - ROR scenarios without a CA system – these were created by degrading the driving behavior for each of the normal driving scenarios. For each scenario, the driver was disengaged from the driving task at a randomly selected time, and remained inattentive for a randomly selected period (up to 12 seconds).
   - ROR scenarios with an active CA system – For each scenario, the CA system issued a warning if it calculated that the value of TLC fell below the prescribed threshold value. The disengaged driver then would become re-engaged, and would resume his driving task after some delay with a steering behavior that may be more sluggish or more aggressive (depending on the driver type) than that before he became inattentive.

3. *The simulation results were parsed/analyzed and interpreted statistically:*
   - The effectiveness of the **CA** system was evaluated based on the percentage of ROR events that were prevented and the warning false alarm rate.

RESULTS

Ability of CA System to Limit Vehicle Excursions

The ability of the in-vehicle CA system to limit vehicle excursions in incipient **ROR** situations is apparent in Figure 2. Cumulative frequency distributions of maximum vehicle lateral excursion *are* plotted for **ROR** scenarios without the CA system and with the CA system set at different TLC warning thresholds. These results are shown for a lane width of 12 ft (3.7m); thus, a vehicle would cross the lane edge and enter the shoulder area at a lateral excursion of 6 ft (1.8m). The percentage of cases below a given value of lateral excursion can increase dramatically with increasing TLC

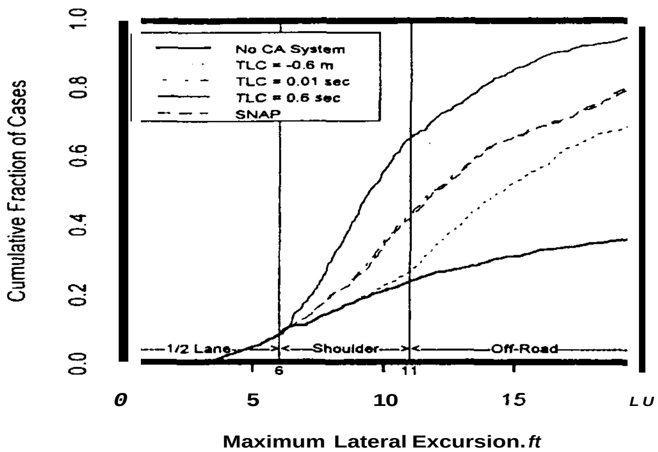


Figure 2. Cumulative frequency distributions of maximum lateral excursions of vehicles with and without a CA system.

warning).

The curve labeled "SNAP" in Figure 2 represents a roadway that has "rumble strips" placed in the shoulder area in a manner similar to the Sonic Nap Alert Pattern used by the Pennsylvania Turnpike Commission. SNAP is a valuable benchmark for evaluating the

because highway accident statistics have shown a significant reduction in **ROR** accidents on those highways where SNAP **was** installed [9]. Figure 2 indicates that the CA system with a TLC threshold of about 0.01 s is roughly equivalent in performance to SNAP. With higher values of TLC threshold, the **CA** system is potentially more effective in preventing **ROR** events than SNAP.

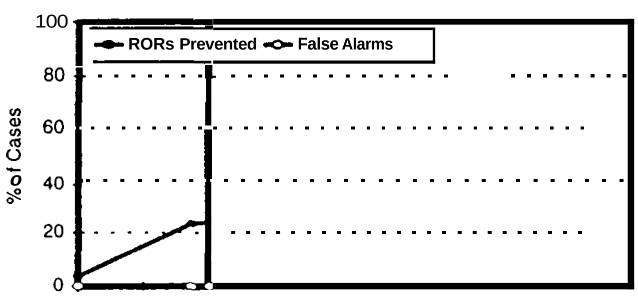


Figure 3. CA system effectiveness on straight and curved roads (5-ft shoulders).

would be given so early that a **ROR** event would not even have begun to develop yet. This trend is indicated in Figure **3,** where the percentages of **ROR** events prevented and false alarms are plotted **as** a function of TLC threshold for all types **of** roads with a shoulder width of 5ft (1.52m). As shown in the

0.6 s, but the false alarm rate increases rapidly for TLC thresholds above this value. For example, at a TLC threshold of 0.6 s, only about 55 percent of ROR cases were prevented, but no false alarms issued. In contrast, for a TLC threshold of 1.8 s, about 90 percent of all ROR events were prevented, but false alarms occurred in nearly 60 percent of the cases.

