Title
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Report for MOU 324

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EXECUTIVE SUMMARY

This document is the final report for the project of MOU324 for the fiscal years of 1997-2000, which is a continuation of MOU252 from the years of 1995-1997. The major accomplishments from this project can be categorized into the following areas:

1. Adoption of a vehicle-collision simulation tool with an interface that allows the implementation of feedback controller.
2. Thorough analysis and modeling of vehicle lateral dynamics in collision situations, which permits the selection and design of controllers for emergency conditions.
3. Validation of feasibility of applying steering control in vehicle-following conditions to stabilize vehicle trajectories, thus establishing an option of control strategies in safety-critical operations.

Collisions between vehicles in typical highway operating conditions can lead to significant deviations of vehicle trajectories from their original lanes. Without proper control, the alteration of vehicle trajectories may result in subsequent impacts and considerable consequences. With the latest developments of advanced vehicle control and sensing capabilities, it is appropriate to consider the post-impact handling strategies for accident mitigation. Since collisions often generate impulses of substantial magnitude, it is unrealistic to apply effective control during the collision phase of an impact. Instead, the problem is approached by treating the vehicle states with given initial condition yielded by the impact and the following attempts to bring the vehicles into the desired states.

This study addresses the feasibility of post-impact maneuvers that aim to mitigate accident sequences. In particular, the discussions emphasize the possibility of applying steering control to stabilize the trajectories of vehicles involved in a collision. The problem of interest is defined with descriptions of accident scenarios, limitations of applicability, and performance requirements. A model of vehicle dynamics is constructed to facilitate the design of steering controllers. Various collision scenarios are simulated to demonstrate the effectiveness of a generic
feedback controller. The analysis provided herein shows steering control is promising as a driver-assistance function in emergency situations.

To evaluate a wide range of operating scenarios, a simple yet robust controller is desirable for the purpose of this study. A generic look-ahead controller, which has been tested extensively in experiments, is chosen for analysis, modeling, and simulation. The analysis shows that the selected generic controller is effective. More importantly, the control parameters selected for a sample vehicle demonstrate robust results for a variety of operating scenarios. The robustness of the control system is extremely critical, because the intended application is open to a number of uncertainty and disturbances in its operating environment.

There are a variety of issues that need to be resolved before the suggested function can be successfully realized for practical purposes. The reliability of sensing systems to provide consistent and accurate information is essential. The strategy of recovering or securing sensing data in emergency and collision situations will determine the validity of feedback control. The physical limitations of control systems must be fully evaluated to establish the accident scenarios suitable for activating the driver-assistance function. These remain topics of future studies.

**KEY WORDS:**

Vehicle Collisions  
Simulation of Vehicle Crashes  
Vehicle Control in Collisions  
Advanced Vehicle Control Systems
1.0 INTRODUCTION

This document is the final report for the project of MOU324 conducted over the fiscal years of 1997-2000, which is a continuation from MOU324 in the years of 1995-1997.

When dealing with hazards of driving on highways, safety countermeasures can be categorized into two major areas: (a) accident prevention and avoidance, and (b) damage mitigation and post-accident handling. This project deals with certain aspects in the second category. Mainly, the study presented here focuses on the feasibility of maintaining vehicle trajectories after a vehicle-following collision has occurred.

Over the last few years, PATH researchers have made significant progresses in demonstrating automated vehicle control systems. [1,2] Automated control vehicles are candidates for future ground transportation systems as well as near-term applications of precision guidance and docking. It has been shown that with the aid of a proper lateral positioning system, vehicles can be laterally controlled within a narrow designated path with precision and robustness [3]. Furthermore, under emergency conditions such as a tire-blowout, the goal of lane tracking can still be effectively maintained. [4]

Another area of studies in recent years at PATH investigated the effects of vehicle collisions under close-following conditions [5,6]. It was found that lateral offset, vehicle speed, and vehicle size all played important roles in affecting the outcome of collisions. Without control efforts after the initial collision, vehicles departed from the original path within one to three seconds. [7] Using an ad hoc approach to apply steering control in exemplar scenarios, it was shown that vehicles involved in a collision could be kept within a designated lane. [8]

The studies reported here contain work extended from the two aforementioned areas. The experiences learned from the research on vehicle-following collisions and control laws for lane tracking were combined to examine the feasibility of using feedback controllers in collision situations. The study utilized an existent and validated vehicle model to simulate collision dynamics, which is summarized in Section 3.0. The formulation of the vehicle lane-tracking problem in collisions and the corresponding controller requirements was presented in Section 4. A generic controller was proposed and incorporated into the vehicle collision and dynamic model that allows the application of steering efforts immediately following a collision. Controller gains and other system parameters were varied to investigate the effectiveness of control efforts in stabilizing vehicle trajectories. The simulation results and related discussions were included in Section 5.

The controller was proven effective in various collision conditions. Straight and curved-roads scenarios are both tested. Time delay in sensing or actuation cycles and wheel angle offset due to collision damage were added to complicate system scenarios. With proper selection of control parameters, the controller is effective and robust, which is significant since the practical
implementation of such a control system as an automated or driver-assistance function requires that the control law is applicable in a wide variety of conditions.

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3. Validation of feasibility of applying steering control in vehicle-following conditions to stabilize vehicle trajectories, thus establishing an option of control strategies in safety-critical operations.

2.0 RESEARCH SCOPE AND APPROACH

In typical highway driving conditions, a collision between two closely following vehicles can result in significant deviation and rotation in vehicle movements. These motions in turn may lead to devastating consequences with other surrounding vehicles. To mitigate the seriousness of such accidents, it will be beneficial to provide a lane-tracking function that helps maintain proper vehicle trajectories once a collision occurs. This is the primary topic of this research project.

Due to the difficulties and costs in testing in collision situations, the study was conducted with a combined model of collision and vehicle dynamics, SMAC (Simulation Model of Automobile Collisions) [9-11]. SMAC allows the longitudinal and lateral movements as well as the yaw motion about the vertical axis of vehicles on a horizontal plane. A controller is incorporated into the model to allow steering inputs.

