Differential Braking for Limited-Authority Lateral Maneuvering

IDEA Program Final Report

for the Period September, 1997 Through August, 1998

Contract No. ITS-57

Report No. UMTRI-98-43

Prepared for the IDEA Program
Transportation Research Board
National Research Council

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September 1998

Technical Report Documentation Page

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Differential Braking for Limited-Authority Lateral Maneuvering

5. Report Date
September 15, 1998

6. Performing Organization Code
0 36/27

7. Author(s)
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8. Performing Organization Report No.
UMTRI-98-43

9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Road, Ann Arbor, Michigan 48109

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
ITS-57

12. Sponsoring Agency Name and Address
National Academy of Sciences
Transportation Research Board
National Research Council
2101 Constitution Ave., NW. / Washington, D.C. 20418

13. Type of Report and Period Covered
Final
9/1/97 - 8/31/98

14. Sponsoring Agency Code

15. Supplementary Notes
IDEA Program Officer: Mr. Keith Gates

16. Abstract

Active safety systems for preventing roadway departure accidents have been under increasing study in recent years. This IDEA project designed a differential (side-to-side) braking system for limited authority lateral maneuvering that can support active ITS vehicle control systems aimed at preventing unintended road departure events. The basic idea is to re-direct a vehicle's departure from the roadway through intelligently applied differential (left and right-side) braking. That is, the vehicle is *steered* left or right by means of *braking forces* appropriately applied to either side of the vehicle by a control algorithm. By utilizing braking to steer the vehicle, the traditional control channel used by drivers to steer the vehicle — the steering system — is not interfered with or modified using this approach.

The work under this project has concentrated on development of the control algorithm aspects within such a system using computer simulation to demonstrate the effectiveness of the concept under different operating conditions (speeds and surface friction). Initial vehicle track tests supported the analysis by providing estimates of how a representative vehicle would respond to differential braking at various speeds and application pressures. In general, the findings indicate that the control algorithm developed under this IDEA project is shown to be effective in controlling a representative passenger car by means of the differential braking mechanism intended for prevention and mitigation of unintended road-departure events. The algorithm is observed to adapt to a wide range of operating conditions and roadway-departure scenarios.

17. Key Words
road departure, control system, differential braking, intelligent vehicle system, brake-steer, simulation, algorithm, safety, accidents

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)
None

20. Security Classif. (of this page)
None

21. No. of Pages
90

22. Price

ACKNOWLEDGEMENTS

The authors wish to acknowledge the helpful discussions and commentary provided by the members of the expert advisory panel that included: Mike Shulman (Ford Motor), Paul Zoratti (ERIM International / Visteon Automotive), Jim Sayer (UMTRI), Jeff Woods (NHTSA), Keith Gates (TRB/NRC), and Eric Anderson (ERIM International). Thanks also to Mike Campbell at UMTRI for his assistance in collecting test track data. The authors also acknowledge the helpful assistance of Keith Gates at TRB/NRC in facilitating project requirements and administrative issues throughout the course of the project work.

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EXECUTIVE SUMMARY

Concept and Product

Active safety systems for preventing roadway departure accidents have been under increasing study in recent years. This IDEA project designed a differential (side-to-side) braking system for limited authority lateral maneuvering that can support active ITS vehicle control systems aimed at preventing unintended road departure events. The basic concept is described in Figure 1 where a vehicle's departure from the roadway is interrupted and the vehicle then re-directed, *through intelligently applied differential (left and right-side) braking*, back on to the roadway or shoulder area. That is, the vehicle is steered left or right by means of braking forces appropriately applied to either side of the vehicle by a control algorithm. By utilizing braking to steer the vehicle, the traditional control channel used by drivers to steer the vehicle — the steering system — is not interfered with or modified using this approach.

The work under this project has concentrated on development of the control algorithm aspects within such a system using computer simulation to demonstrate the effectiveness of the concept under different operating conditions (speeds and surface friction). Initial vehicle track tests supported the analysis by providing estimates of how a representative vehicle would respond to differential braking at various speeds and application pressures. In general, the findings indicate that the control algorithm developed under this IDEA project is shown to be effective in controlling a representative passenger car by means of the differential braking mechanism intended for prevention and mitigation of unintended road departure events. The algorithm is observed to adapt to a wide range of operating conditions and roadway departure scenarios.

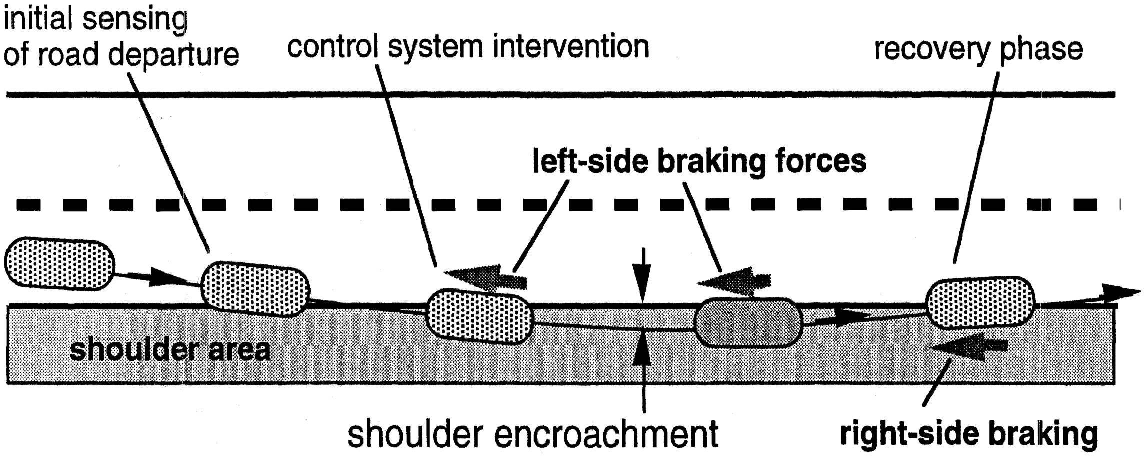

FIGURE 1. Depiction of a differential braking control intervention during a roadway departure event.

The project was organized in two stages. During Stage 1, an open-loop braking system was installed in a test vehicle (seen in Figures 2 and 3 below) in order to characterize the resulting vehicle dynamics during single-wheel braking applications. Test track experiments were then conducted with the system to evaluate vehicle responses from single-wheel braking at left and right wheel locations. The collected data were used primarily to validate a vehicle model used in the subsequent Stage 2 project activities. The collected data also helped to experimentally document the potential effectiveness of differential braking systems in redirecting and altering vehicle trajectories.

Under Stage 2 of the project, a control algorithm was developed and evaluated with the use of a computer simulation tool that included the differential braking system. The purpose of the control system is to sense impending roadway departure events (through a forward-looking camera or equivalent sensor system), provide potential warnings to drivers, and to ultimately intervene with the differential braking system if the driver does not respond. The control system goal is to prevent roadway departure by altering the vehicle trajectory through use of intelligently-applied differential braking for steering purposes. The operational effectiveness of the developed control algorithm and sensing requirements was examined for various combinations of operating conditions (e.g., road friction, vehicle speed, etc.) and control system characteristics (time delays, preview sensing, etc.) using the vehicle simulation tool.

An expert panel consisting of representatives from Ford Motor Co. (industry and vehicle dynamics perspective), the NHTSA (safety and ITS systems), ERIM International (sensor expertise), and UMTRI Human Factors Division (driver behavior) acted as technical advisors to the project. Two meetings were held during the course of the project to brief the participating experts on project results and to solicit their recommendations for improving the project work.

FIGURE 2. Test vehicle used for evaluating the differential-braking-system concept.

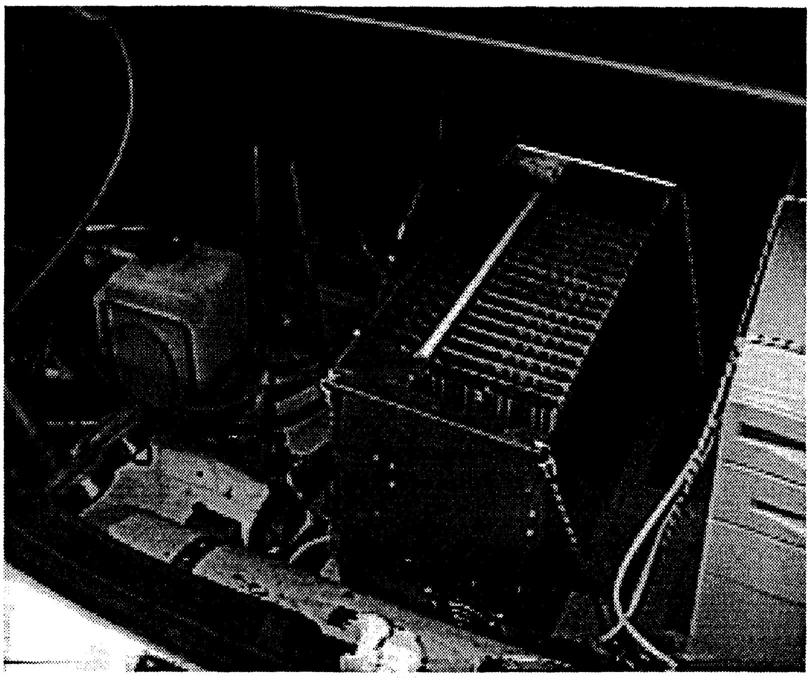

FIGURE 3. Vehicle trunk containing experimental differential braking equipment & data acquisition hardware.

Product Payoff And Technology Transfer

Single vehicle roadway departure accidents account for approximately 25 percent of highway accidents, and 33 percent of highway fatalities in the United States. Reductions in roadway departure events through use of IDEA-sponsored products as developed here can result in significant savings in lives and associated injury costs.

Both Ford Motor Co. and the U.S. Army Tank-Automotive Command have provided previous support (*1*) and interest in further developing the basic technology. Other parties such as the FHWA, the NHTSA, state transportation departments, automotive manufacturers, and various automotive parts suppliers would also be likely to have increased interest as the potential product becomes more mature and proven in use.

IDEA PRODUCT

The product developed here is intended as a driver–assist technology for reducing unintended roadway departure events by equipping vehicles with supplementary sensing and control functionality. Since single vehicle roadway departure accidents account for approximately 25 percent of highway accidents, and 33 percent of highway fatalities in the United States, even modest reductions in roadway departure events achieved through use of the product described here can result in significant savings in lives and associated injury costs.

Commercial and governmental interest in such technologies is also apparent. Both Ford Motor Co. and the U.S. Army Tank-Automotive Command have provided previous support (*1*) and interest in further developing the basic technology described here. Other parties such as the NHTSA, the FHWA, state transportation departments, automotive manufacturers, and various automotive parts suppliers would also have likely increased interest as the potential product becomes more mature and proven in use.

The impact of such a system on transportation practice would be beneficial in terms of its influence on improving the accident record and would have minimal influence in terms of how it adversely affects the existing transportation infrastructure. Since the system developed here is vehicle-based, its implementation can be viewed as a safety enhancement to the vehicle fleet as opposed to an imposition on the existing infrastructure. Depending on the nature of future roadway sensing technologies and capabilities, such as GPS or electronic lane edge markers, certain cooperative vehicle-roadway infrastructure features may become more desirable or practicable as time goes on. The view at this point is that the product developed here could easily evolve with those future trends by simply replacing or upgrading various components. For example, a forward-looking camera sensor system present in an initial version today may be replaced by an equivalent future technology, such as highly accurate and broadband GPS, which may become more prevalent and widely accessible within tomorrow's transportation systems.

The primary emphasis of this IDEA product is on development of a robust control algorithm that can be utilized in such systems, regardless of their particular hardware details.

CONCEPT AND INNOVATION

The IDEA product designed under this project is a differential (side-to-side) braking system aimed at preventing unintended road departure events. The system is intended for use as an active ITS vehicle component having limited control authority for lateral maneuvering. The system implements a "steering" function of the vehicle by means of a yawing (turning) moment produced through differential (left-side / right-side) braking forces applied to either side of the vehicle. In the event of an impending road departure event sensed by the system (e.g., from an on-board camera system or equivalent sensor that measures vehicle position relative to the road edge), the required yaw moment needed to redirect the vehicle back on to a safe path is calculated by the system's control algorithm. The yaw moment calculated by the algorithm for steering the vehicle is converted to an equivalent brake system pressure that is applied in a continuous and modulated manner to either the left or right-side wheels, depending on the direction and severity of required vehicle turning.

The control algorithm utilizes information about the current vehicle position and orientation relative to the road or lane edge. This information is obtained from an assumed forward-looking camera (or equivalent) system that converts camera imagery to vehicle-roadway position information.

