A Lane-Departure Warning and Control System

Kunsoo Huh
Thomas E. Pillutti
A. Galip Ulsoy
Charles C. MacAdam
Chiu-Feng Lin
Robert D. Ervin

University of Michigan
Ann Arbor

The University of Michigan
IVHS
Intelligent Vehicle-Highway Systems
College of Engineering • (313) 764-4332
Professor Kan Chen, 4112 EECS, Ann Arbor, MI 48109-2122, and
University of Michigan Transportation Research Institute • (313) 936-1066
Robert D. Ervin, 2901 Baxter Road, Ann Arbor, MI 48109-2150

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IVHS technical Report Prepared by

Kunsoo Huh (Research Fellow, MEAM Dept.[1])
Thomas E. Pilutti (Graduate Research Assistant, MEAM Dept.)
A. Galip Ulsoy (Professor, MEAM Dept.)
Charles C. MacAdam (Associate Research Scientist, UMTRI[2])
Chiu-Feng Lin (Graduate Research Assistant, MEAM Dept.)
Robert D. Ervin (Research Scientist, UMTRI)

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[1] Department of Mechanical Engineering and Applied Mechanics
[2] University of Michigan Transportation Research Institute

ABSTRACT

The progress on the development of a vehicle warning and control system to avoid run-off-road accidents on highway is summarized. The system proposed is an integrated lateral advisory or control system, which will work by properly combining the information of the previewed roadway, projected route of the vehicle, and the driver status model. The previewed roadway will be obtained based on the measurement of lane geometry. The projected route will be calculated based on the vehicle's current motion and a vehicle dynamics model. The driver status, such as driver alertness or impaired behavior, will be modeled from the perspective of steering performance. Then, finally, the above information is synthesized into a warning/intervention/control system for an autonomous vehicle in order to minimize run-off-road accidents on the highway.

INTRODUCTION

Since the invention of the motor vehicle, passenger safety has always been of prime concern to society. In 1991 in the US, 41,000 people died in traffic accidents and more than five-million people were injured [Chen, 1992]. It is believed that most traffic accidents happen because of driver error rather than a breakdown of the vehicle hardware. Driver error is usually caused by the driver's carelessness, driver impairment (e.g., drowsiness or drunkenness), or poor environmental conditions (e.g., ice or fog). Driver error can result in rear-end collision and/or run-off-road accidents, which together, according to NHTSA data [The Hansen Report, 1992], account for an astonishingly large percentage, approximately one-half, of all vehicle crashes.

In particular, run-off-road accidents are the most critical for highway safety, because they account for approximately one-third of all motor vehicle fatalities [Accident Facts, 1991 Ed.]. The run-off-road accident usually involves a single vehicle, which does not follow the prescribed path (see Figure 1) and runs into a structure off the roadway. These single-vehicle accidents are mainly due to the poor driving performance of the driver. Compared with multiple-vehicle accidents such as rear-end crashes, these single-vehicle accidents induce more fatal injuries because of the high aggressiveness of roadside impacts and rollovers. Therefore, a high priority should be placed on the development of a system for preventing, or at least minimizing, run-off-road accidents. For instance, the number of single-vehicle accidents can be reduced significantly if the influence of the driver's control deficiencies can be minimized.

One way to achieve this goal is an automated guidance system, which can lead a vehicle through the desired path. In this case, vehicle motion is not affected by factors such as the driver's drowsiness, and drivers can shift their focus from driving to other activities. This approach has been investigated to alleviate congestion and increase traffic throughput by the PATH project [Shladover et al., 1991] at the University of California, Berkeley, by the AHS program [Fenton and Mayhan, 1991] at the Ohio State University, and by individual researchers in academia and in the auto industry. In addition, many research results in mobile robots have been proposed for application to this problem [Thorpe et al., 1992, and Davis et al., 1992] beginning with low speeds and in controlled environments. It is recognized, however, that systems of this type require extreme reliability and may not be realized in commercial products within less than, say, thirty years.

Another approach involves an active safety-control system on the vehicle, which allows simultaneous inputs from the lateral controller and the driver. This is obviously a difficult task, since the driver (who operates based on human internal feedback loops) and the control system (which works based on the measured data) must cooperate in an integrated fashion. But, this active control approach may offer some benefits in reliability since the driver can provide backup control under conditions of system failure, unexpected obstacle, missing lane markers, etc., even if we must still provide for a seamless transition from manual to automatic operation.

Although both approaches, the automated guidance system and the active safety-control system for avoiding the run-off-road accidents are recognized, the latter approach is adopted in this project because of two basic reasons: 1) easier implementation of the latter than the former in the near future (or, the fact that the flawless realization of the former is unlikely to be forthcoming in the immediate future), and 2) multiple levels of functionality in the active safety approach, any one of which may be implementable by itself. The proposed active safety system is an integrated control system as shown in Figure 2 in the sense that the system is capable of monitoring the status of the vehicle/driver and that it can correct the vehicle's motion by augmenting driver steering with a lateral controller when a dangerous situation is expected.

Monitoring of the vehicle status can be achieved on the basis of the projected route of the vehicle and the previewed roadway. The projected route as a function of downrange distance can be calculated from the vehicle's current motion (position, velocity, acceleration, wheel angle, etc.) and a vehicle dynamics model. The layout of the previewed roadway can be estimated by means of a remote sensing of lane markers. By comparing the projected route of the vehicle and the previewed roadway, various measures can be developed for monitoring the *lane tracking margin* which prevails until lane-departure. Those measures are lateral clearance to the lane edge, time-to-lane-crossing, lateral acceleration needed to effect a recovery maneuver, etc. In this project, the time-to-lane-crossing (TLC) is selected as a tracking-margin measure for driver warning and/or steering control, because it represents the time required for the vehicle to deviate from the lane. Based on the magnitude of the TLC and the vehicle position, the active safety-control system can decide whether to give a warning signal to the driver or to assist in the steering control of the vehicle.

Monitoring of the driver status is also necessary because the decision to determine warning/intervention/control is a function of human factors, such as the driver delay in responding to a warning signal, and it varies for different people and the different physical conditions of a particular person. For example, the critical value of TLC for issuing a warning signal could be quite distinct based on driving history, style, skill, etc. of the driver as illustrated in Figure 3. Therefore, the steering performance of the driver needs to be modeled as an adaptive process and continually updated, so that the active safety control system can work properly without producing false alarms and yet providing a warning signal in time for the driver to react effectively.

The development of the active safety-control system is divided into three stages in this project.

Stage I: establishment of the basic information for the active safety control.
    1) characterization of roadway sensing
    2) determination of time-to-lane crossing
    3) development of the adaptive driver-state model

Stage II: synthesis for run-off-road warning/intervention/control

Stage III: evaluation through simulations and experiments

An overview of this project is contained in this report, and the research progress to date is summarized. An extensive bibliography has been compiled and included as Appendix A to this report. Preliminary samples and trial runs of software for studying lane-departure warning and control are illustrated in Appendix B. A desktop driving simulator is currently under development and is briefly introduced in Appendix C.

PROGRESS SUMMARY

Stage I: Establishment of basic information

Item 1: Characterization of Roadway Sensing

Performance of roadway sensing needs to be characterized accurately for the steering-control system. The performance properties of interest cover the *type* of previewed roadway information which is generated (viz., continuous, sampled, actively coded with upcoming lane geometry, etc.) and the *quality* of the information, especially as a function of down-range distance from the vehicle. The previewed roadway is only an estimate from road layout data, which can be obtained from the measurement of lane markers using on-board radar, laser, visual, infrared, ultrasonic sensors or inductive sensors based upon magnetic wire embedded along the center or the edge of the lane. Thus, the accuracy and reliability of the estimated roadway largely depend on the choice of sensors and estimation algorithms. Every lane sensor has certain limitations in accuracy error versus range detection, and every estimation algorithm suffers uncertainty in generating a geometrical model of the previewed roadway from the measured road layout data. The resultant uncertainties in distance, width, and slope of upcoming roadway will cause difficulty in monitoring the vehicle status.