To evaluate a wide range of operating scenarios, a simple yet robust controller is desirable for the purpose of this study. A generic look-ahead controller, which has been tested extensively in experiments, is chosen for analysis, modeling, and simulation. The analysis shows that the selected generic controller is effective. More importantly, the control parameters selected for a sample vehicle demonstrate robust results for a variety of operating scenarios. The robustness of the control system is extremely critical, because the intended application is open to a number of uncertainty and disturbances in its operating environment.

2.1 Accident Types and Situations

With regards to the defined problem, a collision can result from the following categories of incidents:

1. A vehicle fails to detect a stationary vehicle or obstacle.
2. A vehicle in front is slowing but the trailing vehicle fails to slow down.
3. A vehicle impacts another vehicle in a lane-changing maneuver.
Depending on the circumstances of accidents, the types of collisions and related maneuvers afterward may fall into the following categories:

1. A vehicle impacts a stopped object. The objective is to maintain the vehicle in a proper path after the impact.
2. Two vehicles travel in the same lane. The trailing vehicle causes rear-ends the leading vehicle. The objective is to maintain the trajectories of one or both vehicles in the original lane.
3. A vehicle, while making a lane change, impacts a vehicle in front before it leaves the original lane due to insufficient spacing. The objective is to finish the lane change maneuver for the subject vehicle and/or maintain the path of the vehicle that was impacted from behind.
4. A vehicle, while making a lane change, impacts a vehicle in front in the target lane. The objective is to finish the lane change maneuver for the subject vehicle and/or maintain the path of the vehicle impacted from behind.
5. A vehicle makes a lane change into an adjacent lane. A vehicle trailing behind rear-ends the lane-changing vehicle. The objective is to maintain the paths of one or both vehicles.
6. A vehicle cuts into the path of another vehicle and causes a sideswipe accident. The objective is to maintain the path of the vehicle that is hit on the side in the adjacent lane and/or bring the intruding vehicle back to the original lane.

Despite the seemingly diverse situations of these accident types, the nature of the problem remains the same. The feasibility of performing lane-tracking control is bounded by the physical limitations of exercising control to keep the vehicles states within acceptable errors and the ability to obtain the necessary information or measurements as inputs to the controller. The physical limitations refer to the integrity of the steering system and the magnitude of disturbances received from the impact. The information needed for controller inputs include the current vehicle states, such as positions within a lane and yaw angle relative to the lane orientation, and the desired trajectory, such as the “proper” lane to settle into. The real challenge lies in the integrity of the sensing system that provides the sources for determining the desired trajectory. For example, if a collision occurs in the course of a lane-change maneuver, the system must recognize the position, angle, and road trajectory despite the extreme disturbances occurring to the vehicles.

Another group of accidents related to the problem of interest is potential multiple-car accidents on a highway. Besides the issues described above, the primary questions in these cases are:

1. Whether a vehicle suffering multiple impacts can be controlled effectively?
2. What is the appropriate strategy of vehicle control to optimize the outcome or minimize the total risks if the movements of all vehicles can be coordinated?

The second question is more closely associated with an automated highway system, such as a platoon operation [12,13], as opposed to an emergency-assistance function being discussed here. From an evaluation perspective, however, the two newly added questions do not alter the nature of the problem. The answer to the first question still resides within the same boundary existent
for other accidents discussed above. When a vehicle is involved in a multiple-car accident, either it experiences multiple impacts simultaneously or it receives multiple impacts in sequence. Both of these situations still require the same assessment of disturbance magnitude and physical integrity of on-board systems.

2.2 System Limitations

In order for the proposed lane-tracking function to perform effectively, the steering system must function adequately after the collision, even if the system only survives for a short time span. This requirement implies that:

(a) The collision does not disable the steering system of either vehicle immediately. In a vehicle-following collision with two equally weighted passenger cars, it probably means that the speed differential between the two vehicles at impact is less than 10-15 m/sec, which is equivalent to a vehicle-to-barrier crash of 5-7.5 m/sec or 18-27 kmph. A crash of this magnitude will be severe enough to crush the bumper and a portion of the vehicle structure, but leave the wheels and the steering mechanism intact. Of course, the exact degree of damage and the corresponding speed threshold depend on the structural integrity and crash characteristics of the vehicles.

(b) A limited degree of damage to the steering system may be tolerable. Potential bias or offset of steering wheel angles caused by the collision damage may be introduced into individual wheels after the initial impact. The offset will cause the steering command to be adjusted, but not detrimental to the final outcome of system performances.

(c) It was found in previous studies that the lane-tracking control system potentially could stabilize vehicle trajectories within two to three seconds after the collision. Although collision situations vary, previous analysis indicates that the steering system only needs to perform for a short period of time especially if the vehicles can be brought to a safe stop after the collision.

In the exemplar cases examined in this study, the vehicles are front steering vehicles. Since the mathematical modeling is based on a bicycle model, the steering angles on both front wheels are assumed to be the same. This does not represent a rigid constraint, but rather a choice of targeted vehicles in the study. As a matter of fact, if four-wheel steering feature is available, strategies to take advantage of the option of individual wheel steering should not be overlooked as a topic of separate studies.

When analyzing system limitations, one can approach the problem with a simplified mathematical model with the limit expressed by the changes incurred by an impact [4]. It can also be evaluated with a more complex model of collision and dynamic simulation [10,11]. The subject demands a thorough investigation of a greater scope, which will not be covered here.
2.3 Modeling, Analysis, and Simulation

In this study, a vehicle control problem in extreme conditions is investigated to assess the feasibility of using steering actions to stabilize vehicle trajectories. A mathematical model is used to formulate the transfer functions and to provide the foundation for vehicle dynamics analysis. Subsequently, a generic look-ahead controller is adopted for the targeted application.

Collisions between vehicles in typical highway operating conditions can lead to significant deviations of vehicle trajectories from their original lanes. Since collisions often generate impulses of substantial magnitude, it is unrealistic to apply effective control during the collision phase of an impact. Instead, the problem is approached by treating the vehicle states with given initial condition yielded by the impact and the following attempts to bring the vehicles into the desired states.