The use of asymmetric (side-to-side) braking/traction as a steering control mechanism is not especially novel (*2, 3*). The basic brake-steer mechanism at work here is the same principle used for steering tracked vehicles such as military tanks and various off-road earth moving equipment. Its desirability in this application to normal highway vehicles is the availability of a separate control channel (braking) to affect vehicle turning motion without interfering directly with the traditional control channel used by drivers for path control – the steered wheel. Consequently, the intent here is to separate the new and additional driver–assist control mechanism (differential braking) from that control mechanism normally expected by drivers as their primary means for affecting path control (steering wheel). Driver expectancy about how a vehicle should respond to steering or braking is often cited as a reason for confusion in accidents. Human factors expertise would likely argue that removal of ambiguity and enhancement of driver understanding about vehicle controllability is the more prudent course to follow when such choices are available.

The other basic advantage of the differential braking concept, in addition to control separation, is that vehicle speed is reduced during a brake-steer control intervention. Reduction in speed, particularly for road departure events, is a logical benefit insofar as it dramatically reduces the potential energy consequences for any unrecoverable or delayed crash events.

Lastly, it should be emphasized that the proposed differential braking system is of low control authority, easily overridden by driver steering activity. Consequently, drivers who are only temporarily distracted and become quickly re-engaged in the driving process during a roadway departure scenario, can easily recover full control of the vehicle through steering action alone, irrespective of whether or not the differential braking system is active at the same time. In addition, the expected frequency of operation of such a system would be very low, only being activated in rare road departure occurrences.

INVESTIGATION

The research investigation was divided into two stages. Stage 1 was focused on 1) instrumenting and testing a representative passenger car (Figures 2 and 3) to gather representative differential braking measurements, and 2) evaluating an existing computer simulation tool for subsequent use later in the project. An initial expert panel meeting was also scheduled during Stage 1 to review progress and obtain feedback from the panel members about their observations.

The Stage 2 activities were focused on development of the differential braking control algorithm, its evaluation using computer simulation, and the subsequent analysis of results. A second expert panel meeting was also scheduled toward the end of the project to review the results and provide a final forum for discussing the project work.

The series of project activities outlined above are presented below in greater detail.

VEHICLE TESTS

During the first months of the project, a Ford Taurus test vehicle (Figure 2) was instrumented and prepared for testing. This included modification of the vehicle's rear-wheel braking system so as to permit operation of either left-wheel-only, or right-wheel-only braking. Even though all-wheel, front-wheel, and rear-wheel differential brake system configurations are addressed within the overall scope of this IDEA project, only rear-wheel braking measurements were conducted during the test program. It was initially proposed that sufficient information concerning differential braking control authority could be obtained from rear-wheel tests alone, thereby simplifying the required vehicle modifications and associated instrumentation within the testing phase.

The test vehicle was instrumented and interfaced to a data acquisition package (Figure 3) to record basic vehicle responses during the tests. The instrumentation included transducers for measuring vehicle yaw rate, lateral acceleration, steering response by the driver, brake line pressures to the rear wheels, and left/right rear-wheel rotational speeds. An onboard computer for storing the collected measurements and signal conditioning package completed the data acquisition system. The vehicle responses recorded during testing are listed in Table 1.

TABLE 1. Vehicle Test Track Measurements.

Vehicle Yaw Rate
Vehicle Lateral Acceleration
Brake Line Pressure to Left/Right Braked Wheel
Driver Steering Response
Left Rear Wheel Speed
Right Rear Wheel Speed

The primary purpose of these tests was to determine the level of control authority available for turning the vehicle by using single-wheel braking applications at different brake pressures. Part of the complication here is that as a wheel is subjected to braking, it also self-steers due to compliances present in the suspension, thereby adding steer-related lateral tire forces to the picture. As a result, the degree of turning authority estimated to be available from braking forces alone, can be modified significantly by the supplemental introduction of lateral tire forces produced by the self-steering compliance effects. The test data were used to sort out these two influences and provide a reasonable characterization within the simulation tool. (In a normal vehicle in which braking is being applied simultaneously to all wheels, these compliance-steer lateral forces tend to cancel one another side-to-side during most straight-line or mild turning maneuvers and are therefore far less influential.)

Following preparation and instrumentation of the Taurus test vehicle, full-scale testing was then conducted at the Dana Corporation test facility near Toledo, Ohio. The facility includes a three-lane, 1.75 mile oval which was used for these tests. Most vehicle testing occurred on the straight sections of the oval (each approximately 0.5 miles long). Several additional tests were also conducted along the circular turns of the oval to measure the likely vehicle response to differential braking from an initial state of steady turning (as opposed to the straight-line running condition). Several high pressure, rear-wheel lock-up and ensuing vehicle responses were also recorded under these conditions to demonstrate potential directional response problems if rear wheel lock-ups are allowed to occur.

A total of about 110 vehicle braking tests were conducted at the Dana site. The tests covered a range of speeds from 40 to 80 mph. All tests were conducted with the driver holding the steering wheel fixed prior to and during the brake application. Following establishment of a constant forward speed and straight-line running condition, a fixed level of brake pressure was applied to one of the rear wheels. Throttle position was held fixed during the brake application. No attempt was made to compensate via throttle adjustment for mild speed loss resulting from the single wheel braking. Brake line pressures ranged from 500 to 1600 psi (1600 psi was nearly sufficient to lock either rear wheel during straight-line tests. Under turning conditions along the oval curve, the 1600 psi level was sufficient to lock the inside wheel at 60 mph.) The number of tests were about evenly divided between left and right-side braking.

An example set of time histories is seen in Figure 4. The figure contains plots of lateral acceleration, yaw rate, brake pressure, and left/right wheel speeds. The time interval of interest on these plots is from 0 to 7 seconds during which the steering is held fixed and braking is applied to the left rear wheel. Immediately following the braking test, the driver regains control of the vehicle by steering it back into the initial travel lane (7-to-12 second period). During the time interval from 3 to 5 seconds, the left rear wheel is being braked at 1600 psi and the vehicle is turning to the left. The indicated level of lateral acceleration is about 0.1 g's.

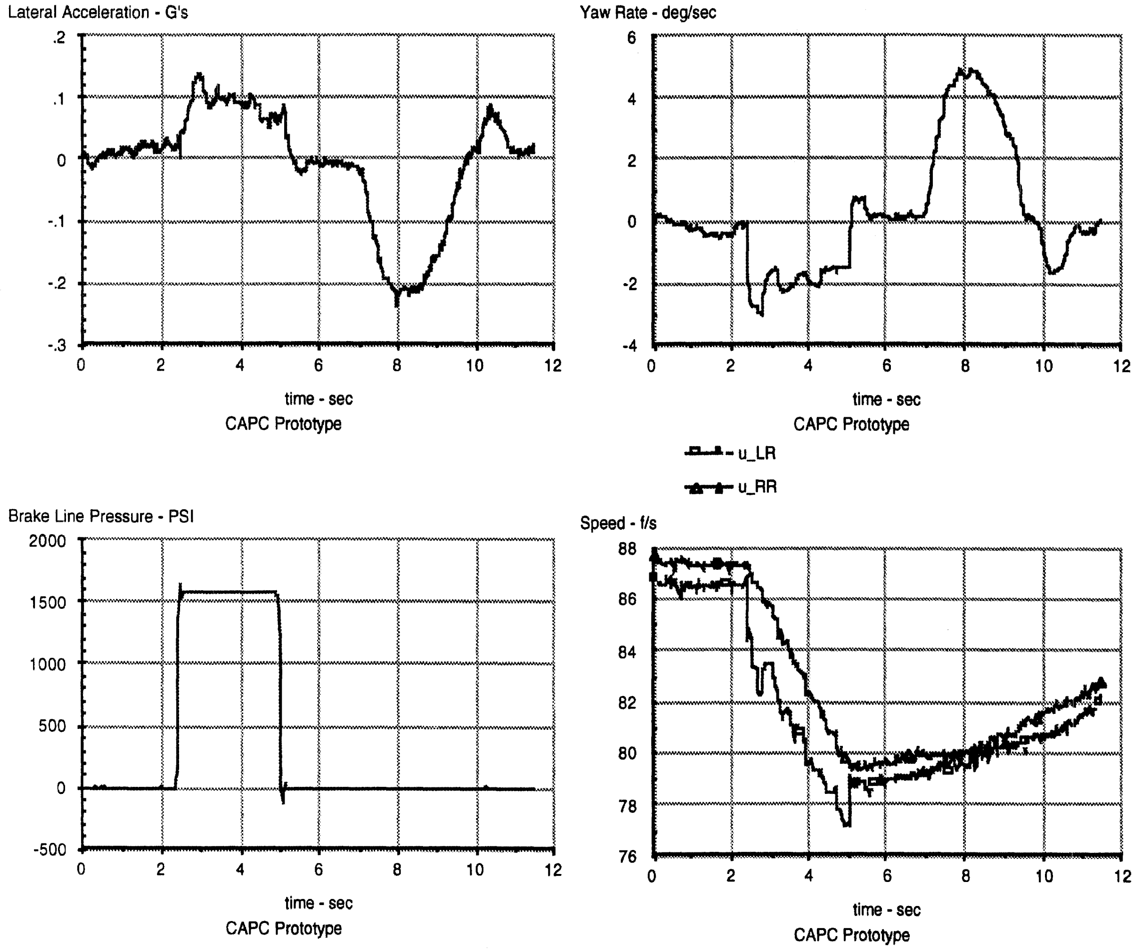

FIGURE 4. Example Test Data Corresponding to a Left Rear-Wheel Brake Application.

All recorded test data were transferred to the UMTRI archive system as time history records of vehicle responses. These were then used to review and evaluate a computer model proposed for use in subsequent analyses and described in the next section.

THE SIMULATION TOOL

The primary candidate for use in modelling the vehicle and conducting the associated analysis of the differential braking systems was a software package called **CAPC**, referring to the prior Army and Ford-sponsored project (*1*) entitled "**C**rewman's **A**ssociate for **P**ath **C**ontrol" under which it was developed. This package contains a number of vehicle and control modules useful for analyzing vehicle and combined driver/vehicle responses resulting from the application of differential braking. The CAPC package also contains a set of basic animation capabilities for viewing results and interacting with the program. Figure 5 contains a screen-shot of the CAPC program during a calculation of a simulated road departure and recovery scenario.

In this figure, several simultaneous views of the vehicle and roadway are seen in each of the four panels. Overhead views of the vehicle and road appear in the leftmost and bottom panels. Views of the roadway as seen from a near-field and far-field camera appear in the other two panels. (Cameras or other sensor technology are assumed available within a road departure system for locating the vehicle with respect to the roadway boundary.) Dots along the right road edge are the estimated locations of the road edge as calculated by the simulated camera systems within the CAPC package.

The CAPC system was evaluated for further use within the second stage of the IDEA project and found to be generally suitable. However, based upon the test track results and observations of certain data, several key items needing attention within the CAPC package were identified during the evaluation review. These were: 1) addition of an anti-lock brake system (even in a rudimentary form) to prevent wheel locks and simulate wheel cycling under high brake pressure applications or low surface friction conditions, 2) upgrading/replacement of existing brake-steer algorithms within the existing package to improve their robustness and extend their basic capabilities when confronted with nominal variations in vehicle properties or operating conditions, and 3) addition of certain key vehicle suspension properties that were initially missing from the vehicle model and would be needed to improve the accuracy of the simulated results (namely, force compliance effects on wheel steer). Summaries of these modifications are addressed below.

Review, Evaluation, and Modification of the Initial Vehicle Modelling Software

Addition of an ABS System to CAPC

The initial version of CAPC did not contain an antilock brake system (ABS) module for simulating brake pressure modulation in response to wheel lock-up or high wheel slip conditions. Since any envisioned system that incorporates a differential brake-steer system is certain also to contain an ABS system for preventing elevated wheel slip conditions during braking, addition of this feature to CAPC was essential. Accordingly, a basic ABS wheel slip algorithm was added to CAPC. Its operation caused brake pressure to drop to zero if wheel slip exceeded 10 percent. Brake pressure was reapplied to the level of the demanded master cylinder pressure if wheel slip fell below 10 percent. The net result was a basic characterization of ABS operation that prevented wheel locks and produced wheel cycling under low friction conditions.

Certain test track data collected under Stage 1 work also demonstrated the obvious need for an ABS system. In some of the braking tests conducted along the curve of the Dana test track oval, significant vehicle yaw divergence (spiraling inward toward the center of the turn) was observed when wheel lock-up occurred on the inside wheel at elevated pressures. The pressure was quickly released by the operator under these circumstances to maintain control. However, those results did emphasize the need (a) to provide an ABS capability with such systems, and (b) to utilize the *front* and rear brakes in any proposed practical implementation. A front *and* rear wheel system (all-wheel configuration) re-distributes brake forces more optimally fore/aft, while also minimizing brake force requirements at any single wheel. This aspect was examined further under the subsequent Stage 2 simulation work where front-only, rear-only, and all-wheel configurations were exercised with and without ABS present to help document its assistance in providing directional stability under marginal friction conditions.