The goal of this Item 1 is to generate *models* for the lane sensing algorithms. These models will be expressed in a mathematical form (e.g., deterministic or stochastic form), such that a set of parameter values in the models represents a paired sensor and processing algorithm. The models could be as simple as an algebraic relation or as complicated as a stochastic differential equation, but are expected to characterize limitations in range detection of different sensing systems and uncertainties at the detected range level. In this way, lane sensor characteristics can be included for estimating the previewed roadway and judging the status of the steering performance of the vehicle. Another advantage of this approach is that from the desired accuracy specifications in estimating the previewed roadway, performance requirements for lane sensors can be obtained and utilized in selecting the best choice of lane sensing system.

A literature review for this item is under way and will be finished by November, 1992. This sensing characterization and modeling work will be completed by June, 1993.

Item 2: Determination of Time-To-Lane Crossing

Time-to-lane-crossing (TLC) is selected as a measure of the *lane tracking margin* and considered as a potential tool for the monitoring of vehicle motion relative to the highway. TLC was initially introduced by Godthelp and Konings [1981] so as to understand a driver's strategy. They assume fixed steering angle and calculate TLC at different speeds on the basis of the lateral lane position, heading angle, vehicle speed, and steering angle. The amount of TLC at every moment represents time after which the vehicle could depart from the lane. Ideally, the value of this measure should be kept large enough for the driver to respond in preventing lane departure.

For the accurate determination of TLC, the projected route of the vehicle and the previewed roadway should be available *a priori* for some distance downrange. The main limitation of conventional methods for determining TLC is that the projected route is calculated based on a fixed linear model of a vehicle, and the previewed roadway is assumed to be measured accurately. However, the model of vehicle curvilinear response to steering is known to have severe nonlinearity depending on speed, road and tire properties, vehicle loading, etc. The previewed roadway can be estimated only with certain nonzero error because of a lack of sensor and processor technology. Therefore, accurate calculation of the TLC for a wide variety of driving conditions requires the consideration of nonlinearity of the vehicle steering mechanism and uncertainty of lane sensing together. The latter will be examined closely in our Item 1 study.

In this item, the non-linearity of the steering mechanism is described by an adaptive modeling technique as shown in Figure 4 so that the vehicle model is updated based on the error between measured and estimated steering angle or lateral motion. Then the time-to-lane-crossing (TLC) will be calculated based on the adaptive vehicle model and Item 1 study (see Figure 5). A preliminary study with a second-order model was finished (August, 1992) and its result demonstrates the feasibility of using a low-order model for calculating the projected vehicle route. Another preliminary study for lane-sensing software including TLC calculation was accomplished by UMTRI researchers and examples of them are illustrated in Appendix B. The development of the proposed TLC algorithm will be completed by June, 1993 in parallel with Item 1.

Item 3: Development of the Driver State Model

In our active safety-control system, the driver is assumed to play an active role. Thus, it is necessary that the driver's status in terms of alertness, drowsiness, or drunkenness should be characterized as inputs to the control system in the form of a model, with numerical values for each model parameter. As the status of the human operator changes due to the above issues during driving, the driver model needs to be updated so that the parameter values of the model represent the current driving status. For example, the status can be modeled as reaction time delay, gain, time constant, or frequency characteristics such as crossover frequency. Of course, the inclusion of the driver model will make the control synthesis problem difficult because the human-factors knowledge base is limited relative to the various forms of degradation in the human steering performance. But, the accurate determination of driver status is key to the operation of an active safety-control system, which properly initiates warning/intervention/control action in order to prevent run-off-road accidents.

The literature review for this item is finished and included in the attached Bibliography (see Appendix A). Several possibilities of the driver status model (e.g., deterministic, stochastic, or artificially intelligent approach) are under study. For example, an adaptive driver model is considered as a potential candidate to represent the driver state changes. In addition, the history of TLC obtained in Item 2 is believed to show the driver's steering performance or driving style in a certain way. This driver model will be developed by UMTRI researchers and MEAM faculty and staff, and is expected to be completed by August, 1993.

Stage II: Synthesis for run-off-road warning/intervention/control

This stage is the integration process of all the information obtained in Stage I so that the integrated system controls the vehicle's lateral motion in cooperation with the driver. In particular, this stage involves decision rules about how and when to produce warning signals, and it is based on many human-factors data and monitoring data of vehicle/driver. If the driver's response to the warning signal is not fast enough, the active safety control system will be designed to compensate the steering error. If the driver does not respond to a critical warning signal, the control system will take over steering control. However, the driver may be expected to take control back in case of a system failure or other emergency situation.

A literature review regarding decision rules such as fuzzy logic and/or neural networks is included in the attached bibliography (see Appendix A). Development of the fuzzy logic controllers for vehicle steering systems is in the conceptual design stage and is expected to be completed by December, 1993.

Stage III: Evaluation through simulations and experiments

To evaluate the proposed active safety-control system, a vehicle simulator is being developed in software and hardware by UMTRI researchers and MEAM faculty and staff. Several versions of driving simulators have been investigated by UMTRI researchers, and a steering-wheel input device was built by ME568 students [ME 568 Project Reports, 1992]. A desktop driving simulator developed by UMTRI researchers is briefly introduced in Appendix C. This simulator will be improved by including an active steering actuator and external controller by June, 1993. This "hardware/software" version of the simulator will be used to carry out experimental studies of not only each item of Stage I, but also stage II.

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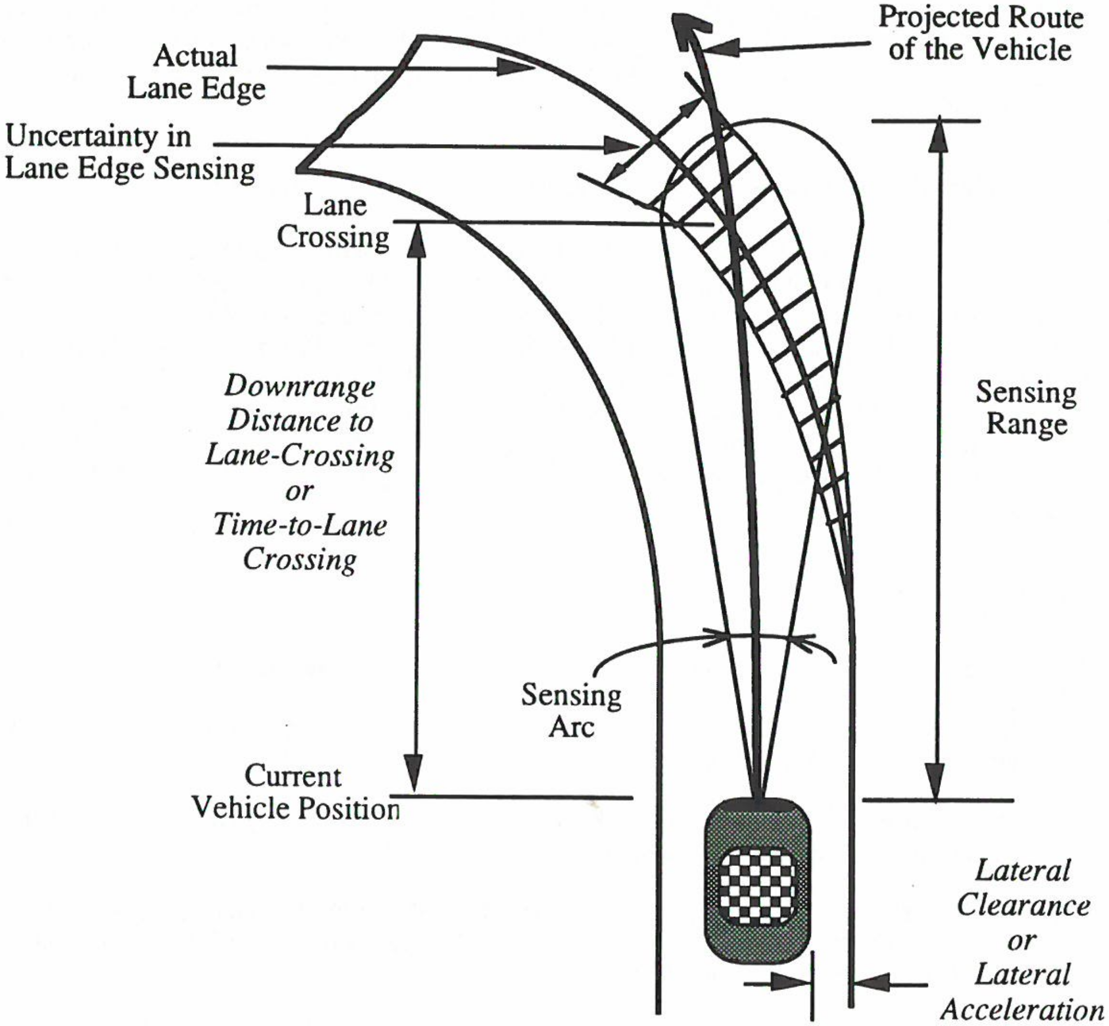