Extensive simulations of the proposed controller were conducted in a variety of collision situations with variations in operating conditions and design parameters. The results from previous simulations validate the mathematical analysis and prove the effectiveness of the controller. The fact that the chosen controller performs well and adequately for a wide range of operating situations illustrates the robustness of the selected approach, which is important for a safety-critical application.

3.0 DEVELOPMENT OF SIMULATION AND ANIMATION TOOLS

In the course of this project, existing software was combined with newly added feature and interface programs to generate simulation tools that facilitate the proposed studies. In this section, we described the work in two areas: vehicle dynamic simulation (SMAC) and simulation visualization (CARMMA), which will be elaborated in the following sections.

3.1 Modification of SMAC Codes

In this project, a simulation program was used to study the phenomena of vehicle dynamics in vehicle-following collisions. As part of the proposed work, the source codes of this simulation program was obtained and modified so that additional features can be incorporated into the codes to serve the purposes of research activities. Only a brief summary of the software is given here, the detailed descriptions can be found in a PATH working paper [9].

3.1.1 Background information on SMAC
The analysis of vehicle collisions in the work related to MOU-252, the predecessor of this project, was conducted with a simulation program developed by Engineering Dynamics Corporation (EDC) for PC-DOS platforms. The software package, EDSMAC (Engineering Dynamics Corporation Simulation Model of Automobile Collisions), is used for the analysis of two-vehicle collisions. It is based on a program called SMAC (Simulation Model of Automobile
Collisions) [10,11] initially developed by Calspan Corporation for National Highway Traffic Safety Administration (NHTSA) and subsequently improved by EDC [14-17]. EDSMAC uses a set of assumed or estimated parameters, including vehicle and roadway properties to predict the outcome of a collision. Engineers have been using this simulation program to analyze vehicle dynamics and the damage resulting from crashes. Researchers have found that the program yields reasonable results with sound input data [18-22].

Attempts were made at the beginning of MOU-324 to acquire the source codes of SMAC directly from NHTSA. Since the program was developed more than 20 years ago, efforts to track down and locate the source codes were not successful. Through a series of contacts, a copy of the source code was finally obtained from the University of Michigan Transportation Research Institute with the help of Charlie Compton and Joel MacWilliams of University of Michigan, Traffic Research Institute (UMTRI). The source code was written in FORTRAN with limited revisions by UMTRI researchers added to the original version.

3.1.2 Structure and Main Blocks of SMAC
The SMAC program is separated into several main parts:

1. Input phase: This portion receives the information regarding the integration and output time steps, the vehicle parameters, state variables such as position and speed, steering and tire torque inputs from an input file.
2. Trajectory phase: A subroutine and associated functions calculate the trajectories of the subject vehicles while the vehicles are not in a collision.
3. Collision phase: The collision routines determine if the vehicles are in contact and calculate the contact forces and its direction, which is then used to determine the subsequent motions of the vehicles.
4. Output phase: The states of the vehicles are printed at specified intervals, and also plotted on the terminal display if desired.

The plotting routines in the output phase were removed from the current version since it was originally designed to work with a plotting library on a mainframe computer. The plotting features can be added back if needed for a particular type of operating systems and their graphic libraries.

3.1.3 Modified and Added Options
These added features are implemented for the purpose of ongoing development work at PATH. The addition of these options allows the studies of vehicle dynamics and control algorithms in collisions.

3.1.3.1 Trajectory option
An integer flag, ITRAJ, is used to indicate the type of trajectories. The options are:

1. ITRAJ = 0: Straight Road Option.
2. ITRAJ = 1: Curved road option.
3. ITRAJ = 2: Designated trajectory given in a file.
3.1.3.2 Control option
An integer, ICNTRL, is used to indicate a few added options of executing the simulation. The options are:

1. ICNTRL = 1: Step input of steering at the front wheels.
2. ICNTRL = 2: Sinusoidal input of steering angle at the front wheels.
3. ICNTRL = 3: Feedback controller.
4. ICNTRL = 4: Feedback controllers with time delay.

In addition, two integer variables, IOPT1 and IOPT2, follow ICNTRL to indicate whether the control for each vehicle is turned on or off. If the integer value is zero the control is off and if the integer value is one then the control is on with the type control determined by ICNTRL.

3.1.4 Summary
This section summarizes the contents of SMAC source codes. The detailed documentation is provided in the related reports [9], which will allow future developers to utilize this program as a validation model or combine it with other simulation tools.

The author would like to express special thanks to Charlie Compton and Joel MacWilliams of University of Michigan, Traffic Research Institute (UMTRI) for their help in providing the source codes of SMAC. I would also like to thank Seymour Stern of National Highway Traffic Safety Administration (NHTSA), who directs me to Joel after a search for the source codes at NHTSA was unsuccessful.

3.2 Utilization of SMAC and Carmma for Animation and Visualization

This section gives a description of the functional capabilities of a series of computer programs that can be used to investigate the consequences of vehicle collisions. The core element of the simulation tools for vehicle collision dynamics is SMAC (Simulation Model of Automobile Collisions) program, which was highlighted in the previous section. Another main tool is Carmma, which possesses animation capability for simulations. It has been used to create highway scenarios and to generate and/or animate vehicle simulations. The combination of the two programs yields an interface between the simulation and animation programs so that users can observe the vehicle movement profiles before and after a collision given the input scenarios for vehicle operations.

3.2.1 Background Information on Carmma
Carmma was developed by PATH, at UC Berkeley Institute of Transportation Studies, as part of the National Automated Highway Systems Consortium Project. It was used to animate simulations of vehicles as part of the investigation of the feasibility of implementing future automated highway systems (AHS). It can be used to create and animate vehicle simulations or to animate data from other simulators such as SMAC. A graphical user interface can be used to create a highway scenario file, which defines the highway length, number of lanes and the initial
states of the vehicles. It can also be used to create animations using data from a highway scenario file with the vehicle trajectories created by other simulators. Revisions to the program were made to define the animation for either a straight or curved road depending on the vehicle trajectories determined by SMAC. Reference [23] contains a description of the Carmma Program.