Addition of Certain Suspension Properties

Review of the test track data also indicated that the test vehicle was achieving only about half of the turning response as that predicted by the baseline CAPC model. The example set of time histories seen earlier in Figure 4 is representative. During the time interval from 3 to 5 seconds in Figure 4, the left rear wheel is being braked at 1600 psi and the vehicle is turning to the left in response with an indicated lateral acceleration level of about 0.1 g's. For the same set of conditions, the initial unmodified CAPC code indicated a turning response closer to 0.2 g's.

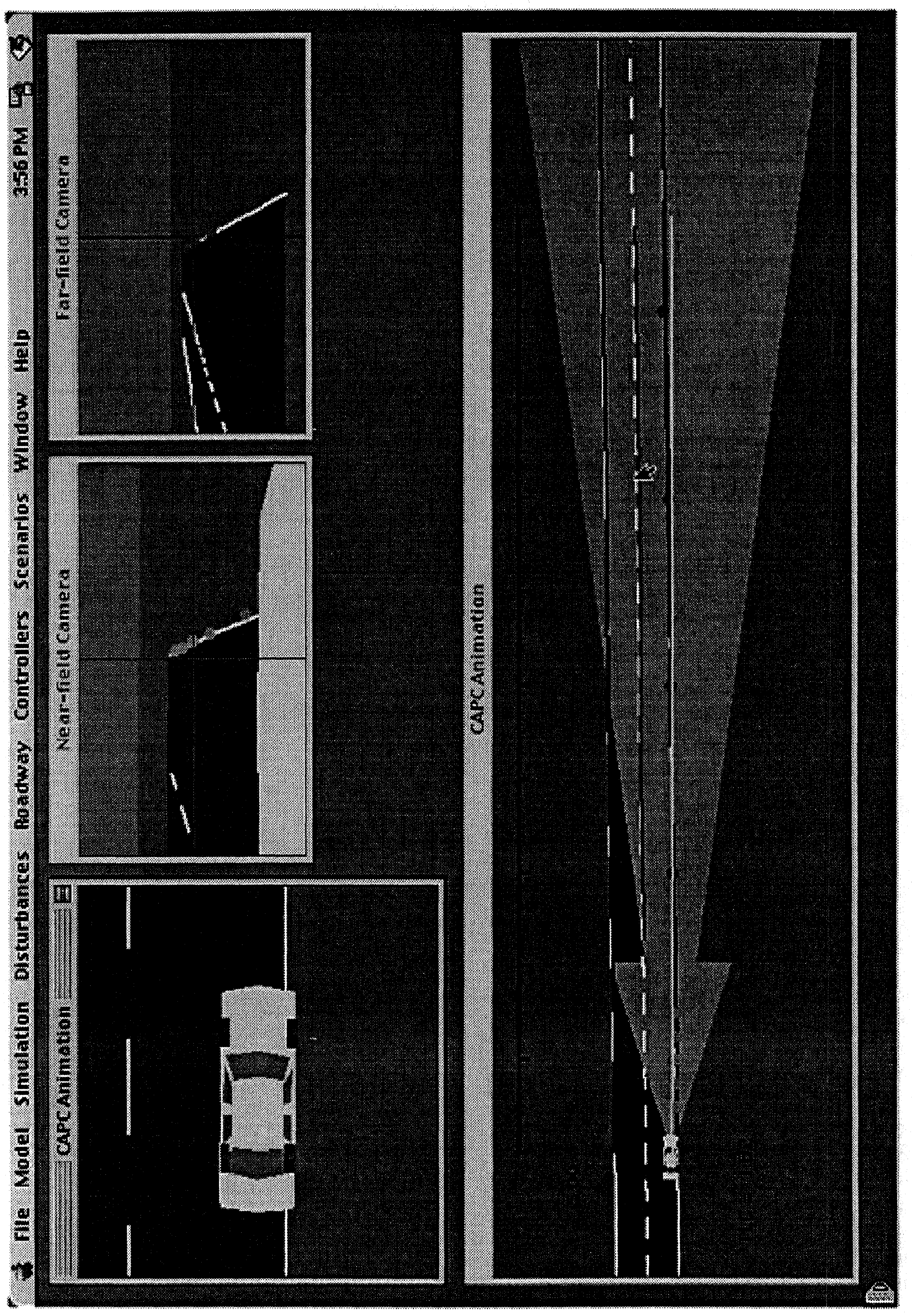

FIGURE 5. Example Screen-Shot from the CAPC Brake-Steer Simulation Analysis Software.

Upon further review it was determined that certain suspension properties were not being represented within the CAPC code. While these properties are not critical under many operating maneuvers for conventional vehicles when all four wheels are being utilized symmetrically for control, they can become important under asymmetrical control scenarios such as occurs with the differential braking concept. In this case, it was concluded that compliance-steer effects due to braking were causing the observed discrepancy between the test data and the CAPC program. When brake force is applied to either of the rear wheels, suspension kinematics and compliances in the suspension, such as bushings, allow the wheels to steer a small amount in response to the applied braking force. In this case, the rear wheel is toeing (steering) outward, causing the turning moment imposed on the vehicle from the tire braking force to be diminished by a smaller opposing moment introduced by the compliance-steer and its associated lateral tire force. Compliance-steer effects due to braking were then added to the CAPC code using applicable suspension parameter values for a Ford Taurus (*4, 5*). The revised simulation results were in basic agreement with the test data.

Modification / Addition of Brake-Steer Control Algorithms to CAPC

Simulation of relatively benign operating conditions and modest road departure drift rates are handled fairly effectively by the initial LQR and PID control algorithms present in the CAPC package. However, those initial controllers, which were apparently "tuned" to certain nominal conditions, appear to be less robust than desired when certain vehicle properties or operating conditions are altered. Example variations that tended to degrade the performance of the initial CAPC algorithms included lowered surface friction conditions (even with an ABS system active) and various suspension influences that can affect steering but were not apparently accounted for in the controller designs.

Consequently, as part of the original Stage 2 algorithm development, it seemed advisable to replace the initial controller options with a more robust controller design that could better address the needs of the IDEA project. To that end, a preview-based control scheme that has been used effectively at UMTRI for steering control purposes and which could be easily extended to the brake-steer problem posed here was adopted. That controller was also implemented in a prior Army-sponsored project (*6*) at UMTRI in the late 1980's for simulating human path control for a variety of military vehicle applications. One of those applications included a brake-steer implementation applicable to tanks and other non-steered-wheel vehicles that maneuver by application of a yawing torque generated by asymmetric braking/traction forces. Since major portions of that control algorithm were already implemented within the CAPC program for simulating driver *steering* behavior for path-following purposes, applicable portions of the code were modified and adopted for use as the default differential braking control algorithm. A basic description of the preview control algorithm appears in the next section.

THE CONTROL ALGORITHM

The brake-steer control algorithm is based on a driver steering model originally proposed in 1981 (*7*). The model was later extended under contract support from the U.S. Army to cover a broader set of vehicles and operating conditions (*6*). The product of that work was a driver steering control algorithm capable of accurately representing human path-following behavior for many ground vehicle applications. The model employs an optimal preview control strategy that attempts to minimize errors between a desired previewed path and the predicted future position of the vehicle being controlled as depicted in Figure 6. The model incorporates knowledge of the vehicle dynamics (i.e., the expected vehicle response) within its structure and can therefore project into the future an estimate of the vehicle position at an advanced point in time. Simultaneously, the use of *preview* permits the driver model to observe directly (or "look ahead at") the corresponding desired path to follow. The difference between these two future projections (predicted vehicle position and previewed desired path) corresponds to a previewed error signal which is minimized by the steering control computational strategy.

Since those original designs, the driver model has been implemented in a variety of forms to simulate vehicle handling performance of passenger cars and commercial vehicles (*8, 9, 10*). For this IDEA project, where the differential brake-steer concept is being employed (as opposed to a steered-wheel controller), the control model steers the vehicle with yaw torque generated via differential brake forces applied to either side of the vehicle. To turn left, brake pressure is applied to the left-side wheels; to turn right, the right-side wheels are braked. By modulating the timing, amplitude, and polarity (left/right) of the brake pressure control signal, based on the previewed path-error-minimization algorithm, path following behavior similar to a steered-wheel vehicle can be achieved. However, in this case, the brake-steer controller also produces, as a beneficial byproduct, a reduction in forward speed due to the associated brake applications.

The basic computation of the model is to calculate, at each point in time, the steering (yaw) control torque, M, which will minimize the error between a desired path input and the projected future lateral displacement of the vehicle over a specified preview time interval, T. The model is able to estimate the future response of the vehicle being controlled by utilizing an internal representation of the vehicle within its own structure. The internal model is essentially a linear approximation of the nonlinear vehicle code and whose parameters are updated continuously to reflect changes in operating conditions such as vehicle speed. Consequently, the driver model incorporates an internal "mapping" of the estimated vehicle path response resulting from a particular yaw control torque applied to the vehicle. Obviously, the better the internal model is at representing the vehicle being controlled, the better will be the estimate of the projected vehicle response.

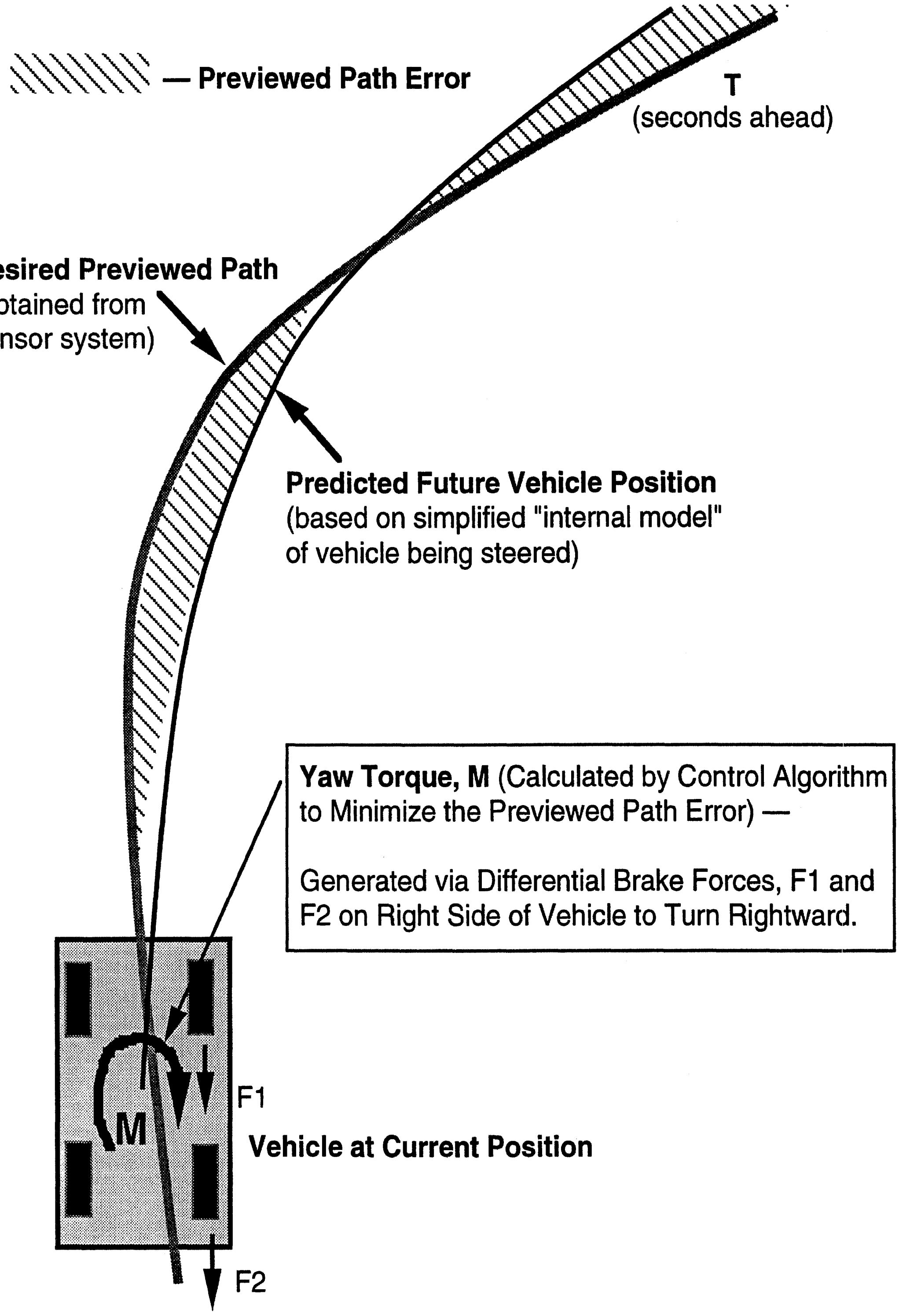

FIGURE 6. Steering control strategy. The yaw torque, M, is calculated to produce a future vehicle trajectory (dark line) which will minimize the previewed path error (cross-hatched area).