Figure 1: Elements of lane sensing and analysis of tracking margins

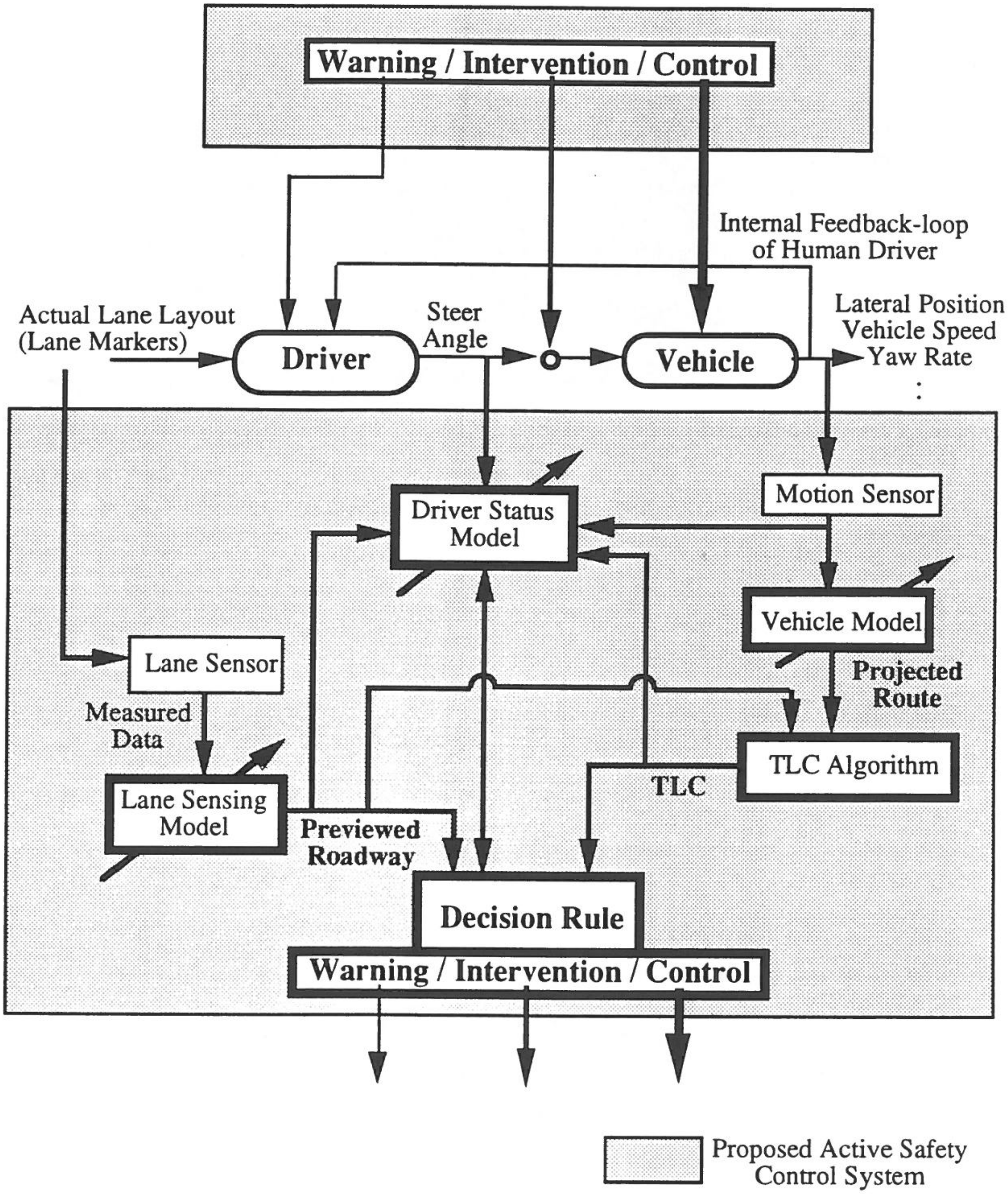

Figure 2: Structure of the active safety control system

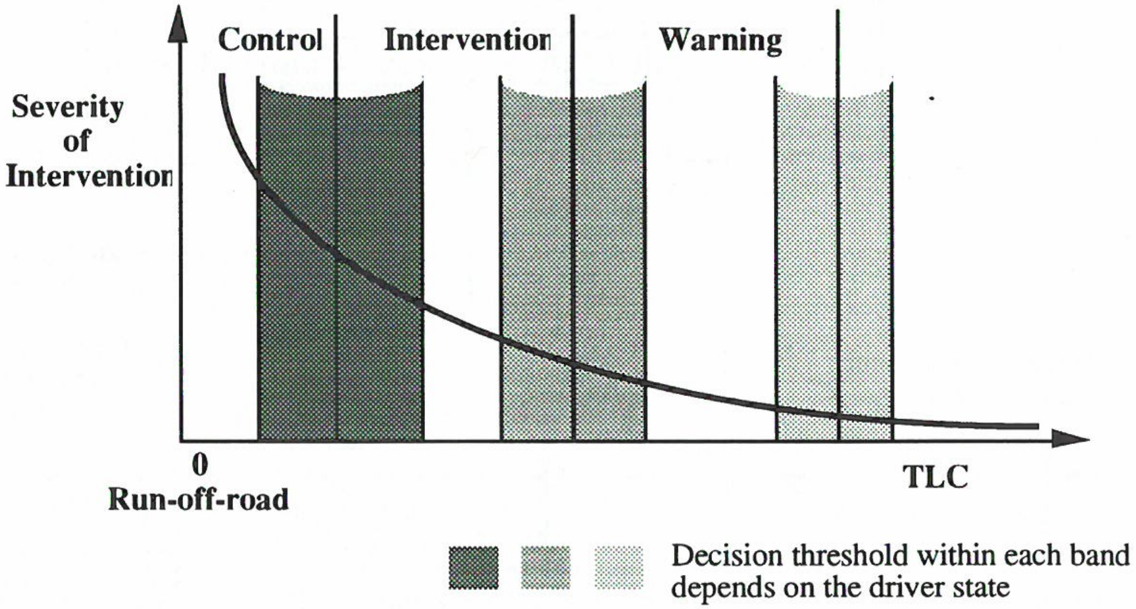

Figure 3: Decision for warning/intervention/control

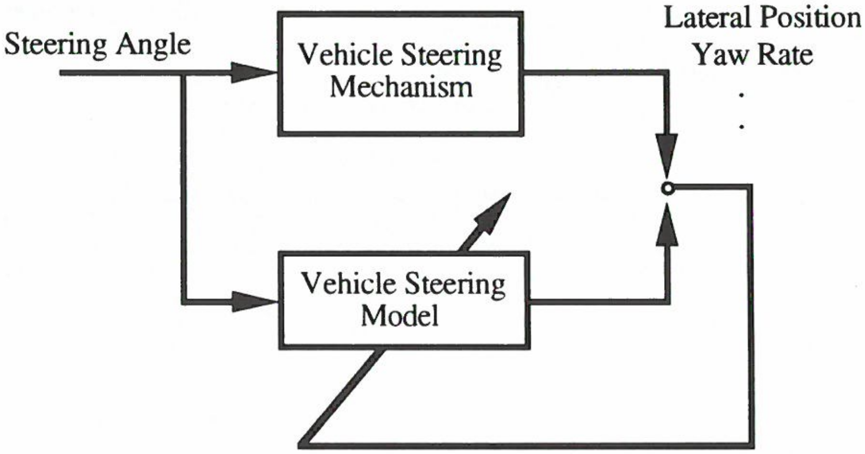

Figure 4: Adaptive modeling of the steering system

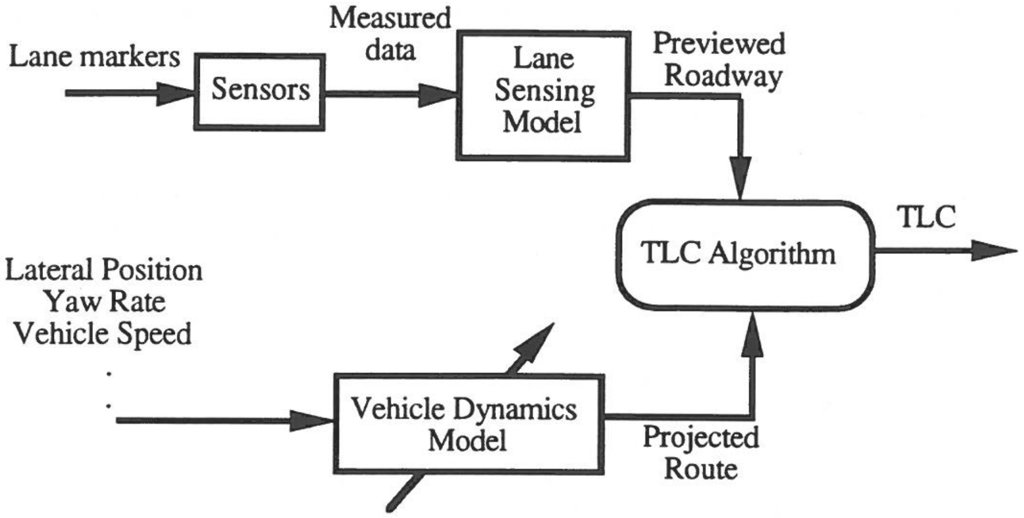

Figure 5: The proposed TLC determination scheme

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APPENDIX B. SOFTWARE AND EXAMPLE CALCULATIONS.

This appendix contains a summary discussion of the lane-sensing software being developed under this project and a set of example calculations to illustrate the current capabilities of the evolving software tool. Figure B.1 contains a diagram of the principal ingredients of the lane-sensing software. The top portion of the figure represents a typical driver/vehicle system with an input from the "Road Ahead" block that represents the normally previewed roadway scene that all drivers see when driving. In the lower portion of the diagram, a similar block represents a potential on-board *codriver* technology that might be envisioned for warning and control purposes as part of a lane-sensing system. It is assumed that such a codriver technology would be able to predict future motion of the driver/vehicle system (contained in the upper portion of the diagram) and also to sense/measure road lane edges for comparison with the predicted vehicle motion. An interface block, labeled *Vehicle/Driver Sensor Package*, between the driver/vehicle system and the codriver technology blocks, explicitly identifies the potential use of additional sensors to measure driver and vehicle responses as part of a candidate lane-sensing system. This additionally sensed information supplements the *Lane Sensor* block (within the codriver structure) and would normally be used to monitor the driver/vehicle system responses. This information is also used to update or correct the codriver's current model in order for path prediction, warning, and control. Driver warning or control intervention algorithms could then be based, as depicted in the diagram, upon predicted path errors by the codriver, or possibly, upon differences in steering control responses by the actual driver and the codriver. Consequently, a variety of software modules are represented within the lane-sensing software tool, each of which may be developed with varying degrees of detail, depending upon a particular user's needs or purposes.

In order to illustrate how such a package might be used to examine variations in system performance for a candidate lane-sensing concept, a set of example calculations follow. These calculations are for a nominal passenger car/driver system maneuvering along an S-curve roadway at 45 mph. The geometry of the example road is illustrated in Figure B.2.

Three sets of calculations are shown. The first set is for a normal driver/vehicle system equipped with a lane-sensing system operating normally insofar as its ability to accurately predict future vehicle motion over a preview time (or distance) of several seconds. The path prediction algorithm relies upon current vehicle position, heading angle, and lateral acceleration (as deduced from driver steering and an appropriate gain factor). A second set of calculations illustrates the same baseline driver/vehicle system operating with a lane-sensor package that possesses a faulty sensor (lateral accelerometer, or gain factor in this case), thereby causing exaggerated predictions of future vehicle path in response to normal driver steering motion. The third example calculation, assumes an impaired driver (represented by a large driver time delay) operating with a normally or well operating lane-sensor system. These three brief examples help to illustrate how such a software tool can be used ultimately to study and design various lane-sensing concepts, as well as how such systems are likely to interact with and affect actual vehicle responses or driver behavior.