3.2.2 Program Structure and Inter-relationship
In addition to SMAC and Carmma there are additional functions to aid the user in defining the input parameters and in preparing the necessary data for animations. A brief description of each function follows.

3.2.2.1 Posvel - Set vehicle positions and velocities in file INPUT.DAT
This function is not necessary if the user wishes to set all data in INPUT.DAT directly using an editor. The Posvel function prompts the user for the positions and velocities of the vehicles in meters and meters/sec. It leaves the other parameters in file INPUT.DAT at the original values. This function must be run before SMAC is run.

3.2.2.2 SMAC – Generate vehicle motion data
The SMAC simulator determines the distance/velocity profiles of two vehicles using input parameters including initial lateral and longitudinal positions and velocities. The input parameters are defined in file INPUT.DAT and the output files are OUTPUT.DAT, VEH1.DAT and VEH2.DAT.

3.2.2.3 Hwydata - Set vehicle scenario data for Carmma program animation
The Hwydata function uses the vehicle position and velocity data provided by SMAC in VEH1.DAT and VEH2.DAT to create the highway scenario file. This file contains the simulation data in a format usable by Carmma.

3.2.2.4 Carmma - Vehicle simulation animation program
Carmma is an animation program with a menu-driven user interface. It is used to animate simulations that have data defined in the highway scenario format.

3.2.2.5 Source Code and Executables for SMAC, Posvel, Hwydata and Carmma
The source code for SMAC is in FORTRAN 77. Posvel and Hwydata source code is written in the C language. Carmma source code is written in Tcl/Tk.

3.2.3 Summary
This section summarizes the functional capabilities of computer programs used for investigation of vehicle collisions. The tools include SMAC and Carmma, and the interface between the two main programs. By combining the simulation, animation and other tools into a coherent set of programs a user who conducts simulation studies can gain insight into vehicle behavior from the generation of detailed simulation output and the visual observations of the animations of vehicle trajectories. For more details, one can refer to the code documentations [24].
4.0 MODELING AND ANALYSIS

Presented in this section is an analysis of vehicle lateral dynamics and the approach suggested for controller design. A linearized lateral model was adopted to investigate the characteristics of vehicle dynamics and the performance requirements of steering controllers in vehicle-following collisions. Based on the mathematical models and assumed system conditions, a feedback controller was designed to serve the lane-keeping function immediately after the collision phase.

4.1 Problem Definition

The problem of interest is the effects of impulsive disturbances, such as those created by a collision, and the feasibility of applying steering control to stabilize vehicle trajectories under these conditions. The basic assumption is that the collision is not severe enough to disable the steering system. To account for potential damage in a collision, steering wheel offset should be allowed in these situations.

It is essential to first examine the magnitude of disturbances in a collision situation. In very general terms, the vehicle will experience sudden changes in velocities and yaw rates. For example, two vehicles of the same mass collide with a speed differential of 10 m/sec will each experience a 5 m/sec change in speed within a time frame of 80-150 milliseconds. For typical passenger cars, the peak acceleration measured at the center of gravity in such a collision may rise beyond 10 g (1g=9.8m/s²). The exact magnitude and direction of the changes in acceleration and velocity depend on vehicle structural characteristics as well as collision conditions.

If the acceleration magnitude as cited above is so much greater than what can be generated by tire forces, can a steering effort correct the trajectory of a vehicle in a collision? The answer lies in the nature of vehicle dynamics. The dynamic changes due to collisions are mostly settled in one or two-tenths of a second, while the effects of tire driving forces take effect in a matter of seconds. In relative terms, the changes in velocities or yaw rates in a collision appear as impulsive disturbances for the vehicle control process. In other words, the feasibility of steering control in these conditions addresses the problem of overcoming large disturbances of short duration in vehicle movements.

The following statements describe the targeted scenario as the starting point for this feasibility study. These conditions are not given as requirements that will limit the applications of the resulting analysis. Rather, it is used as an illustration of the types of collision conditions investigated by this study.

Two vehicles are traveling in a straight lane or a curved road. The leading vehicle is traveling at a slower speed and is rear-ended by the trailing vehicle. The speed differential at the time of first impact is of a moderate magnitude, 10-15 m/sec. The vehicles may be laterally offset prior to the collision, thus generating vehicle rotation effects as a result of the collision. Since the vehicle may be turning before the collision occurs, there can be a misalignment in the heading angles of the two
vehicles. Both vehicles are front steering vehicles. The steering systems of both vehicles are still functional after the collision. Potential bias or offset of steering angles caused by the collision damage can be introduced into individual wheels after the initial impact. Control actions can be activated on one or two vehicles.

4.2 Lateral Dynamics and Control Design

The purpose of this section is to establish the mathematical basis for analysis and to propose a generic baseline lane-tracking controller for the scenario of vehicle-following collision.

4.2.1 Vehicle Lateral Model

A linearized model is sufficient for studying vehicle steering under normal conditions [1,25]. In the case of collision, the use of such model requires more discretion. Since typical collision occurs during a relatively short time span of around 0.1 second, one can separate the analysis into two phases: during the impact and after the impact. As will be shown later, the model is sufficient to address these two different phases. Assuming small angles, this allows the use of the classical bicycle model shown in Fig. 4.1. The linearized state-space model, derived by balancing the force and moment equations, can be found in [26] as

$$\frac{d}{dt} \begin{bmatrix} \beta \\ \psi \end{bmatrix} = \begin{bmatrix} -\frac{c_f + c_r}{Mv} & -1 + \frac{c_f l_f - c_f l_r}{Mv^2} \\ -\frac{c_f l_f - c_f l_r}{I_x} & -\frac{c_f l_f^2 + c_r l_r^2}{I_x v^2} \end{bmatrix} \begin{bmatrix} \beta \\ \psi \end{bmatrix} + \begin{bmatrix} \frac{c_f}{Mv} & \frac{1}{Mv} & 0 \\ \frac{c_r}{l_f} & 0 & \frac{1}{l_x} \end{bmatrix} \begin{bmatrix} \delta_f \\ F_y \\ M_z \end{bmatrix}$$  \hspace{1cm} (4.1)

where $\beta$ is the side slip angle between vehicle longitudinal axis and velocity vector $v$ at CG, and $\psi$ the vehicle yaw rate. The inputs to the vehicle are: $\delta_f$ the front steering angle, $F_y$ the impact lateral force applied at the CG and $M_z$ the impact moment applied at the vehicle vertical axis. Other variables in Eq. (4.1) are: $I_x$ the yaw moment of inertia, $M$ the mass of the vehicle, $l=l_f+l_r$ the wheel base, $c_f$ and $c_r$ the linear cornering stiffness of the front and rear tires respectively.