Once the optimal yaw torque is calculated by the control algorithm, it is then converted to an equivalent braking force applied to one side of the vehicle or another, depending on the turn polarity. (The product of the braking force and the offset distance of the tires from the vehicle centerline equals the yaw torque calculated by the brake-steer algorithm.) If a front-only or rear-only brake-steer configuration is designated, all the brake force is applied at that respective wheel. For an all-wheel configuration, the total brake force is distributed fore/aft in proportion to the front/rear suspension loads and the effectiveness of the front/rear brakes.

Additional mathematical details of the brake-steer control algorithm are well documented and described further in reference [*6*].

SIMULATION RUNS

A series of simulation runs was designed to examine several different road departure scenarios and a wide range of operating conditions (vehicle speeds and surface frictions). The designated simulation runs cover two basic operating scenarios in which the vehicle departs the roadway (a) drift-off of a straight road segment, and (b) departure from a curve following an initial transition into the curve from a straight road segment. Two angles of road departure (1 degree and 3 degrees) were selected for the straight-road scenario. At elevated highway speeds of 60-to-70 mph these would correspond to slow and rapid drift rates, respectively, out of the travel lane and on to the shoulder area. See Figure 7.

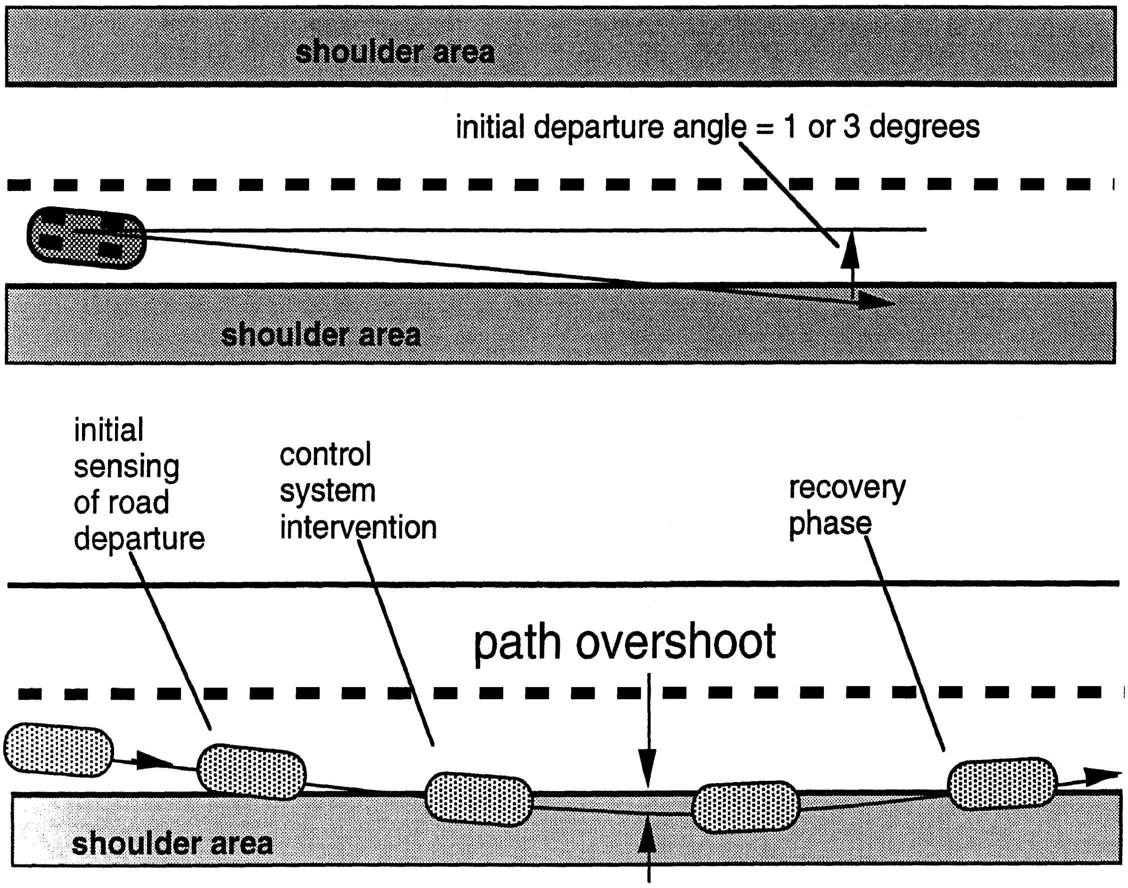

FIGURE 7. Departure from a straight-road scenario.

Likewise, for the road departure from a curve scenario seen in Figure 8, two different curve radii (2000-ft and 1000-ft) were selected to represent modest and severe challenges, respectively, to a driver not anticipating an upcoming curve. The 2000-ft radius turn would correspond to many interstate geometries for speeds of 60-to-70 mph, while the 1000-ft radius turn would more resemble a rural road setting requiring a more demanding 0.3 g's to negotiate at comparable speeds. Each turn radius is preceded by a spiral transition that blends the initial straight segment into the fixed radius curve.

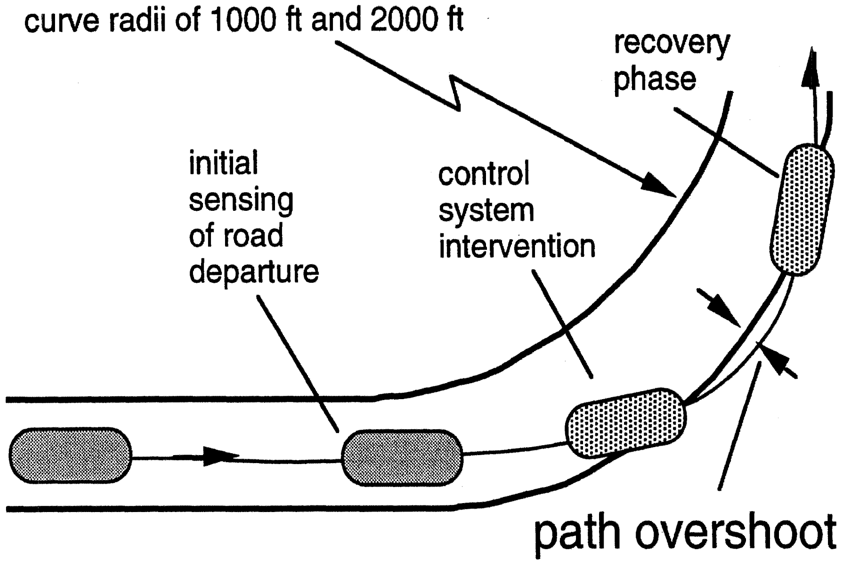

FIGURE 8. Departure from a curve scenario.

Operational variables for the simulation study included speed of the vehicle and tire/pavement friction level. The nominal reference vehicle (a) was equipped with active ABS braking, (b) utilized both front and rear wheel braking within the differential brake-steer algorithm (the "all-wheel" configuration), (c) used the preview brake-steer algorithm with a preview parameters setting of 1.5 seconds, and (d) focused on cases in which the steering was held fixed throughout the brake-steer intervention (as though the driver was drowsy or temporarily impaired). Identical sets of comparison runs were also performed for the front-wheel-only and rear-wheel-only system configurations to evaluate their relative performance for the same sets of conditions.

Other special cases were also studied in which driver steering was activated subsequent to the brake-steer activation at various delay times (as though the driver was suddenly reawakened or alerted to the impending road departure). These cases were also combined with scenarios in which the differential brake-steer system was then inactivated at other delay times following driver reengagement. The basic question being examined by these particular scenarios was whether delayed driver steering reengagements, combined with simultaneous brake steer operation and/or its sudden withdrawal, could produce unwanted steering reactions on the part of the driver, such that the driver-vehicle system becomes temporarily destabilized by the control conflicts or by the sudden shut-off of the brake-steer system.

A final set of runs was also conducted for cases that did not include ABS braking. These runs documented the importance of providing ABS braking within any brake-steer system so as to help prevent wheel-locks and the associated directional instability of the vehicle. Lastly, a few selected runs were performed that altered the principal preview controller parameter away from its 1.5 second nominal setting. These served to examine the sensitivity of system performance to nominal changes in combined gain and damping characteristics of the controller algorithm.

Table 2 summarizes the basic elements considered in the simulation runs.

TABLE 2. Principal Elements and Variables of the Simulation Runs.

Scenarios	**Operational Variables**
• Drift-off of straight road • Curve departure following entry from straight	• Vehicle speed • Road / tire friction level
Control Algorithm Characteristics	**Driver Steering Involvement**
• All wheel system configuration • Front-wheel-only system configuration • Rear-wheel-only system configuration • Modification of the algorithm preview parameter	• None, steering held fixed at zero • At the time of brake-steer activation • Delayed from brake-steer activation

ANALYSIS OF SIMULATION RESULTS

The results of the simulation runs are presented in this section as graphs that describe stability boundaries and maximum path deviations of the vehicle as a function of initial vehicle speed and surface friction. At a specified initial travel speed of the vehicle, there is a surface friction condition below which the vehicle will lose stability during a brake-steer controller intervention and attempted recovery. Stability of the vehicle refers here to either *directional* stability or *path* stability. Directional instability is characterized by the tendency of the vehicle to "spin out" or to oscillate in directional orientation such that the vehicle is not pointing along the roadway in a controlled manner following the controller intervention. Path instability refers to the vehicle's tendency to continue drifting outward away from the road edge despite the controller's attempt to return it to the roadway. This latter type of defined instability typically occurs under low friction conditions for which the control authority is insufficient to turn the vehicle back toward the road edge, even though the vehicle may be directionally stable. A maximum lateral excursion of 1.35 meters (vehicle centroid beyond the lane edge) was selected to define the limit of allowable path excursion for path instability. The 1.35 meter dimension represents a lateral displacement of the outside tire on the roadway shoulder equal to approximately one and a half vehicle-widths beyond the lane edge boundary.

So, during any particular scenario (the 1 and 3 degree straight-road departure scenarios, or the 1000-ft and 2000-ft radius curve scenarios), the controller is either able to intervene successfully and steer the vehicle back on to the road edge, or else one of the two aforementioned instabilities will occur, depending on the prevailing speed and surface friction conditions. That is, the vehicle will become directionally unstable, or will drift too far off the road during the attempted recovery. The speed and surface friction conditions existing at the onset of either type of instability thereby define the curves that appear on the following stability plots.

The 1-Degree Straight-Road Departure Scenario

The first stability plot, seen in Figure 9, applies to the 1-degree straight-road departure scenario. Three curves appear on this plot and correspond to: a) the all-wheel brake-steer configuration, b) the front-wheel-only configuration, and c) the rear-wheel only configuration.

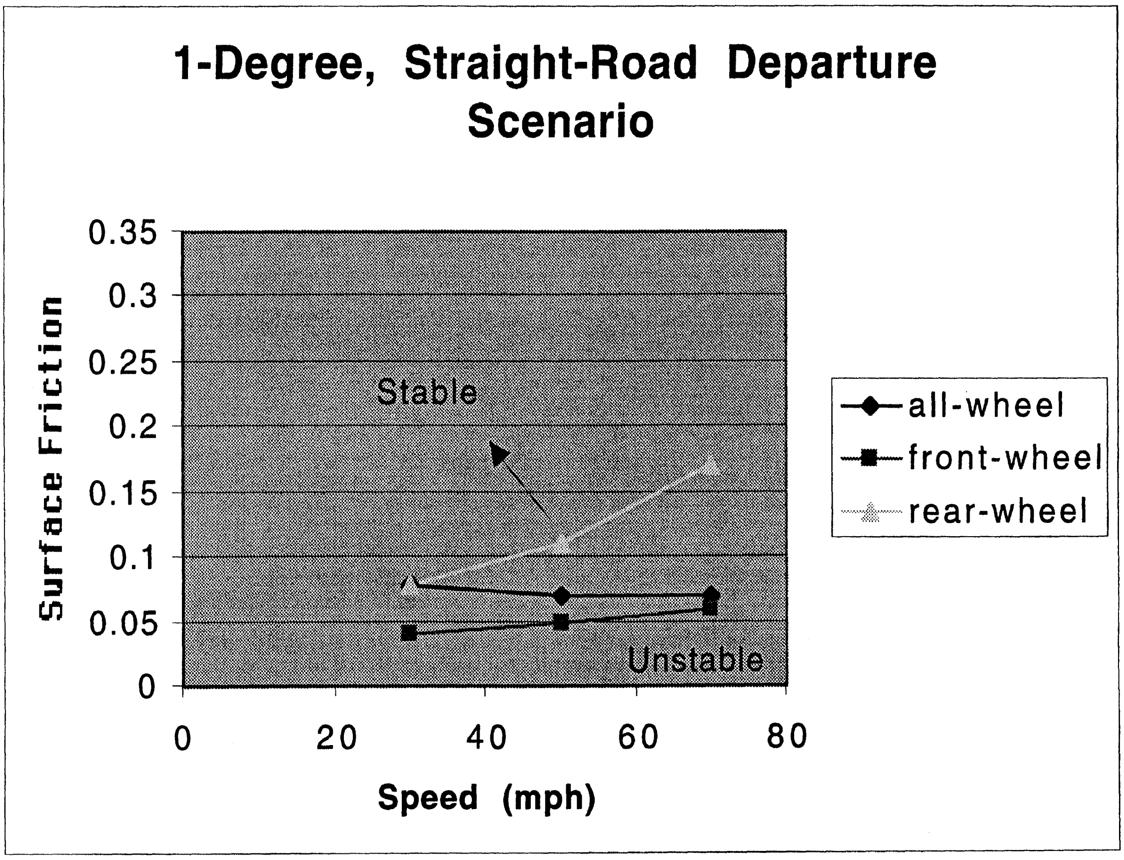

FIGURE 9. Stability Plot for the 1-Degree Straight-Road Departure Scenario.