Output from a computer animation program is used in Figures B.3-a, b, and c, to show results from each of the three sets of calculations mentioned above. Figure B.3-a corresponds to the baseline driver/vehicle system equipped with a well operating lane-sensing and path prediction system. Eight frames appear in each figure and correspond to snapshots of the maneuver at 1-second intervals. (A frame count and time measure appear in the upper left corner of each animation frame.) A curved trajectory also appears in each animation frame in front of the vehicle. This curved line represents the future path being predicted by the codriver technology over a 1.5-second preview interval at that particular point in the maneuver. As seen in Figure B.3-a, the codriver for the baseline vehicle case is able to accurately predict in most instances the future trajectory of the vehicle.

In Figure B.3-b, the lateral accelerometer sensor gain has been *detuned* to represent a faulty sensor example. In this case, the future path being predicted by the codriver technology (which uses the accelerometer information) is erroneous and far too aggressive in its estimate of future vehicle position. Needless to say, such a system, if implemented, would be issuing faulty warnings at frequent intervals.

In Figure B.3-c, an impaired or intoxicated driver is being simulated (through use of an increased time delay characteristic in the driver model) while operating with a normally functioning codriver lane-sensing system. As seen in this set of animation frames, the path response of the vehicle (controlled by the impaired driver) is highly erratic as evidenced by the vehicle leaving the roadway on the outside of each curve. However, the future paths being predicted by the lane-sensing system are quite accurate as to where the vehicle is headed at each instant of time. Accordingly, a well operating lane-sensing system in this type of scenario could be particularly useful in providing warnings or control assists to a driver.

As noted previously in the main body of this report, one method of issuing warnings to drivers by lane-sensing systems could be through the use of time-to-line-crossing (TLC) calculations within the codriver system. To illustrate what TLC calculations look like over time, a set of TLC time history calculations were performed for the three example cases just described. In Figure B.4, the TLC time history calculation is seen for the baseline case corresponding to Figure B.3-a. As TLC values decrease, the likelihood of leaving the roadway increases; as TLC values increase, the likelihood of roadway departure decreases. The "dips" or reduced values of TLC seen in Figure B.4 correspond to locations along the S-curve maneuver where the vehicle is entering or leaving each curve. Minimum values of 1.6 seconds in this example indicate a danger of exceeding the +/- 10-foot envelope surrounding the roadway centerline (set as a threshold in this particular codriver algorithm) in that time interval if no further steering corrections are provided by the driver.

To see how TLC calculations vary when the baseline driver/vehicle system calculations are compared with the fault sensor and impaired driver cases, all three TLC calculations are overlaid in Figure B.5. Although this chart is somewhat difficult to read, the two alternate cases clearly indicate lower minimum values of TLC, as well as lower TLC values through most of the maneuver.

The final figure, B.6, shows time history plots for driver steering requirements from the simulation software. These waveforms indicate the level and nature of road-wheel steering needed to negotiate the indicated S-curve maneuver. The baseline and faulty sensor cases show the same driver steering response. (Since the sensor information is not being used for control purposes, it does not affect the driver steering response in these two cases — only the degree of accuracy in codriver path prediction.) The impaired driver steering waveform, however, does show the influence of increasing the driver's latency, which, in turn, causes the driver steering response to be less accurate and to exhibit oscillatory and more lightly damped characteristics. The driver response impairment and resulting steering behavior are more clearly illustrated in Figure B.3-c where the degraded path-tracking ability is very evident.

Figure B.1 Structure of the lane-departure warning and control software tool.