Figure 4.1. Bicycle Model
4.2.2 Impact Analysis

During the impact phase, the lateral acceleration at CG and the yaw acceleration are of great interest since they determine the impact magnitude. The transfer function of yaw acceleration is obtained from Eq. (4.1) as:

\[ \dddot{\psi}(s) = V_\psi(s)\delta_f(s) + V_{\psi,r}(s)F_{iy}(s) + V_{\psi,m}(s)M_{iz}(s), \quad (4.2) \]

with

\[ V_\psi(s) = (c_f l_f Mv^2 s + c_f c_i l_f) / D(s) \]
\[ V_{\psi,r}(s) = (c_r l_r - c_f l_f) v_s / D(s), \]
\[ V_{\psi,m}(s) = (Mv^2 s + (c_f + c_r)) / D(s). \quad (4.3) \]

Similarly, the lateral acceleration at CG:

\[ \dddot{y}_{CG}(s) = V_{CG}(s)\delta_f(s) + V_{CG,r}(s)F_{iy}(s) + V_{CG,m}(s)M_{iz}(s), \quad (4.4) \]

where

\[ V_{CG}(s) = (c_f l_f v_s^2 + c_f c_i l_f v_s + c_f c_i l_f v_s^2) / D(s), \]
\[ V_{CG,r}(s) = (l_f v_s^2 + (c_f l_f^2 + c_f l_f^2) v_s + (c_f l_f - c_f l_f) v_s^2) / D(s), \]
\[ V_{CG,m}(s) = ((c_f l_f - c_f l_f) v_s + (c_f + c_f) v_s^2) / D(s). \quad (4.5) \]

\[ D(s) \] is the vehicle lateral characteristics equation:

\[ D(s) = I_\psi Mv^2 s^2 + v(I_\psi (c_f + c_r) + M(c_f l_f^2 + c_f l_f^2)) s + Mv^2(c_f l_f - c_f l_f) + c_f c_i l_f^2 \]

To simplify the analysis during the impact phase, the internal energy conversions are not considered, instead, the velocity difference of either vehicle before and after the impact, \( \Delta v_i = |v_i - v_{i0}| \), as well as the impact duration \( \Delta t_i = t_i - t_0 \) is used to measure the degree of impact to that vehicle. Since only the scenario of the vehicle following collision is studied in this paper, \( \theta_i \), the angle of \( \Delta v_i \) with respect to the vehicle traveling direction is usually small. Therefore, one can approximate

\[ F_{iy} = \begin{cases} F_i \theta_i & \text{for } t_0 \leq t < t_i \\ 0 & \text{for } t < t_0 \text{ and } t \geq t_i \end{cases} \]

and \( M_{iz} = \begin{cases} F_i d_i & \text{for } t_0 \leq t < t_i \\ 0 & \text{for } t < t_0 \text{ and } t \geq t_i \end{cases} \)

where \( d_i \) is the moment arm from the impact point to the vehicle CG, and the average impact force, \( F_i \equiv M(\Delta v_i / \Delta t_i) \).

Under the assumption that the steering angle remains zero during impact, and since the open-loop vehicle is a stable system, the maximum vehicle accelerations at impact can be computed using Eqs. (4.2) and (4.4) as
\[ |\dot{y}_{CG}(t)| \leq (k_{yF}\theta_i + k_{yM}d_i)M\frac{\Delta v_i}{\Delta t_i} \text{ for } t_0 \leq t < t_1, \text{ and} \]
\[ |\dot{\psi}(t)| \leq (k_{\psi F}\theta_i + k_{\psi M}d_i)M\frac{\Delta v_i}{\Delta t_i} \text{ for } t_0 \leq t < t_1. \]  

(4.6)

The corresponding maximum vehicle acceleration gains are:
\[ k_{yF} = \max_{\omega \in R, v \in [v_0, v_1]} |V_{CG,F}(j\omega)|, \quad k_{yM} = \max_{\omega \in R, v \in [v_0, v_1]} |V_{CG,M}(j\omega)|, \]
\[ k_{\psi F} = \max_{\omega \in R, v \in [v_0, v_1]} |V_{\psi,F}(j\omega)|, \quad k_{\psi M} = \max_{\omega \in R, v \in [v_0, v_1]} |V_{\psi,M}(j\omega)|. \]  

(4.7)

By examining the coefficients of \( s^2 \), one can observe that \( k_{yF} \geq 1/M \) and \( k_{\psi M} \geq 1/I_\psi \). This implies that the predicted vehicle accelerations during impact are at least as large as those when there is no tire resistance. It also suggests that the use of the linear model during impact does provide conservative bounds for the analysis. Therefore, the initial conditions for the steering controller immediately after the impact can be bounded as follows:
\[ \ddot{\psi}(t_1) = 0, \]
\[ |\dot{\psi}(t_1)| \leq (k_{\psi F}\theta_i + k_{\psi M}d_i)M\Delta v_i = \dot{\psi}_1, \]
\[ |\psi(t_1)| \leq \frac{1}{2}(k_{\psi F}\theta_i + k_{\psi M}d_i)M\Delta v_i \Delta t_i = \psi_1; \]
\[ |\ddot{y}_{CG}(t_1)| \leq v_1\dot{\psi}_1, \]
\[ |\dot{y}_{CG}(t_1)| \leq (k_{yF}\theta_i + k_{yM}d_i)M\Delta v_i = \dot{y}_{CG1}, \]
\[ |y_{CG}(t_1)| \leq \frac{1}{2}(k_{yF}\theta_i + k_{yM}d_i)M\Delta v_i \Delta t_i = y_{CG1}. \]  

(4.8)

The collision steering controller design is therefore transformed into a lane-tracking controller design against the large initial conditions described by Eqs. (4.8) and (4.9).