The 1-degree departure angle scenario produces a relatively slow drift rate not unlike many situations that occur everyday. It is not a particularly challenging control task to recover from and correct. The results seen in Figure 9 bear this out indicating that for all three system configurations, the system operation is challenged only for very low friction conditions (ice-like friction levels of 0.1 to 0.2). For surface friction conditions above about 0.17, all three systems are stable (directionally and path-wise) for operating speeds up to 70 mph. The all-wheel system displays the highest level of stability and overall range of operating performance. The front-wheel system is next in order, followed by the rear-wheel system, which displays the most restricted (though still highly effective) operating range for this relatively mild roadway departure scenario.

Figure 10 contains corresponding path overshoot information for each of the three configurations as a function of surface friction. The path overshoot is defined as the distance beyond the right lane edge that the vehicle travels during the recovery portion of the maneuver. The path overshoot is also defined in the diagram of Figure 7. As indicated here, all three system configurations easily handle this particular road departure scenario, showing very small path overshoot levels of 0.1 meters or less. (During the control recovery portion, the controller attempts to center the vehicle just on or slightly outside the right lane edge line — not back in the center of the initial travel lane. The simulated camera that collects look-ahead lane-edge information for the control algorithm contains a specified level of sensor noise that can produce small variations in exact placement of the vehicle along the lane edge.)

Figures 11 and 12 contain corresponding path overshoot information for the front-wheel and rear-wheel system configurations, respectively. The front-wheel system results in Figure 11 are similar to the all-wheel system. The rear-wheel path overshoot levels of Figure 12 show more notable increases with elevated speed.

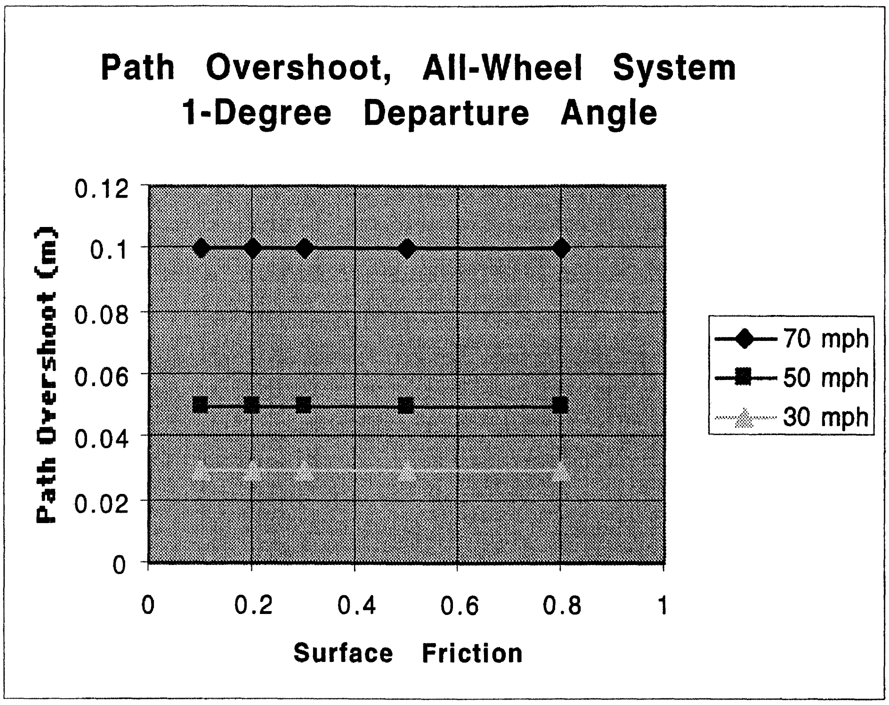

FIGURE 10. Path overshoot for the 1-degree straight-road departure scenario, all-wheel system.

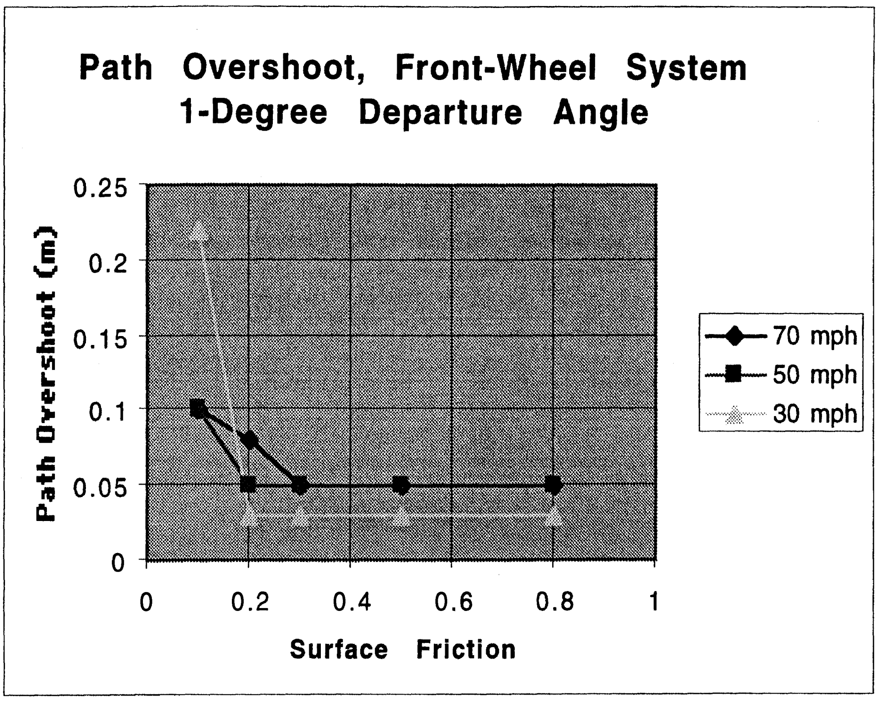

FIGURE 11. Path overshoot for the 1-degree straight-road departure scenario, front-wheel system.

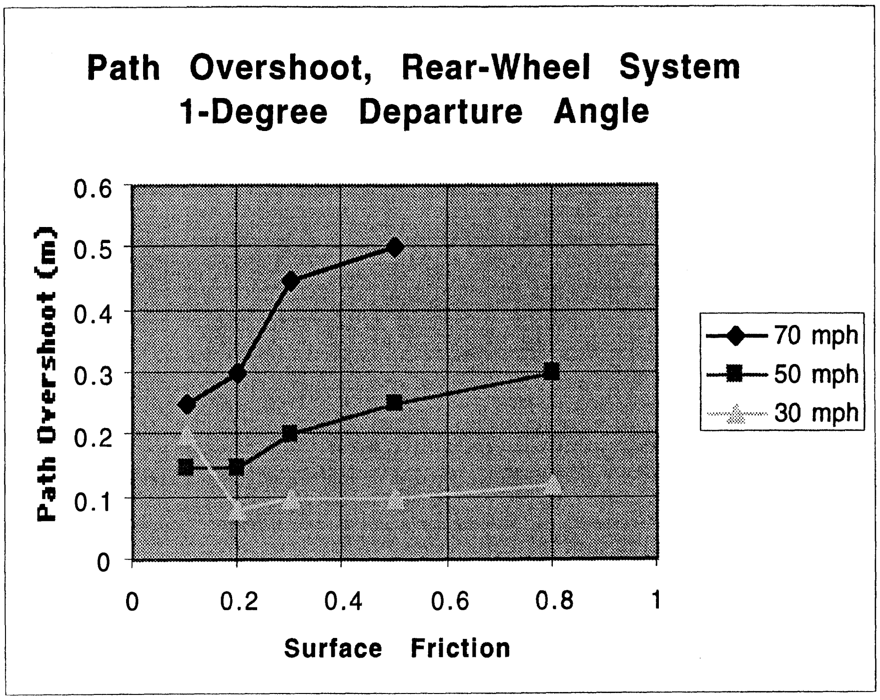

FIGURE 12. Path overshoot for the 1-degree straight-road departure scenario, rear-wheel system.

The 3-Degree Straight-Road Departure Scenario

If the angle of road departure is now increased to a level of 3 degrees, the rate of lateral movement and burden of recovery is significantly increased for the controller. The stability plot seen in Figure 13 applies to the 3-degree straight-road departure scenario. This scenario represents a fairly rapid road departure rate, especially at elevated speeds. As seen before in Figure 9, three curves appear on this plot and correspond to the three system configurations. The all-wheel system again displays the highest level of stability and overall range of operating performance. The front-wheel system is next in order, followed by the rear-wheel system, which displays the least operating range. Because of the increased severity of this scenario and additional demand it places on the control system for recovery, a diminished operating range is now observed vis-a-vis the results for the previous 1-degree road departure scenario. The minimum friction level for stable operation at 70 mph is now increased from about 0.15 to 0.30, depending on the system configuration. The stability results also show a strong dependency on operating speed, with near-ice friction levels providing sufficient stability if speeds are reduced to 30 mph or so.

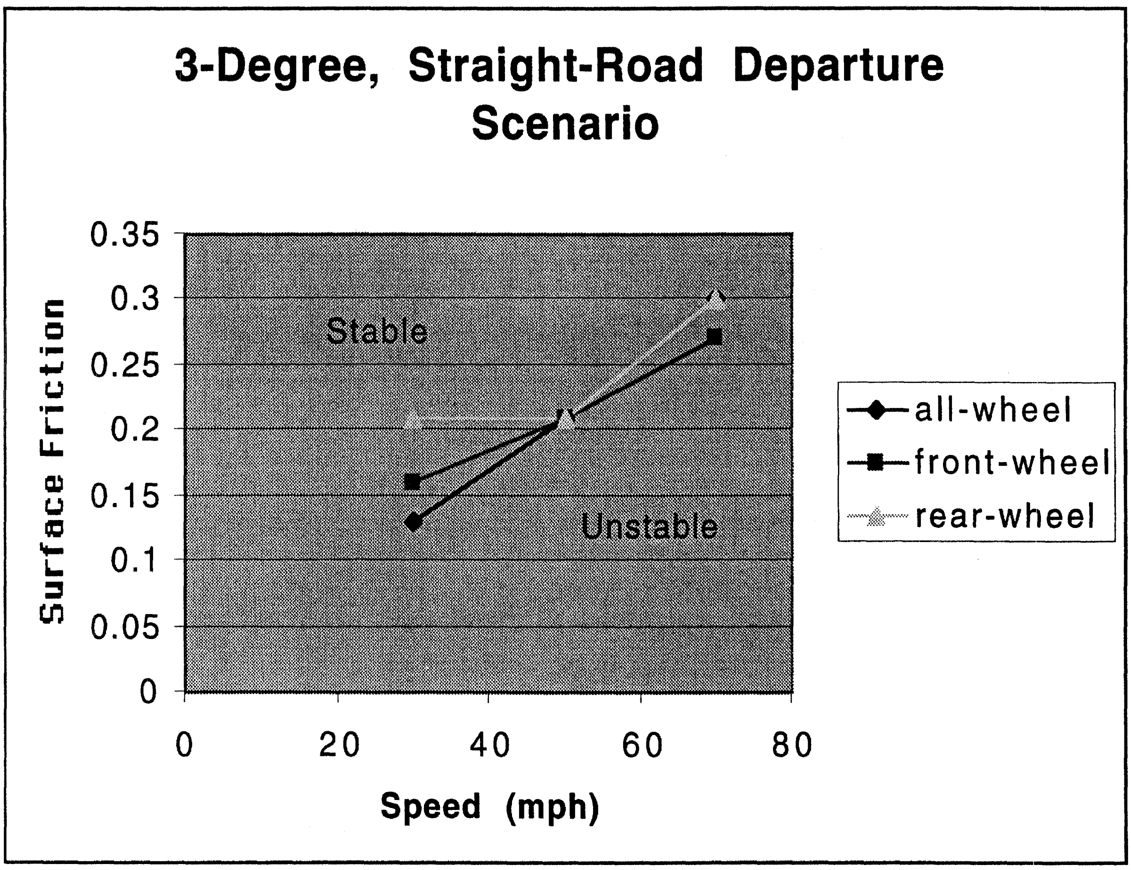

FIGURE 13. Stability plot for the 3-degree straight road departure scenario.