A critical challenge in the development of an effective CA system is to optimize the warning criteria based on this trade-off between preventing accidents and minimizing false alarms. An interesting issue is whether a low false alarm rate is more beneficial to the driver than no false alarms. **A** warning that occasionally sounds in “near ROR’ situations (e.g., when a driver momentarily strays too close to the lane boundary) – say, at a rate of about once per month – might be effective in reminding the driver of the presence of the CA system and the characteristics of its warning. This is an important human factors issue that could be addressed via a well-designed experimental program.

Influence of Roadway Characteristics

Two aspects of the roadway that have a significant influence on CA system performance are the horizontal curvature and the shoulder width. The results shown in Figure ***3*** are separated into straight road cases only in Figure 4, and curved road cases only in Figure 5. The curved roads that were simulated had curvatures of 250 ft, 500 ft, 1000 ft, and 2000 ft (76 m, 152 m, *305* m and 610 m) in both directions. From the standpoint of preventing ROR events, the CA system requires a higher TLC threshold on curved roads than on straight roads. For example, to prevent 90 percent of ROR events, a TLC threshold of at least 0.9 s would be required on straight roads, while a value of at least 1.8 ***s*** would be required on curved roads. **A** higher TLC threshold (and hence an earlier warning) is required to prevent ROR events on curves, because after the driver relinquishes control on a curve, the vehicle very quickly reaches a “point of no return” from which recovery is impossible.

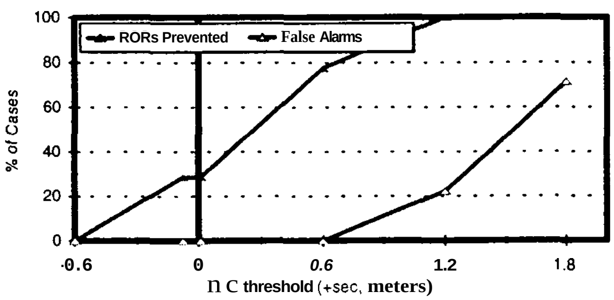


Figure 4. CA system effectiveness on straight roads (5-ft shoulders).

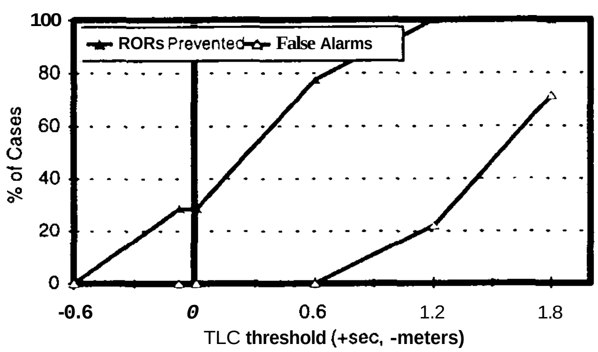


Figure *5*. CA system effectiveness on curved roads (250 ft – 2000 ft radii and 5-ft shoulders).

The availability of a shoulder for executing a recovery maneuver influences strongly the performance of the CA system. This is illustrated in Figure 6, in which the percentage of ROR events prevented is plotted as a function a TLC threshold for three values of shoulder width. For a given value of TLC threshold, the percentage of ROR events increases significantly with increasing shoulder width. For example, about 90 percent of ROR events were prevented in simulations with a TLC threshold of 0.6 s when there was a 13-ft (3.96 m) shoulder available (a typical shoulder width on U.S. interstate highways). However, the same 0.6 s TLC threshold prevented only about *55* percent of the ROR events on roads with only a *5* ft (1.52 m) shoulder was available, and prevented almost no ROR events on roads where there was no available shoulder. These results suggest that, as simulated here, the CA system is more effective when a shoulder is available for the driver to maneuver to safely avoid a ROR event.