4.2.3 Steering Control Analysis

Fig. 4.2 depicts a schematic diagram of the steering control system immediately after the impact phase of the collision. The vehicle dynamics are governed by the lateral and yaw accelerations’ transfer functions \( (V_{CG}(s), V_\psi(s)) \). All the changes in the lateral dynamics that were generated by the impact forces are represented by the initial conditions adding to the vehicle kinematics relationship as shown in Fig. 4.2. The task of the controller \( (C_y(s), C_\psi(s)) \) is to regulate these two outputs \( (y_{CG}, \psi) \) to the values before the impact as well as to maintain acceptable transient errors. Eq. (4.10) provides such performance requirements based on the impact velocity difference:
\[ |y_{CG}(t)| \leq K_y\Delta v_i \text{ for } t \geq t_1, \]
\[ |\psi(t)| \leq K_\psi\Delta v_i \text{ for } t \geq t_1. \]  

(10)
Since the goal of this paper is to investigate the feasibility of applying steering control to mitigate the vehicle following collisions, it is important that the analysis results can be easily generalized and interpreted. The “look-ahead” steering controller proposed in [3,25] is one such candidate. In the prior analysis, this controller was shown repeatedly to be robust with good tracking performance. The basic look-ahead control law takes the form of

$$
\delta_c = G(s)y_s = G(s)(y_{CG} + L\psi)
$$

(4.11)

where $y_s$ is the lateral displacement at the distance $L$, the look-ahead distance, in front of the vehicle CG. The look-ahead displacement $y_s$ is the input to the controller $G(s)$.

In order to apply the above look-ahead control law to the collision control scenario in Fig. 2, the vehicle transfer function is re-written based on $y_s$ as

$$
\dot{\dot{y}}_s(s) = \ddot{y}_{CG}(s) + L\dot{\psi}(s)
$$

(4.12)

$$
= V_s(s)\delta_f(s) = \frac{c_f(Ml/L + I_w)v^2s^2 + c_fcl(l + l_v)vl + cclc_i\nu_1}{D(s)}\delta_f(s)
$$

Using Eqs. (4.8, 4.9), the corresponding initial conditions are:

\[ \dot{\dot{y}}_s(t_1) \leq v_1\psi_1, \]
\[ \dot{y}_s(t_1) \leq \dot{y}_{CG1} + L\psi_1, \]
\[ y_s(t_1) \leq y_{CG1} + L\psi_1. \]

(4.13)

Fig. 4.3 shows the modified schematic control diagram of the corresponding vehicle-following-collision steering control problem. The goal of the controller design after impact is to design the controller $(G(s))$ for the modified “look-ahead” closed-loop system

$$
y_s(s) = \frac{s^2}{s^2 + G(s)V_s(s)} \left( \frac{y_{CG1} + L\psi_1}{s} + \frac{\dot{y}_{CG1} + L\dot{\psi}_1}{s^2} + \frac{v_1\psi_1}{s^3} \right)
$$

$$
= \frac{(y_{CG1} + L\psi_1)s^2 + (\dot{y}_{CG1} + L\dot{\psi}_1)s + v_1\psi_1}{s^2 + G(s)V_s(s)} \frac{1}{s}
$$

(4.14)

to satisfy the following performance and stability requirements:
\[ |y_1(t)| \leq (K_y + LK_y)\Delta v_i, \text{ for } t \geq t_i, \quad (4.15) \]
\[
\left< \frac{G(j\omega_0)V_S(j\omega_0)}{-\omega_0^2} \right>_0^\infty > -\frac{5}{6} \pi, \text{ at } \left| \frac{G(j\omega_0)V_S(\omega_0)}{-\omega_0^2} \right| = 1. \quad (4.16)
\]

Fig. 4.3. Modified Look-Ahead Steering Control Structure

Eq. (4.16) specifies the robustness requirement: at least 30-degree phase margin is required at any gain crossover frequency of the open loop system \((G(s)V_S(s)/s^2)\). The usual 60-degree margin is not used because some oscillation would be tolerable during such emergency steering control.

Applying a conservative inequality of the Laplace transformation to Eqs. (4.14, 4.15) and dividing both sides by the common factor \(\Delta v_i\), the bound of \(y_s\) due to a unit impact velocity difference can be obtained for \(t \geq t_i:\)

\[
\frac{|y_s(t)|}{\Delta v_i} \leq \left| \frac{(y_{CG1} + L\psi_i)s^2 + (\dot{y}_{CG1} + L\dot{\psi}_i)s + v_i\dot{\psi}_i}{s^2 + G(s)V_S(s)} \right| \frac{1}{\Delta v_i} \leq (K_y + LK_y). \quad (4.17)
\]

4.2.4 Vehicle Types

The vehicles examined in the paper include two models. The first model represents a modern passenger sedan used in recent PATH experiments, and the second represents a mid-size sedan selected from an existing database [27]. The first model possesses under-steering characteristics, while the second is neutral steering. The steering characteristics of these two vehicles are analyzed in more details in previous publication [8]. Some key parameters of the two vehicle models are given in Table 4.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance CG to front axle</td>
<td>1.06</td>
<td>1.30</td>
<td>m</td>
</tr>
<tr>
<td>Distance CG to rear axle</td>
<td>1.76</td>
<td>1.41</td>
<td>m</td>
</tr>
<tr>
<td>Total Vehicle Mass</td>
<td>1750</td>
<td>1510</td>
<td>kg</td>
</tr>
<tr>
<td>Moment of Inertia, yaw</td>
<td>3217</td>
<td>3452</td>
<td>N·sec²·m</td>
</tr>
<tr>
<td>Front Cornering Stiffness</td>
<td>34962</td>
<td>38787</td>
<td>N/rad</td>
</tr>
<tr>
<td>Rear Cornering Stiffness</td>
<td>65069</td>
<td>35982</td>
<td>N/rad</td>
</tr>
</tbody>
</table>

Table 4.1. Parameters used in Vehicle Models
4.2.5 Steering Controller Design

In this section, lane-keeping controllers that mitigate the vehicle-following collision for the two vehicle models listed in Table 4.1 are designed based on the analysis in Section 4.2.3. Since this study focuses on the feasibility evaluation of such controllers, the goal is to provide a simple control structure that fulfills the basic requirements. Designs that are complex and not as conservative are left for future studies.