Path overshoot information corresponding to the 3-degree road departure scenario appears in Figures 14 - 16. The all-wheel system configuration performance seen in Figure 14 shows some superiority over the front-wheel and rear-wheel results of Figures 15 and 16. The all-wheel system indicates a maximum path overshoot of less than 0.6 meters at 70 mph for surface friction levels for which it is directionally stable (> 0.30). In comparison, for the same friction condition (0.3) and speed (70 mph), the front-wheel and rear-wheel systems display path overshoot levels of 0.9 and 1.1 meters, respectively.

Thus, as the demands of the road departure scenario increase, differences in performance between the three system configurations begin to appear, primarily reflected as different mixtures of path control and directional stability. For more demanding road departure events, reflected in the curve departure scenarios of the next two sections, these differences become further amplified.

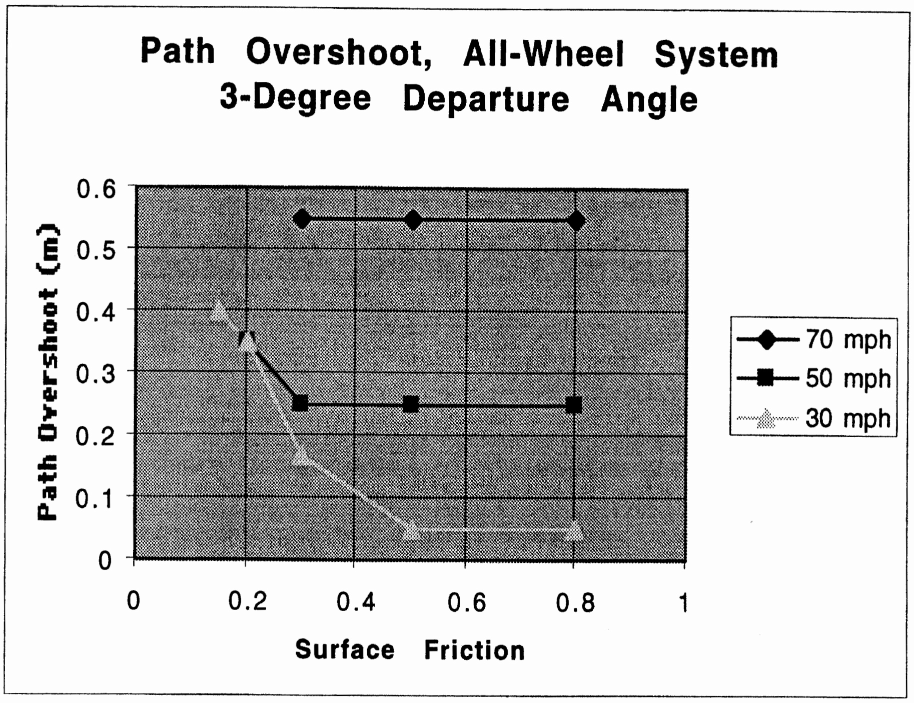

FIGURE 14. Path overshoot for the 3-degree straight-road departure scenario, all-wheel system.

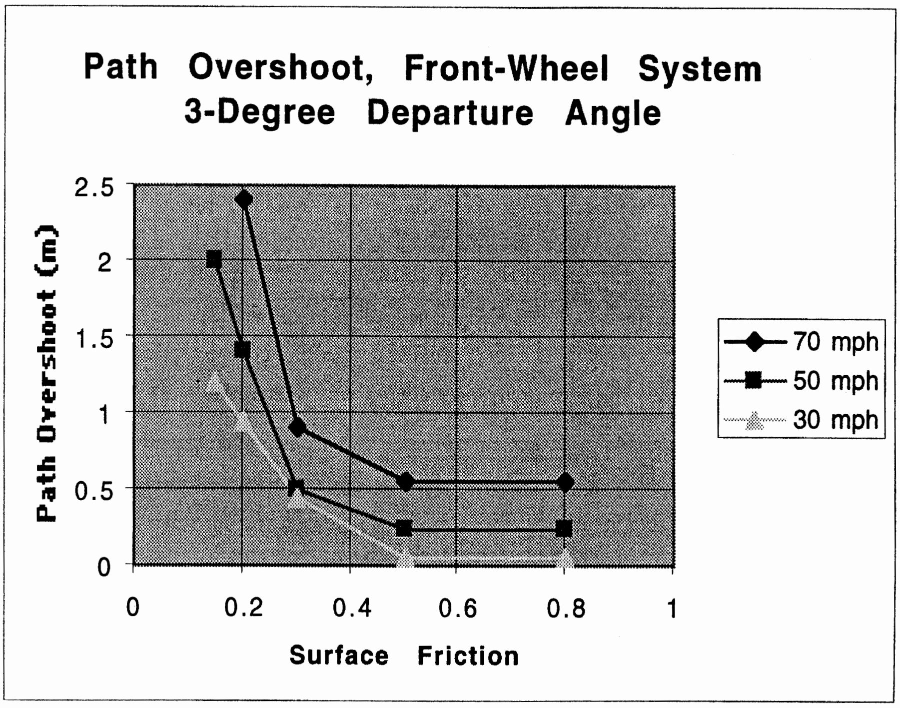

FIGURE 15. Path overshoot for the 3-degree straight-road departure scenario, front-wheel system.

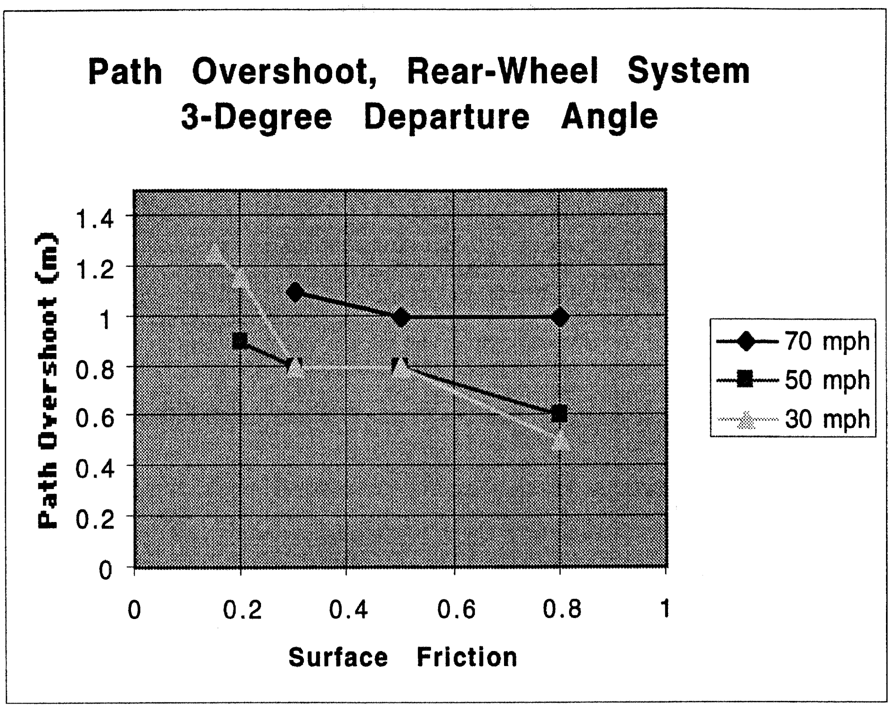

FIGURE 16. Path overshoot for the 3-degree straight-road departure scenario, rear-wheel system.

The 2000-ft Radius Curve-Departure Scenario

The next stability plot, seen in Figure 17, applies to the more complex scenario of entering a 2000-ft radius turn from an initial straight road segment. The initial straight and the fixed radius portion of the turn are connected by a spiral curve that blends curvature linearly along its connector. Full curvature is achieved at an arc distance equal to about 40 percent of the turn radius, and a build-up of 6 percent superelevation also occurs along the spiral. When compared to the previous straight-road scenarios, the curve transition scenario places an even greater demand on the control system because recovery now means regaining control of the vehicle along a curve. This requires active differential braking to be present continuously for path control along the curve, as well as for recovering the vehicle from its initial lane departure out of the curve.

This particular roadway scenario is perhaps representative of some interstate highway geometries. At a speed of 70 mph along the fixed-radius 2000-ft superelevated curve, the so-called 'friction factor,' indicative of the idealized estimate of *minimum* lateral friction needed at the tire/road surface for vehicles to traverse the curve, is equal to about 0.1 g. However, because the scenario entails a transient road departure event requiring even greater maneuvering demands to be placed on the vehicle during its recovery, minimum friction levels greater than the 0.1 level should be expected. The results seen in Figure 17 support this, indicating a need of 0.2 g's or more for stability at 70 mph. The additional maneuvering margin of 0.1 g's is needed for the road departure recovery. Since speed is also reduced slowly during the brake-steer recovery, frictional demand is diminished as the maneuver progresses.

Again, the three curves appearing on the stability plot in Figure 17 correspond to the three system configurations. As in the straight-road cases, the all-wheel system is seen displaying the highest level of stability and overall range of operating performance, followed closely by the front-wheel system, and then the rear-wheel system. However, a more restricted stability boundary is now noted for the rear-wheel configuration. Since this particular system can only utilize the more lightly loaded rear wheels for control purposes, its diminished control authority requires higher brake pressures to be applied to those wheels to achieve turning ability that is similar to the other two systems, thereby increasing the chances for ABS wheel cycling (wheel lock tendencies) and associated diminishment of the vehicle's directional stability.

The path overshoot graphs seen in Figures 18 - 20 also reflect degradation in path tracking performance of the rear-wheel system relative to the other systems. Again, as greater maneuvering demands are placed on the vehicle because of more complex road departure scenarios, the rear-wheel system suffers the greatest relative loss in performance due to its more limited control authority and reduced stability margin deriving from increased utilization of rear wheels for control purposes.

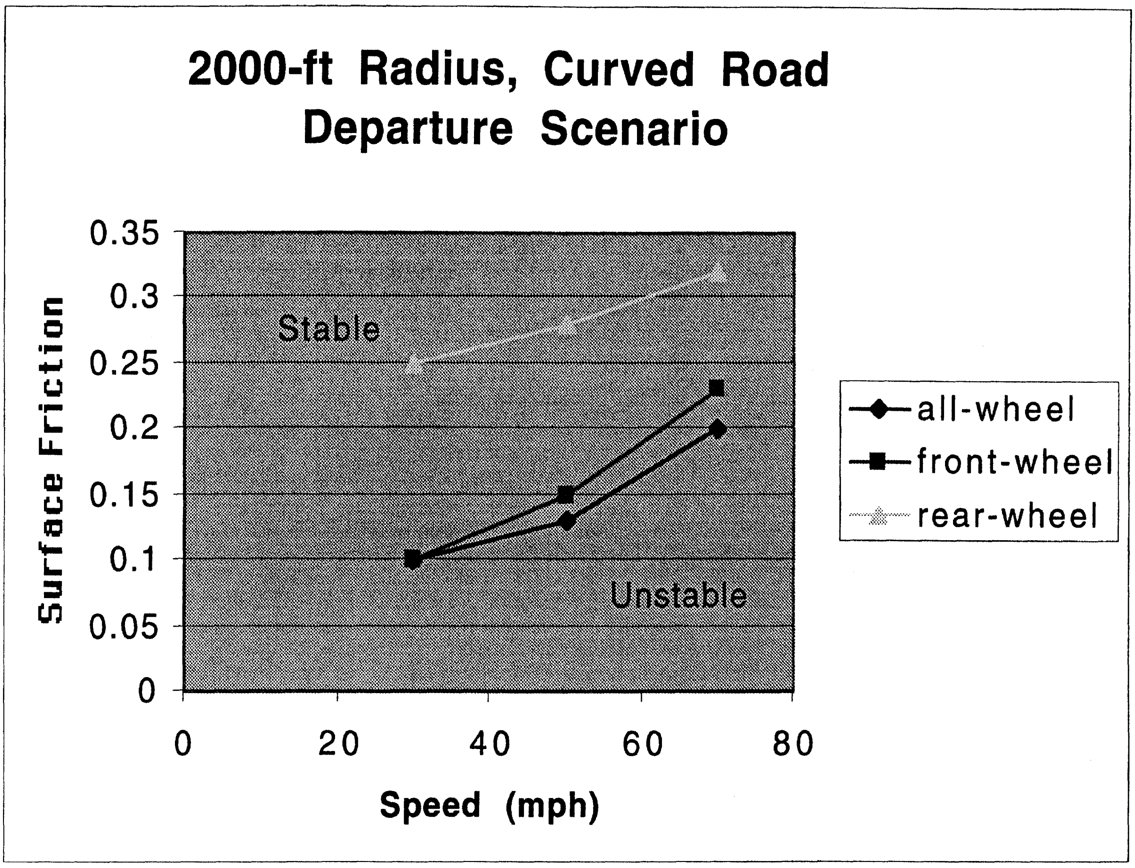

FIGURE 17. Stability plot for the 2000-ft radius curve-departure scenario.