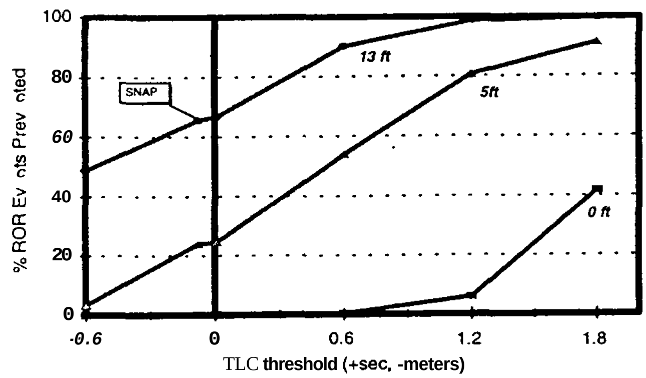
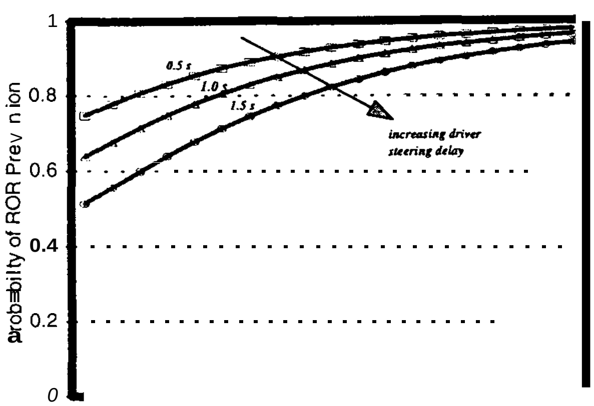


Figure 6. Influence of TLC threshold on CA system effectiveness for three values of shoulder width (straight and curved roads).

These results also suggest that to provide maximum performance, it may be necessary to continuously adjust the warning criteria on a CA system as the vehicle encounters different roadway alignments and shoulder characteristics. Current efforts in our research program include the development of a statistical methodology that will enable us to determine TLC thresholds for maximum CA system performance. Further, conditions that require relatively high TLC threshold settings may result in high false alarm rates. Because false alarm rates can be annoying and can reduce the driver's sensitivity to the alarm, it is important that CA systems are designed to distinguish incipient ROR events from non-ROR events with good reliability.

Influence of Driver Behavior

The ability to maneuver safely to avoid a ROR event depends strongly on the driver characteristics, which in turn vary widely among the driving population. A CA system must perform effectively over this wide range of driver characteristics. The simulation studies included variances in the driver normal weaving behavior, steering reaction (delay) time and aggressiveness of steering response to a warning.



Statistical (logistic regression) models were developed using the simulation results to more clearly identify the influence of these parameters on the probabilities of preventing a ROR event and of a false alarm. The influence of TLC threshold on the probability of preventing a ROR event is shown in Figure 7 for several values of steering reaction time on with 5-ft (1.52m) shoulders. As expected, the probability of preventing a ROR event decreases with

react or directional control of the vehicle [illegible] not lost (e.g., spin outs, skidding). [illegible] indicated [illegible]
Figure 8, we did not have a driver over-reaction or loss of vehicle control situation under the

conditions simulated in these studies. Further studies are being conducted to identify driver behaviors that result in loss of control. The increase in probability of a false alarm increases with increased driver weaving behavior, as shown in Figure 9. This result also is expected, as minimum TLC will decrease with increasing amplitude of weaving. The results shown in Figures 7-9 driver. tend to support an argument for avariable TLC threshold that is tailored to characteristics of the individual

SUMMARY/CONCLUSIONS AND ONGOING RESEARCH

The results of this study provide insight into the factors affecting the safety-related performance of a **CA** system for preventing ROR events. **A** major challenge in the development ***of*** an effective **CA** system is to mitigate the fundamental conflict between the need for a sufficiently long warning time for a driver to safely maneuver to avoid an accident and the need for a sufficiently short warning time to avoid excessive false alarms. The simulation results indicate that for maximum effectiveness, a **CA** system may need an adaptive TLC threshold that is dynamically adjusted for maximum effectiveness over the wide ranges of driver characteristics, roadway designs and driving scenarios.

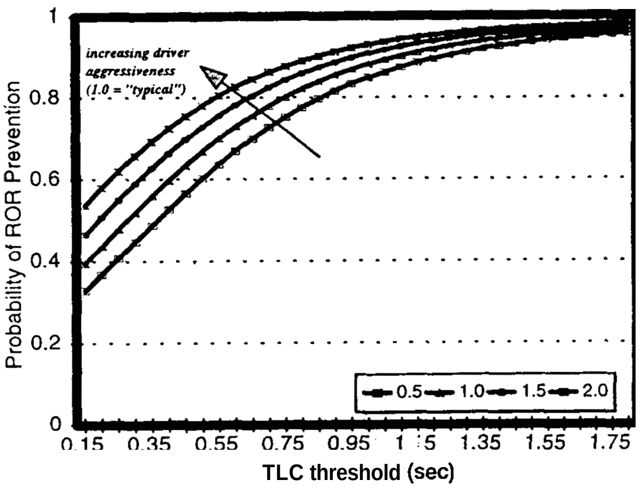


Figure 8. Influence of driver's aggressiveness of steering response on CA system false alarm rate.