The simplest lane-keeping controller structure that has been found to be applicable to this scenario is the “look-ahead” control law described by Eq. (4.11). Choosing constant gain $G(s)=k$, the following benchmark case is used to demonstrates the steering controller design: $v=20m/s$, with $d_i=0.3m$ and $\theta_i=5$degree. This case represents a relatively severe vehicle-following collision. Fig. 4.4 shows the bounds for the negative lateral displacement at the look-ahead location ($-y_s$) for a unit impact velocity difference ($\Delta v_i$) at various look-ahead distances ($L$) and at different feedback gain ($k$) for both vehicle models described in Table 1. These bounds are calculated using Eq. (4.17) with coefficients from Eqs. (4.8,4.9). The “negative” bound is chosen to clarify the illustration. These bounds are calculated using equations from the models described in the last section. Fig. 4.5 provides the phase margins using Eq. (4.16) for the same benchmark case with respect to $L$ and $k$. Observing from Figures 4.4 and 4.5, vehicle model 2 exhibits worse performance than that from the vehicle model 1. As a practical consideration on choosing the control candidate, lower gains are always preferable because of the reduced sensitivity to noises. The following are the controller gains suggested by Fig. 4.4 and Fig. 4.5:

- For Vehicle Model 1: $5m \leq L \leq 15m$, $0.1 \leq k \leq 0.2$ with $k_y = 0.2m$, $k_\psi = 2$ deg.
- For Vehicle Model 2: $15m \leq L \leq 20m$, $0.05 \leq k \leq 0.1$ with $k_y = 0.35m$, $k_\psi = 2$ deg.
Fig. 4.5. Phase Margins for various Look-ahead \((L)\) and Gain \((k)\):
\((v=20\text{m/s}, d_i=0.3\text{m}, \theta_i=5\text{deg}, \Delta t_i=0.1\text{sec})\)

5.0 SIMULATION

The problem to be addressed is whether a steering controller can be applied to maintain a vehicle in a designated trajectory when it is involved in a collision. The basic assumption is that the steering systems of the vehicles are still operational after the collision. Some other limitations are also assumed for the collision conditions in this study, which will be described fully later.

The immediate question that arises before this problem can be discussed is what happens to a vehicle when a collision occurs? In very general terms, the vehicle will suffer sudden changes in velocities and yaw rates. For example, two vehicles of the same mass collide with a speed differential of 10 m/sec will each experience a 5 m/sec change in speed within a time frame of 100-200 milliseconds. For typical passenger cars, the peak acceleration measured at the center of gravity in such a collision may rise beyond 10 g, where 1 g is equivalent to the acceleration caused by gravity force. The exact magnitude and direction of the changes in acceleration and velocity depend on the vehicle parameters as well as the setup or configuration of the collision. Previous studies of the effects of various operating parameters on the outcome of a vehicle-following collision have addressed these issues extensively [28].

If the acceleration magnitude as cited above in the example is so much higher than what can be generated by tire forces, can a steering effort correct or maintain the trajectory of a vehicle right after the collision? The answer lies in the nature of vehicle dynamics. The dynamic changes due to the collisions are mostly settled in one or two-tenths of a second, while the effects of tire driving forces take effects in a matter of seconds. In relative terms, the changes in velocities or yaw rates in a collision appear as impulsive disturbances for the vehicle control process. In other words, the feasibility of steering control in these conditions address the problem of overcoming large disturbances of short duration in vehicle movements. Clearly, the effectiveness of the control efforts are confined by the magnitudes of the disturbances and the subsequent deviation...
allowed in vehicle motions before the vehicle is satisfactorily brought back to stay within its
designated trajectory.

5.1 Collision Scenarios and Performance Specifications

The following statements describe the targeted scenario as the starting point for this feasibility
study. These conditions are not given as requirements that will limit the applications of the
resulting analysis. Rather, it is used as an illustration of the types of collision conditions
investigated by this study.

(1) Two vehicles are traveling in a straight lane or a curved road. For the cases examined in this
paper, the curved road is configured with a straight section followed by a circular-arc section
with a radius of curvature of 400 meters. The collision can occur either prior to or after the
vehicles entering the curved section.

(2) The leading vehicle is traveling at a slower speed than the trailing vehicle.

(3) The trailing vehicle rear-ends the leading vehicle. The speed differential at the time of first
impact is no more than 10 m/sec.

(4) The vehicles may be laterally offset to one side prior to the collision, thus generating effects
of vehicle rotation as a result of the collision.

(5) Since the vehicle may be turning before the collision occurs, there can be a misalignment in the
heading angles of the two vehicles. The exact angles are determined by the states of the
vehicle movements.

(6) The steering systems of both vehicles are still functional after the collision. Potential bias or
offset of steering angles caused by the collision damage can be introduced into individual
wheels after the initial impact. Both vehicles are front steering vehicles.

(7) Control actions can be activated on one or two vehicles. The examples presented assume the
use of control in both vehicles.

5.1.1 Vehicle Types
The vehicles examined the study included two models: one representing a modern passenger
sedan used in recent PATH experiments and the other from an existing database in EDSMAC
[17]. Some key parameters of the two vehicle models are given in Table 4.1 in Section 4. Each
vehicle is paired with one of the same model in the exemplar collision scenarios described in this
paper.