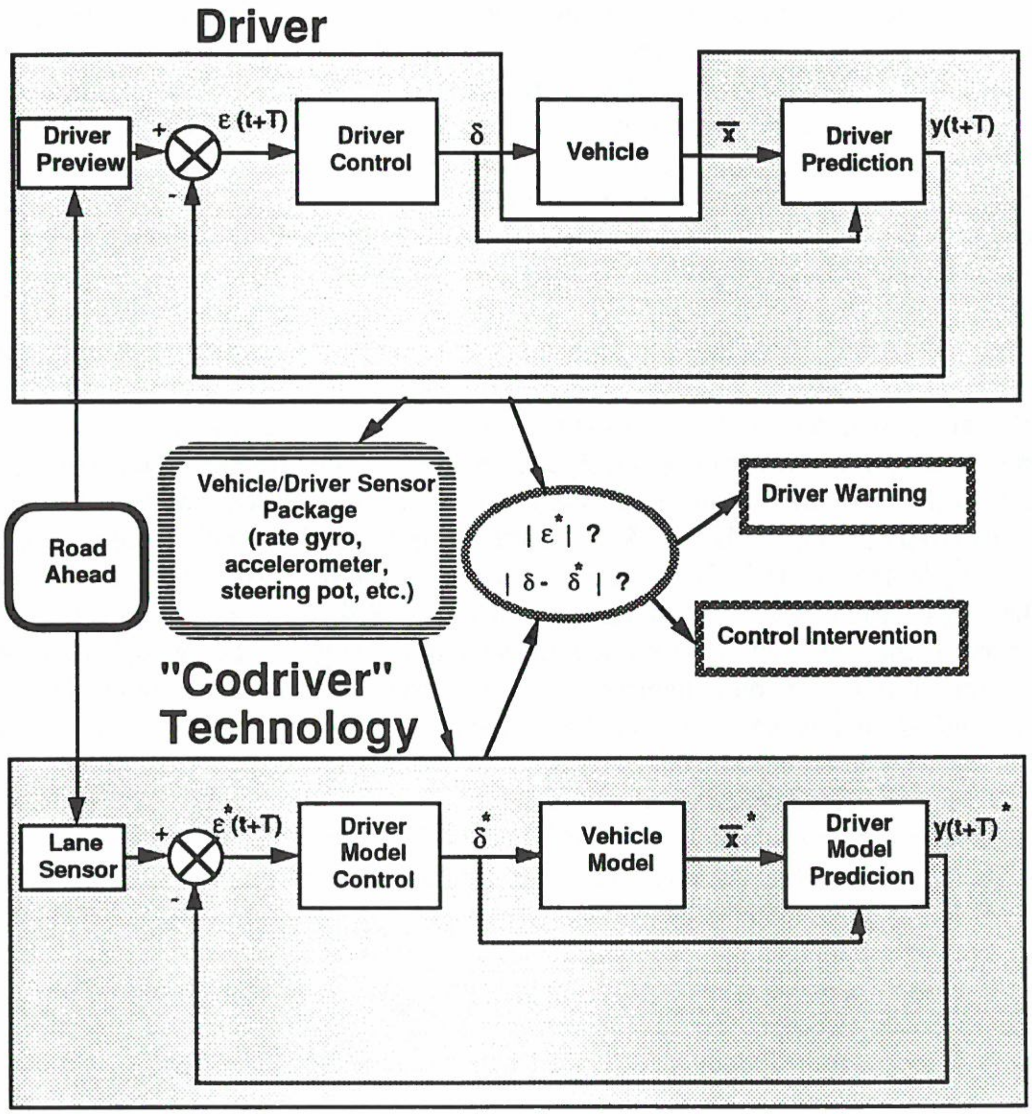


Figure B.2 Geometry of the S-curve used in the example calculations.