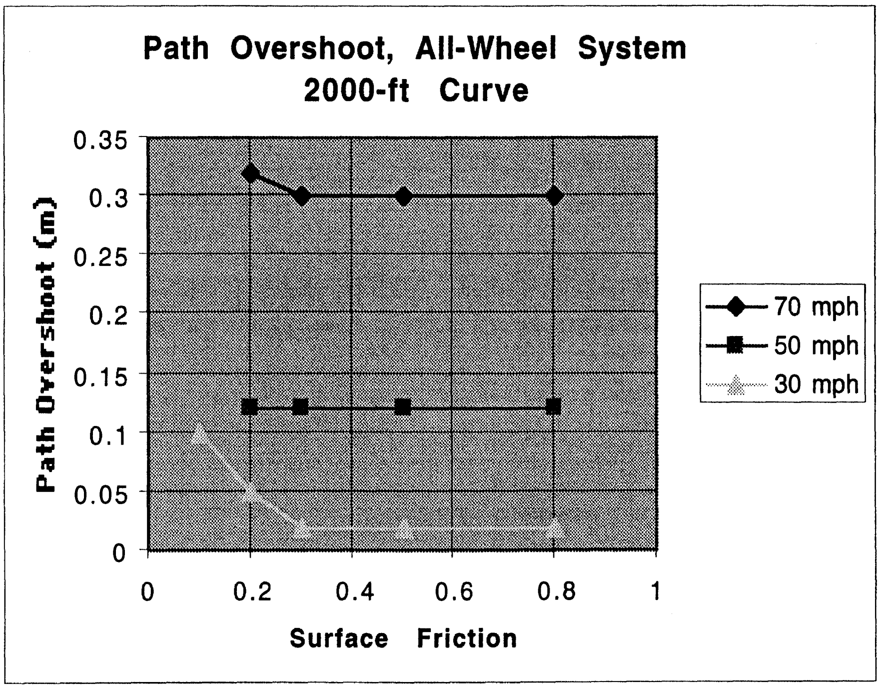

FIGURE 18. Path overshoot for the 2000-ft radius curve-departure scenario, all-wheel system.

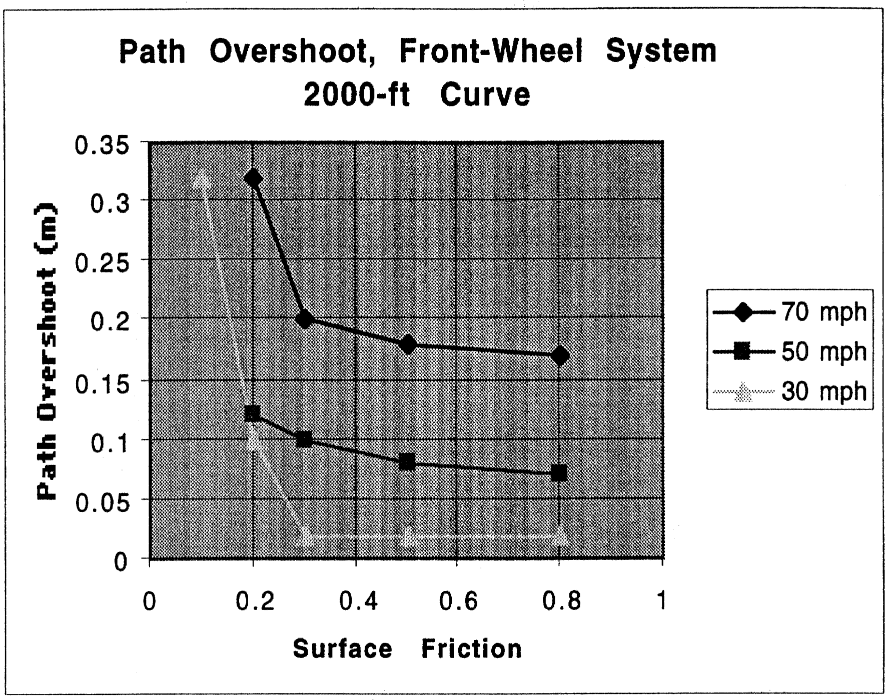

FIGURE 19. Path overshoot for the 2000-ft radius curve-departure scenario, front-wheel system.

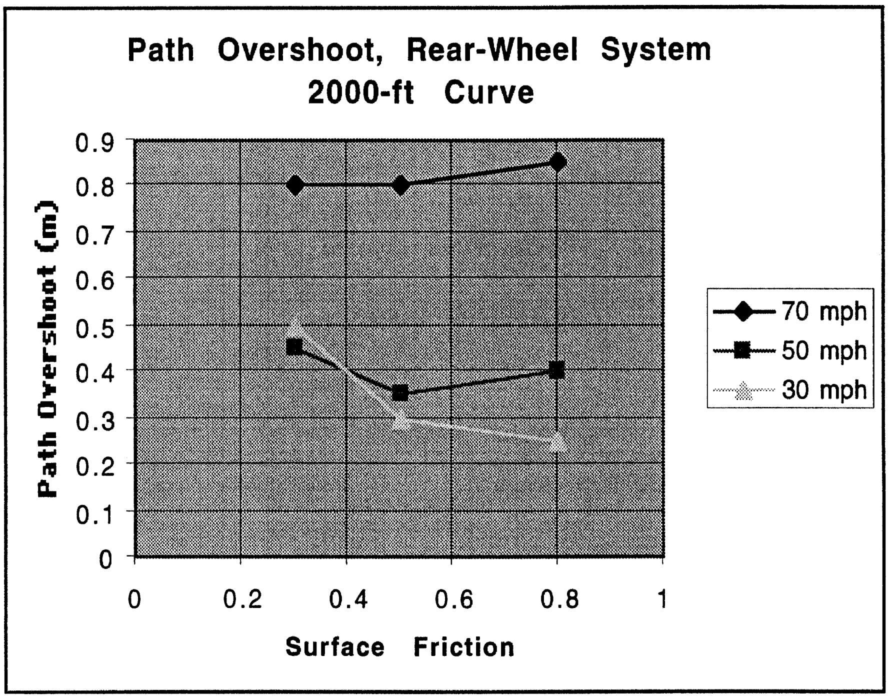

FIGURE 20. Path overshoot for the 2000-ft radius curve-departure scenario, rear-wheel system.

The 1000-ft Radius Curve-Departure Scenario

The most demanding road departure scenario is represented by the 1000-ft radius curve equivalent of the previous scenario. However, in this case, the superelevation along the curve is only increased to a level of 3 percent (not 6 percent), thereby producing an equivalent friction factor of about 0.3 at a speed of 70 mph, versus the previous scenario's 0.1 value. Consequently, one can view this scenario as approximately three times more demanding than the 2000-ft radius curve scenario at a speed of 70 mph. (Even though the curve radius is halved in this scenario, the friction factor lateral acceleration requirement at 70 mph is tripled, not doubled, because of the difference in the two superelevation rates — 6 percent versus 3 percent. This particular roadway scenario is probably more representative of certain rural road settings than most interstate geometries.)

The stability plot seen in Figure 21 applies to the scenario of entering the 1000-ft radius turn from an initial straight road segment. The straight and fixed radius turn are again connected by a spiral curve that blends curvature linearly along its length. Full curvature is achieved at an arc distance equal to about 40 percent of the turn radius and a build-up of 3 percent superelevation also occurs along the spiral.

Only two curves appear on this stability plot and correspond to the all-wheel and front-wheel system configurations. The rear-wheel system, because of its more limited, rear-wheel-dependent control authority, is unable to generate sufficient turning ability to respond quickly enough to negotiate the curve described in this scenario for speeds above 30 mph. This observation is in basic agreement with the test track data collected under the project's Stage 1 activities which showed that the UMTRI rear-wheel-only test vehicle could only generate about 0.1 g's of turning ability at 60 mph. At lower speeds this control authority is progressively reduced. Furthermore, during a road departure event, some additional margin of lateral acceleration maneuvering ability is required to recover the desired turning path, beyond that needed to just maintain the desired turning path.

As in the case of the 2000-ft radius curve, the all-wheel system displays a higher level of stability and comparable range of operating performance when compared with the front-wheel configuration. However, for both systems, this turning scenario significantly restricts the range of operating conditions compared with prior cases. This of course is to be expected at some point given the limited control authority available for such systems. Since the intended application of this IDEA product is actually focused on more benign and less severe turning scenarios, the fact that two of the system configurations can be extended to this level of performance is nevertheless encouraging.

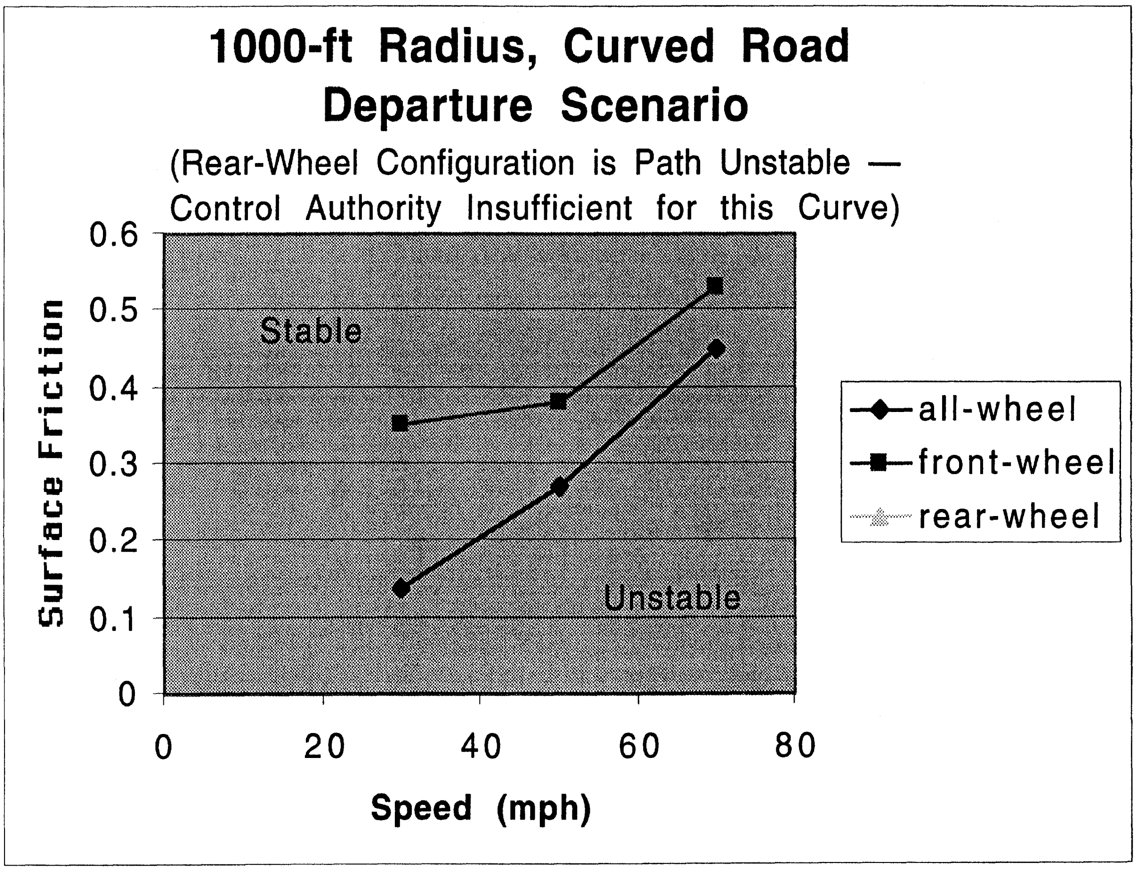

FIGURE 21. Stability plot for the 1000-ft radius curve departure scenario.

Lastly, Figures 22 and 23 summarize the estimated amount of path overshoot corresponding to the all-wheel and front-wheel configurations for the 1000-ft radius turn scenario. In this case the front-wheel system displays somewhat superior tracking ability at elevated friction conditions. The all-wheel system displays an advantage in stability, extending its available operating range to lower friction surfaces.