The results indicate that ROR accident. Further, RORSIM has been demonstrated to be a valuable analytical tool in-vehicle **CA** systems are potentially effective in providing drivers with an early warning of an incipient for evaluating the performance of **CA** systems for a wide range of driver behaviors, vehicle types, and operating/environmental conditions.

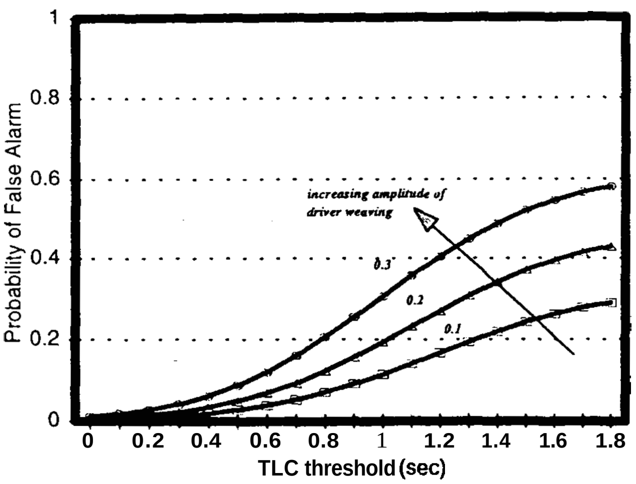


Figure 9. Influence of driver's weaving behavior on CA system effectiveness.

The study was limited in the sense that only one vehicle type was used, and more extreme conditions (e.g., solid ice surfaces and highly-excessive speeds) were not considered. Further, the study was limited to steering maneuvers only; combined braking/steering and throttle/steering actions were not addressed. These and other issues are currently being addressed in the final phase of our research program.

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REFERENCES

1. Carnegie Mellon University and Calspan Corporation, "Run-Off-Road Collision Avoidance Using IVHS Countermeasures: Task 1 Report," Report to DOT/NHTSA, Contract No. DTNH22-93-C-07023, August 31, 1994.

2. Burgett, August, "DOT's Approach to ITS Safety Evaluations," paper presented at the ITS America Workshop on ITS Safety Evaluations, May 1, 1995.

3. Pomerleau, D., and Jochem, T., "Rapidly Adapting Machine Vision for Automated Vehicle Steering", *ZEEE **Expert,*** Vol. 11, No. 2, 1996, pp. 19-27. (Also available as **http://www.cs.cmu.edu/-pomerlea).**

4. Ervin, R.D., editor, "The Crewman's Associate for Path Control (CAPC)", Report NO, UMTRI-95-35 to the **U.S.** Army/TACOM, Contract DAAe07-93-C-R124, University of Michigan Transportation Research Institute, 1995.

5. Carnegie Mellon University and Battelle Memorial Institute, "Run-Off-Road Collision Avoidance Using IVHS Countermeasures - Task 6 Supplemental Report: Computer Simulation Studies of Countermeasure System Effectiveness," Report to DOT/NHTSA, Contract No. DTNH22-93-C-07023, November 19, 1996.

6. Allen, R.W., Szostak, H.T., Klyde, D.H., Rosenthal, T.J. and Ownes, K.J., "Vehicle Dynamic Stability and Rollover," Report to DOT/NHTSA, Contract No. DTNH22-88-C-07385, 1982.

7. Pape, D.B., Narendran, V.K., Koenig, M.J., Hadden, J.A., and Everson, J.H., and Pomerleau, D., "Dynamic Vehicle Simulation to Evaluate Countermeasure Systems for Run-Off-Road Crashes," SAE Paper No. 9605 17, 1996.

8. Stein, M.I., "Large Sample Properties of Simulations Using Latin Hypercube Sampling," ***Technometrics,*** Vol. 29, No. 2, pp. 143-151, 1987.

9. Hickey, J.J., "Shoulder Rumble Strip Effectiveness: Drift-Off-Road Accident Reductions on the Pennsylvania Turnpike," TRB Paper No. 970624, presented at the 76th Annual Meeting of the Transportation Research Board, January 12-16, 1997.