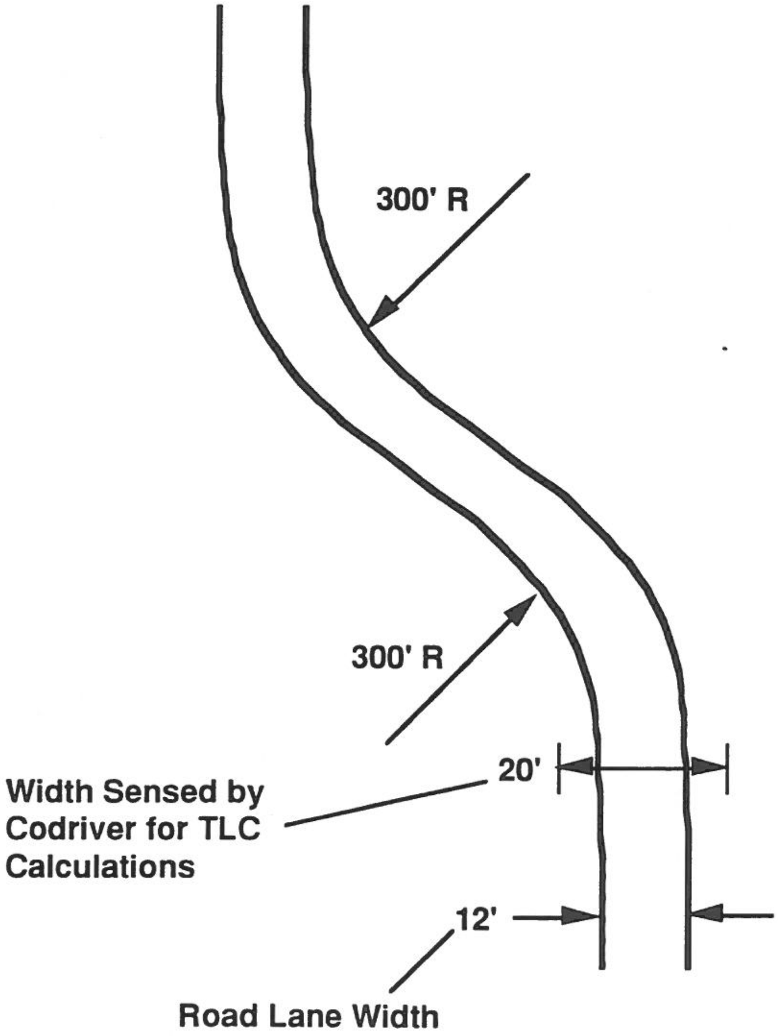


Figure B.3-a. Baseline Driver/Vehicle System & Co-Driver

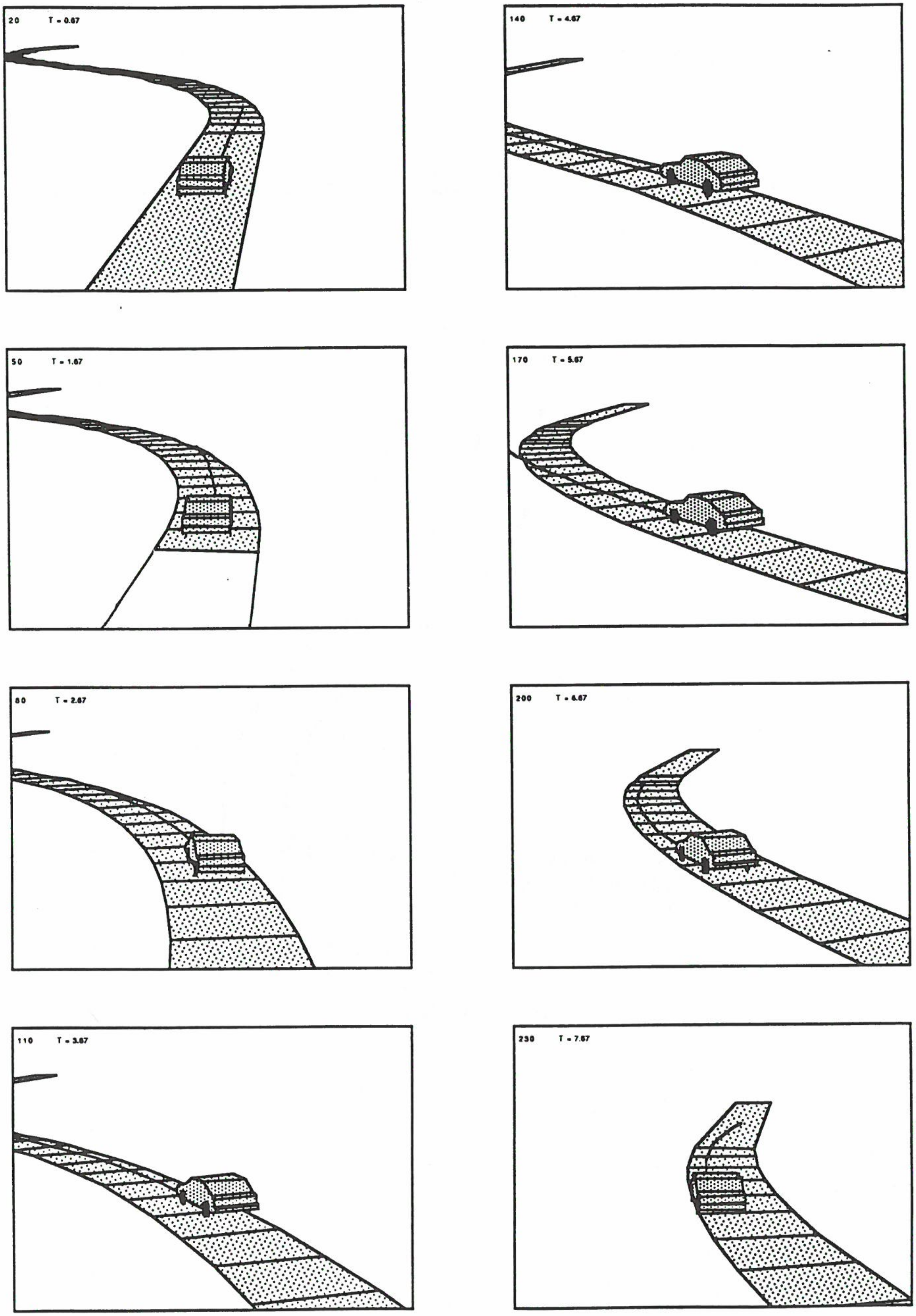
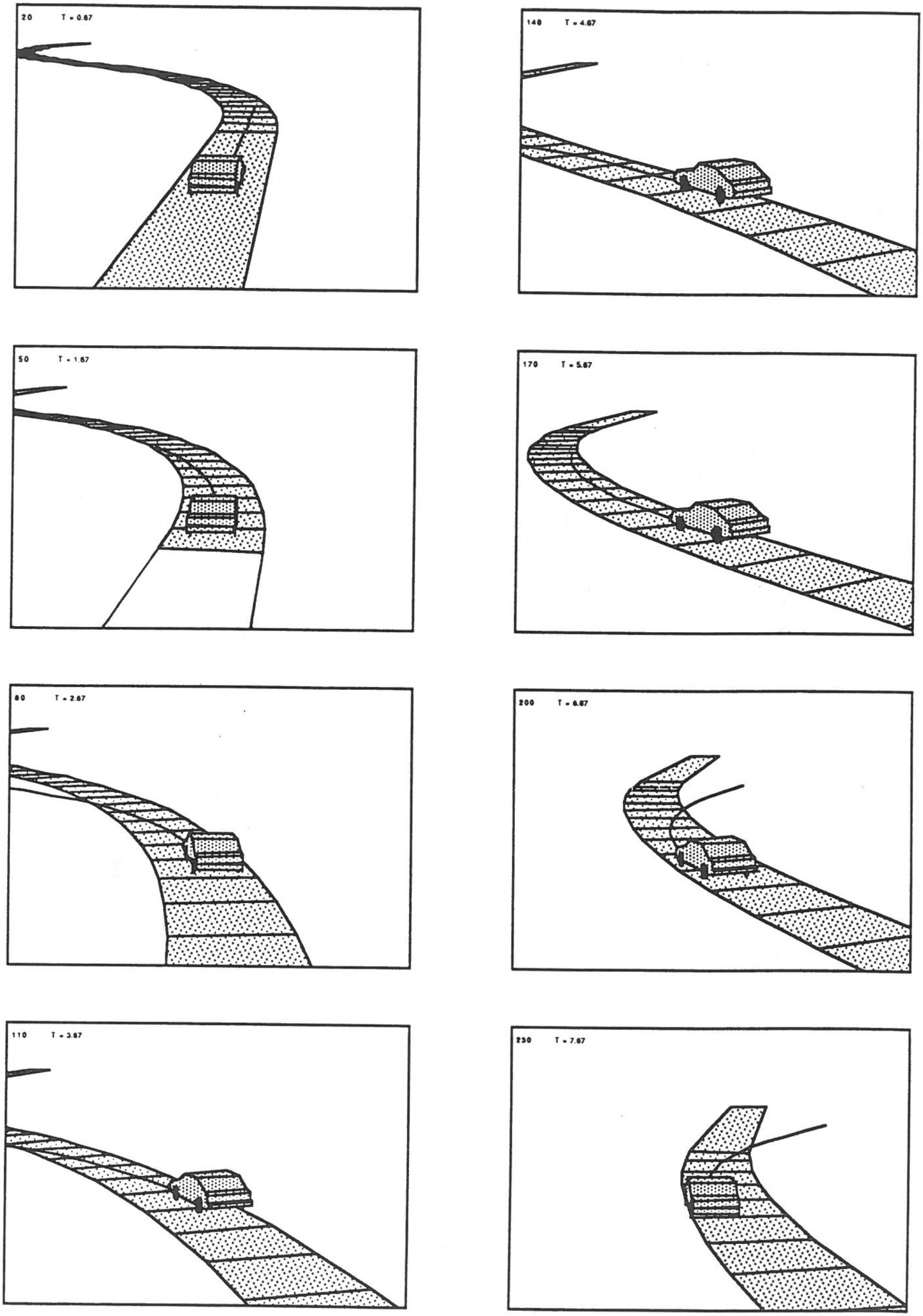


Figure B.3-b. Faulty Sensor Gain Example.