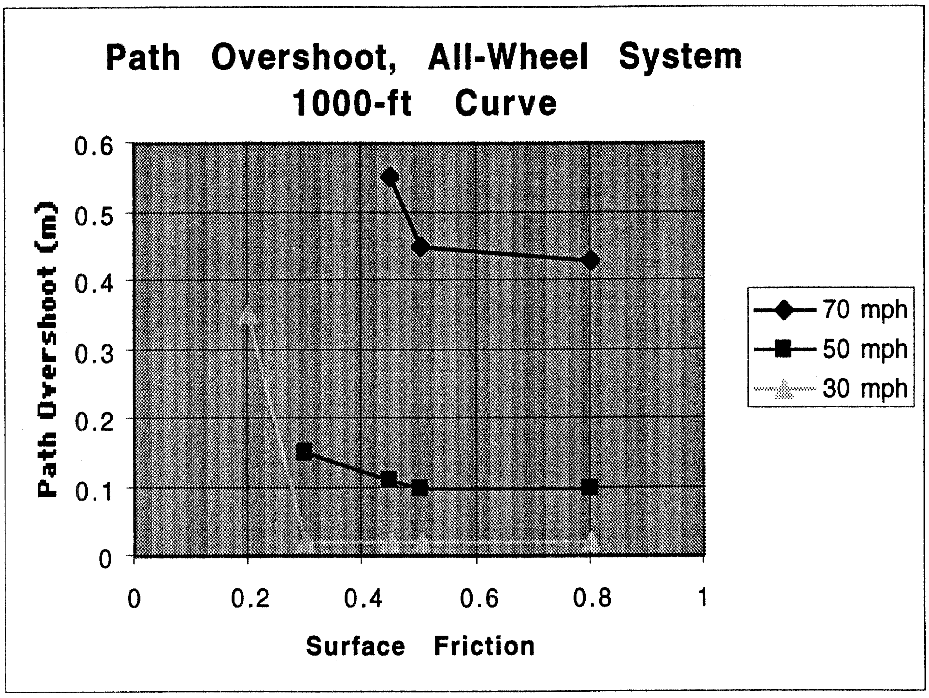

FIGURE 22. Path overshoot for the 1000-ft radius curve-departure scenario, all-wheel system.

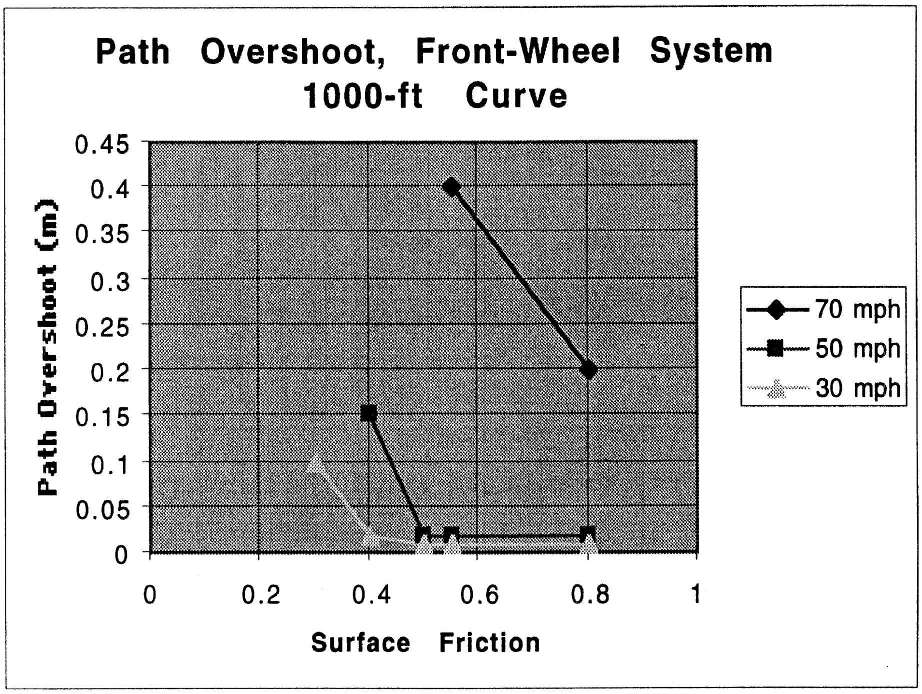

FIGURE 23. Path overshoot for the 1000-ft radius curve-departure scenario, front-wheel system.

Simulation Runs Involving Driver Steering Reengagement and System Inactivation During Recovery

A series of additional ad hoc simulations was also conducted in which driver steering activity was simulated simultaneously during the brake-steer activations. The purpose of these simulation runs was to examine whether or not any adverse system responses would result from the potential control conflict.

The basic driver reengagement scenario was defined by the following:

- Once the brake-steer system became activated during a road departure event, the driver steering model was activated and attempted to steer the vehicle back into the center of the travel lane from which it initially started (right travel lane).
- At the same time, the brake-steer system was attempting to direct the vehicle (via its side-to-side differential braking mechanism) back on to the center of the lane edge (6 feet to the right of where the driver was attempting to steer the vehicle.)
- The resulting path control conflict between where the driver wished to steer the vehicle (lane center) and where the brake-steer system attempted to position the vehicle (right lane edge), generally produced a path response somewhere between the two and which gradually was overridden by the driver steering activity.
- Various delays between when the brake-steer system became activated and when the driver first became engaged were used. Most ranged from 0 seconds up to 5 seconds.
- Other delays were also used in these driver conflict scenarios to disengage the brake-steer system following its activation. Those delays ranged from 0 seconds up to 10 seconds following the initial engagement of the driver steering activity.

In cases examined for driver-reengagement scenarios, no particularly adverse system responses were noted. Part of the explanation for this observation may be that since both the simulated driver steering activity and the brake-steer controller were attempting, albeit by different control mechanisms, to direct the vehicle to the same general area of the roadway, the path conflict that did exist (6 feet) was insufficient to cause any serious control problem. Secondly, in all cases, the control authority emanating from the steered front wheels is more influential than the path control authority deriving from the brake-steer mechanism. Consequently, driver steering "wins" under such circumstances.

However, an additional question is raised as to whether or not competing control activities can still affect the responsiveness of path recovery. Based on the set of runs conducted within this study the answer on this is less clear. If responsiveness applies to moving the vehicle back on to the shoulder area, the answer is no because both the driver and the brake-steer controller are working in concert to achieve at least that goal. In fact, it may be that under some of these circumstances a faster shoulder recovery is achieved, depending on when driver steering is re-engaged. However, if the center of the travel lane is the definition of responsiveness, based on the drivers' target/goal, there may be some additional delay. A more thorough and effective examination of these types of details can be handled more readily using actual drivers in full-scale vehicle tests or driving simulators.

Special Case Simulation Runs to Demonstrate Advantages of Including ABS Braking

A small set of additional simulation runs was also conducted with the ABS system inactivated to examine the extent to which system stability and performance were affected. The most notable influence appeared for the rear-wheel system configurations. Because rear-wheel lock-up will generally produce a directionally unstable vehicle, the importance of ABS for such configurations is significant. Typically, the presence of ABS helped to extend the operating range for rear-wheel systems from surfaces having normalized friction coefficients of about 0.4 or so down to a level of approximately 0.2 (as reflected in the stability plots for straight-road departure scenarios), depending on the specific operating speed and departure angle.

The presence of ABS for the front-wheel and all-wheel system configurations was also beneficial but to a lesser degree. It should also be noted that traction, both longitudinally and laterally, is improved with ABS, and to some extent this helps to improve path-keeping performance by reducing the amount of overshoot during path recovery.

ASSEMBLY OF AN EXPERT PANEL

The remaining project task provided for assembly of an expert panel consisting of representatives from Ford Motor Co. (industry and vehicle dynamics perspective), the NHTSA/FHWA (safety and ITS systems), ERIM International (sensor expertise), and UMTRI Human Factors Division (driver behavior) to act as technical advisors to the project. An initial meeting was held at UMTRI to review project results following the vehicle tests and to solicit ideas and recommendations from the panel on the future project work. Feedback obtained from that panel meeting was supportive of the basic work and included several suggestions about applying future sensor technologies to lessen the cost burden to the vehicle manufacturer.

Some of the participants noted that the project should consider the possibility that future GPS technology may provide enough accuracy and sufficient update rates on vehicle position (including preview information on upcoming roadway segments) that most on-board vision-based technology could be eliminated or play a more diminished cooperative role with GPS. Also, the Ford driving simulator was suggested as a possible test platform for conducting special experiments with subjects to evaluate how a brake-steer controller system and simultaneous driver steering may interact (i.e., steering intervention by the driver while the brake-steer system is active). This latter issue was examined in a preliminary manner through some of the computer simulation runs noted above. However, follow-up experiments on a driving simulator may prove helpful in clarifying various observations from the simulation study.

PLANS FOR IMPLEMENTATION

Both Ford Motor Co. and the U.S. Army Tank-Automotive Command have provided previous support and interest in further developing the basic technology described here. Other parties such as the NHTSA, the FHWA, State Transportation departments, automotive manufacturers, and various automotive parts suppliers would also have likely increased interest as the potential product becomes more mature and proven in use.

As noted elsewhere in the report and conclusions, certain issues related to human factors and to specific sensor technologies likely remain as topics for further examination. However, the control algorithm component developed within this IDEA project appears to be mature enough to undergo more rigorous testing within either computer simulator or on-road environments.

CONCLUSIONS

The control algorithm developed under this IDEA project is shown to be effective in controlling a representative passenger car by means of the differential braking mechanism intended for prevention and mitigation of unintended road departure events. The algorithm is observed to adapt to a wide range of operating conditions and roadway-departure scenarios. Specific observations related to different possible implementations are:

- An all-wheel system configuration offers the best combination of directional stability and path-keeping performance over the likely range of operating conditions and potential roadway-departure scenarios.

- A front-wheel configuration is an acceptable alternative that exhibits marginal reductions in stability and path-keeping performance relative to the all-wheel system.

- The rear-wheel system is not recommended as a viable product configuration due to reduced stability and path-keeping abilities, particularly under more demanding road-departure scenarios and along curves.

- Antilock brake systems should accompany and be fully integrated with any implementation of a brake-steer system to help prevent wheel-lock conditions and enhance the basic directional stability and traction of the vehicle during differential-braking applications.

- No evidence was observed in the simulation analyses to indicate that simultaneous driver steering intervention and brake-steer system operation produce unwanted control conflicts. Driver steering control authority is dominant under such scenarios and can override the steering effects provided by the brake-steer controller. In most conflict situations, the task of both the driver and the brake-steer system will be in general harmony, which is, to redirect the vehicle back on to the road surface or shoulder area.

- Vehicle suspension compliances that affect wheel steer (e.g., compliance-steer due to braking) should be evaluated and accounted for in any brake-steer implementation. Compliance-steer effects were observed to significantly affect the turning response of the vehicle during single-wheel braking maneuvers.

- Nominal variation of the primary control algorithm parameter (preview or 'look-ahead' time) provides good control over system damping and gain characteristics. No unusual sensitivities in system performance were observed for normal variations in this parameter.

In addition to the aforementioned conclusions, certain other observations are offered that relate to potential implementations and practical issues. These are:

- Image processing technologies that provide information about vehicle location relative to the road edge may be supplemented or replaced by future sensor technologies such as higher bandwidth GPS or cooperative roadway markers. To the extent that this may occur over time or be adopted as a more cost-effective implementation of sensor needs, the basic conclusions and algorithm capabilities examined in this IDEA project are largely unaffected and still apply.

- The issue of system intelligence and determining when an *unintended* road departure incident is actually occurring versus the scenario of *intended* road departure on to a shoulder area remains as a practical matter yet to be fully addressed in such systems. The potential for annoyance to drivers if brake-steer system activations occur too erroneously is a concern. However, many of the likely scenarios in which drivers would want to depart the road for the shoulder could perhaps be anticipated by additional intelligence built into such systems. For example, "arming" of the system could be speed-dependent (or could sense driver steering/braking activity) to eliminate many likely false alarms when drivers slow down and drive onto a shoulder intentionally. Likewise, a simple disengagement button/switch may be provided for conditions in which drivers know in advance about an upcoming or planned roadway departure.

Lastly, recommendations that can be offered for furthering this work and product would include:

- Verifying the basic findings reported in this simulation study with similar experiments conducted in suitable driving simulators and/or with full-scale road tests. Of particular interest would be driver control interactions with the brake-steer system, subjective evaluations, and recommendations for enhancing its usage.

- Examination of human factors issues related to likely driver reactions to, and acceptance of, such systems as in-vehicle safety assists.

- Analysis of the potential impact of more futuristic road-edge sensing technologies that could replace the currently-assumed (and more expensive) on-board camera system. This would include such technologies as high bandwidth, high-accuracy GPS location technologies or various cooperative road-side technologies that could provide electronic detection of road edges to passing vehicles. Technical issues here would be primarily related to update rate requirements, accuracy, and the associated extraction of vehicle trajectories relative to road edges, assuming the probable availability of such measurement technologies. The likely interest in such capabilities relates primarily to cost benefits to the vehicle manufacturer and the accompanying effect it would have for potential market penetration and availability.

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