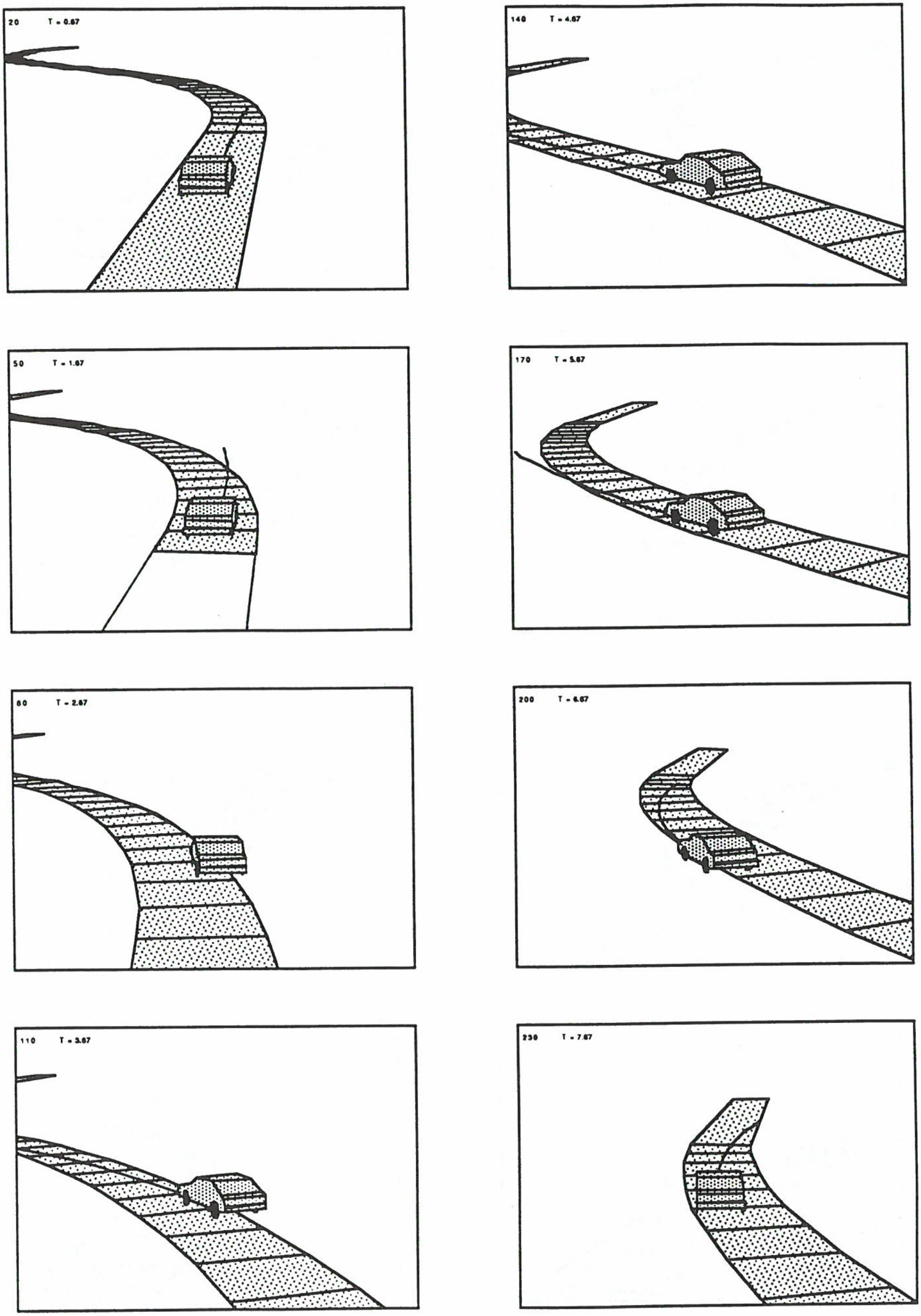


Figure B.3-c. Impaired Driver Case.

Figure B.4 Time-to-lane-crossing (TLC) calculation for the baseline driver/vehicle system. (S-curve maneuver at 45 mph.)

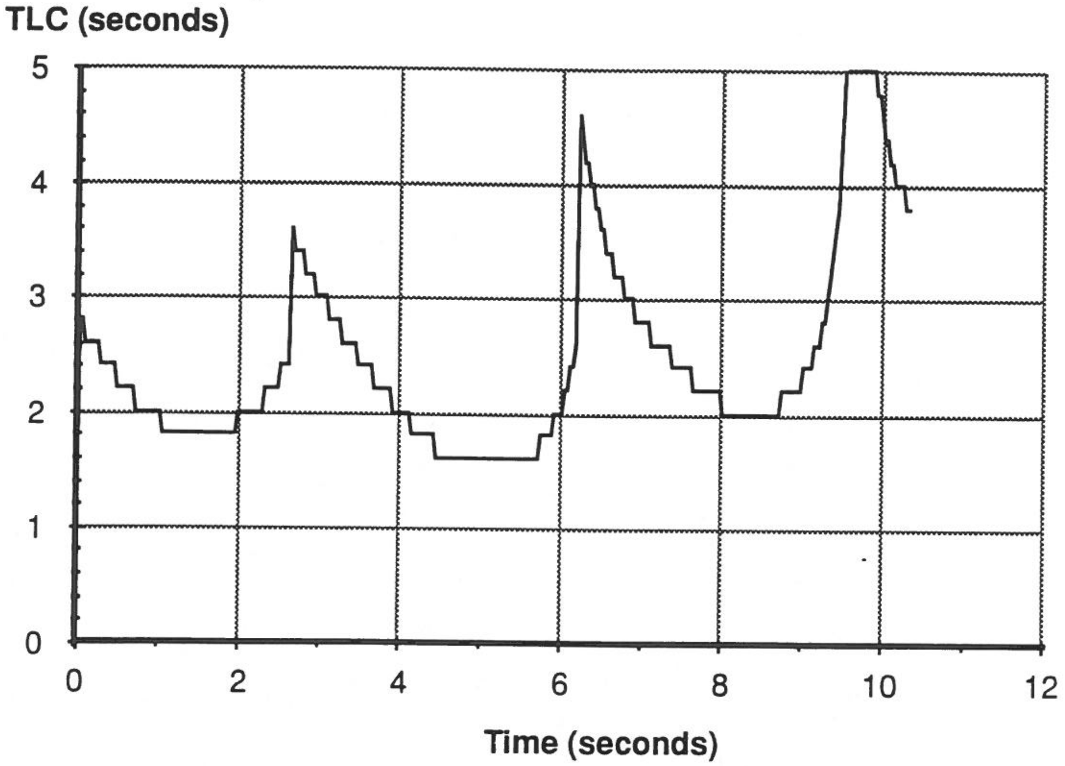


Figure B.5 Time-to-lane-crossing (TLC) calculation for the baseline driver/vehicle system and two system variations. (S-curve maneuver at 45 mph.)

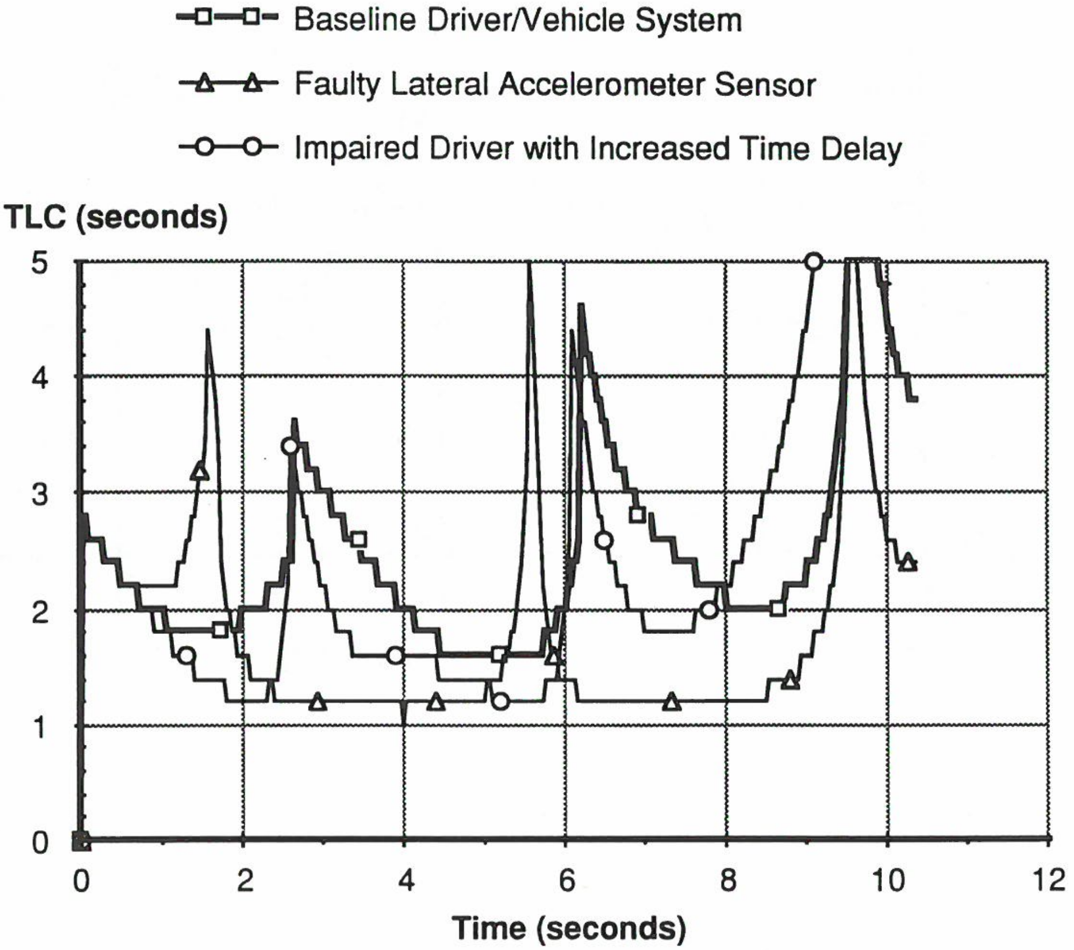
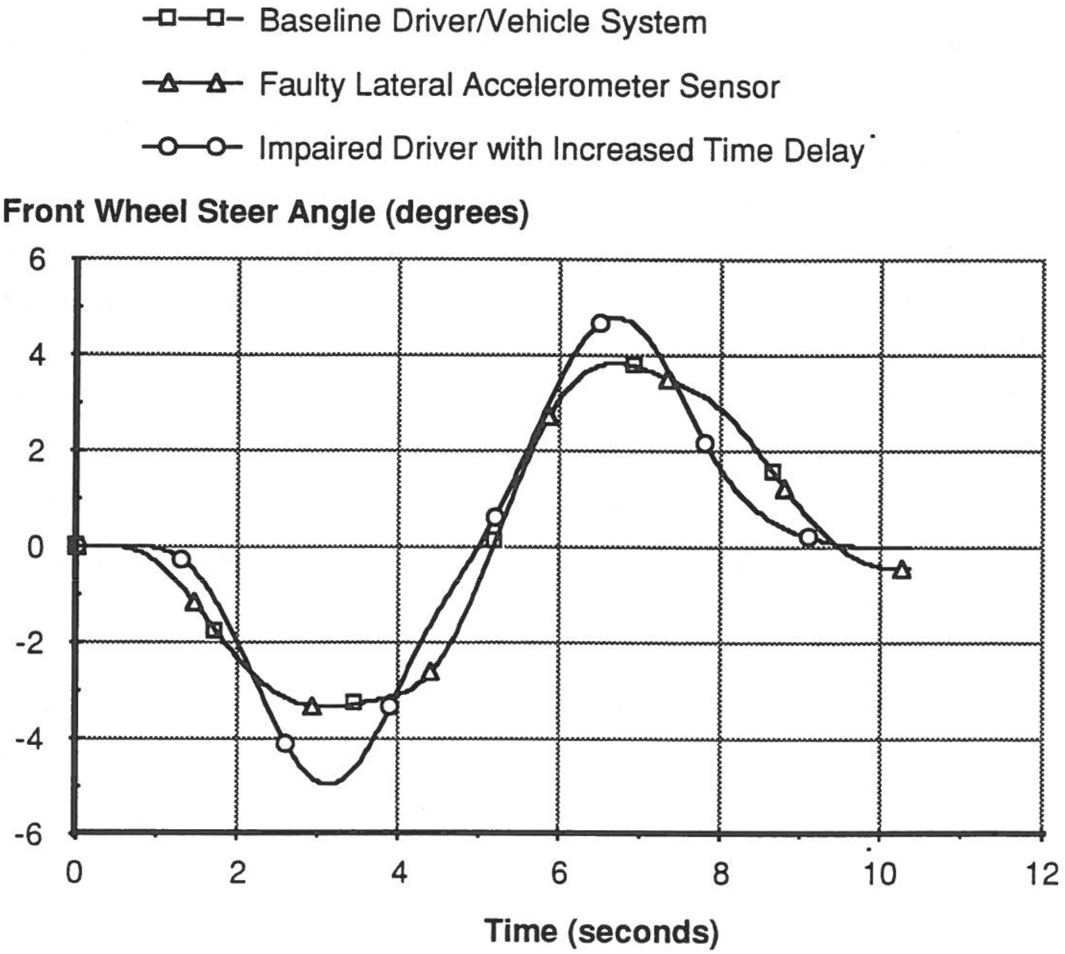


Figure B.6 Driver steering control responses.
S-curve maneuver at 45 mph.



APPENDIX C. DESKTOP DRIVING SIMULATOR EXAMPLE.

Figure C.1 presents an example of a desktop driving simulator that could be used to study and try out various types of lane-sensing concepts within a simplified but real-time driving environment. The primary driving simulator and screen display seen here are programmed and generated on a Macintosh Quadra 700 seen on the left of Figure C.1. (An optional side-task simulator and its display are seen on the right side of the figure.) The Quadra generates scene information in this particular application at a frame rate of 25 Hz. In addition, the Quadra simulator easily collects eight channels of driver-vehicle data at 25 Hz during subject tests and can be used to conduct postprocessing data analyses.

The automobile steering wheel seen in Figure C.1 is mounted on a portable board-like assembly. An elastic cord wound around a hub on the steering-wheel rotational axis provides a modest centering torque for the driver. A rotary potentiometer attached to the end of the steering shaft provides an electrical measurement of the driver steering angle. The steering-wheel signal is digitized during each calculation frame by an analog-to-digital interface card in the Quadra, and that signal is then used in the simulation equations to steer the vehicle.

Figure C.2 shows the basic driving scene used in the desktop simulator. Pull-down menus and associated dialog boxes provide a convenient software interface for interacting and controlling the simulator characteristics. Devices similar to this could be used as preliminary test-beds for evaluating various lane-sensing concepts developed initially with the software tools discussed previously in the body of the report and Appendix B.

Figure C.1 Basic desktop simulator arrangement with optical side-task display

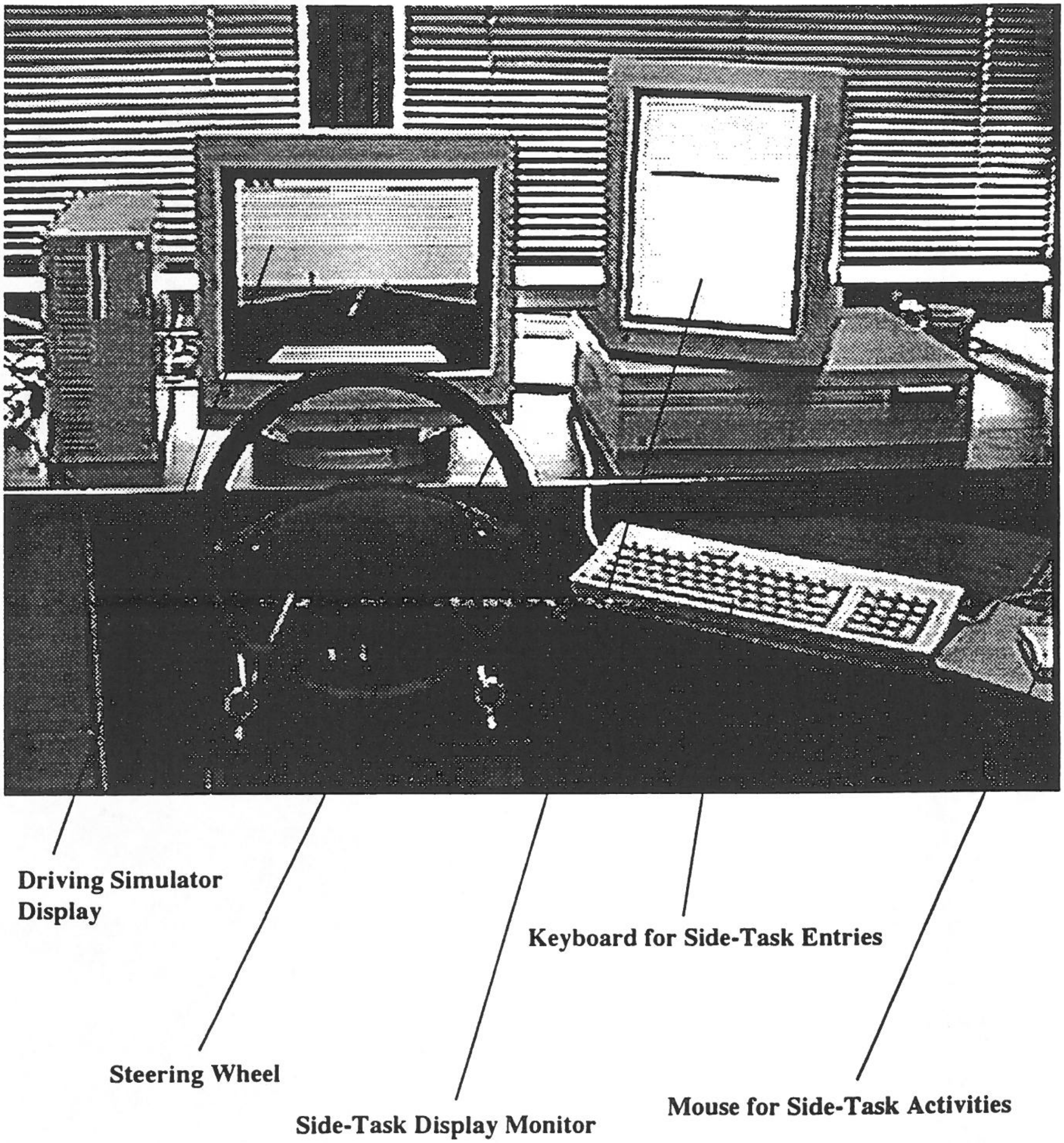


Figure C.2 Example Driving Scene.