It should be noted here that collisions with mixed sizes of vehicles and the resulting outcome have
been extensively discussed in previous studies [28] and will not be explicitly covered here.
However, the analysis of control strategies for each vehicle in collisions of mixed sizes is a
potential topic for future studies.

5.1.2 Simulation Model
Due to the limitations and difficulties of experimentation with crashes, the study is conducted
with a reliable simulation model that can estimate the motions of vehicles under normal
maneuvers as well as in collision conditions. An existing simulation program, Simulation Model of Automobile Collisions (SMAC) is selected. Section 3 has given a description of the simulation software.

5.1.3 Performance Specifications of Control Systems
The approach taken for this feasibility study starts with a simulation model to analyze the behaviors of two vehicles in collisions. The steering characteristics of the two vehicles are taken into consideration to determine the responses of vehicles in maneuvers. Once a controller is selected, tests are conducted with a series of simulation with varying operating or control parameters to validate the effectiveness of the controller.

The following specifications are used as guidelines to judge the effectiveness of the steering controller:
(1) Can the vehicles stay within the designated lane after the collision? This condition is measured by checking the lateral displacement of the center of gravity of each vehicle. To conform with the typical width of a highway lane, 3.6 meters, and a typical vehicle width of 1.8 meters, a vehicle is defined to depart from a lane when the center of gravity moves more than 0.9 meters at any time.
(2) Does the yaw angle of a vehicle deviates from the desired angle and diverges continuously without being corrected? This typically indicates a spin-out. A vehicle is defined to have lost direction control when the deviation is beyond 45 degrees.
(3) When a vehicle experiences disturbances caused by a collision, can the deviations in lateral position and heading angle converge to a desired range? The allowable errors in positions and heading angles depend on the damage of the vehicles. For example, an offset of rear wheel angles will cause the heading angle of a vehicle to stay in a non-zero state even though the vehicle continues to move in a straight line.

5.2 Controller Description for Collision Simulations

The primary objective of the control efforts intended in the collision scenarios associated with this work is to achieve robust lane-keeping functions. The control system aims to bring the vehicle back to the center position of a designated lane without extensive vehicle parameters or complicated control algorithms. Following the discussions of the preceding section, a steering control law is proposed:

\[ U = -G(\Delta Y + L \ast \Delta \psi) \tag{5.1} \]

where
U: steering input
G: control gain
L: look-ahead distance
\( \Delta Y \): lateral deviation
\( \Delta \psi \): heading angle deviation
This control law essentially attempts to correct the current and foreseen deviation from the desired position. It also represents a combination of controller with proportional and differential natures. The lateral deviation or offset is measured from the center of gravity position. The heading angle deviation, in straight-lane scenarios, is equivalent to the yaw angle. The control gains are adjusted by changing \( G \) and \( L \). In cases presented in the next section, the control parameters were varied based on the suggested values in Section 4.2 to evaluate the effectiveness of the controller.

It should be noted that the simulation models used in this paper do not include sensor or actuators sub-systems. Therefore, errors or noises in the sensing inputs and delays or backlash in the actuation outputs are not represented. The measurement of the position and the yaw angle are assumed to be accurate. The steering input calculated from the controller is assumed to be precisely executed. Since time delays are usually present and can be a key factor in vehicle control systems, a time-delay routine was built into the controller models to account for the possible effects generated in sensing or actuation cycles. The embedded time delay creates an artificial time lag between the sensed inputs values and the executed steering angle. In other words,

\[
U(t) = -G(\Delta Y(t - \Delta t) + L \Delta \psi(t - \Delta t)), \quad (5.2)
\]

where \( \Delta t \) is the time delay.

In curved-road situations, due to the proportional nature of the controller, there is a steady-state position from the desired values. To reduce such errors, a compensator that increases the steady state gain is introduced to the position portion of the controller. The alternative controller becomes

\[
U = -G(C(s)\Delta Y + L \Delta \psi), \quad (5.3)
\]

where \( C(s) \) is chosen to be a lag-lead compensator represented by the following Laplace-transfer function

\[
C(s) = \frac{s + 2 \pi f_1}{s + 2 \pi f_2} \quad (5.4)
\]

where \( f_1 \) and \( f_2 \) are selected to be 0.1 Hz and 0.02 Hz, respectively, for the cases examined in this paper. This lag-lead compensator increases the very low frequency gain of the look-ahead controller since \( f_1 \) and \( f_2 \) are chosen much smaller than the bandwidth of the vehicle closed-loop system. This compensator reduces the steady-state tracking error of the lane-keeping controller without altering the overall collision control system characteristics.

In addition to the aforementioned adjustments to the controller, the rate of change of the steering angle is limited to 30 degrees/sec. This reflects a restraint on the bandwidth or power of the
steering actuator. Also, the demanded wheel angle is monitored throughout the simulation so that the steering angle does not become excessive.

5.3 Simulation Results and Validation of Controller

The controller devised is incorporated into the vehicle models and tested for its effectiveness. In this section, the simulation results are presented and discussed. Among the exemplar cases presented, the following common conditions are specified:
1. Before the collision occurs, the leading vehicle is traveling at 20 m/sec and the trailing vehicle at 30 m/sec at a distance of 12.5 m behind. Note that a velocity differential of 10 m/sec is quite significant. An impact with this magnitude often warrants the deployment of occupant restraints, such as air bags. The assumption is that the vehicles are still operative to allow the steering inputs to take effect.
2. The leading vehicle is offset to its right by 0.45 m prior to the collision. This offset was adopted to create rotating motions of the two vehicles as the collision progresses.
3. Both vehicles are preceding with zero yaw angles prior to the collision. No steering control inputs were applied to either vehicle before the collision occurs in the straight road scenarios. In the curved road scenarios, steering actions are initiated as the simulation begins regardless of whether a collision has taken place or not.
4. Two vehicles of the same model were paired in a collision.
5. The vehicles run for 8 seconds in the simulation. Since the collision is set to occur within one second in the simulation, the 8-second period allows the vehicle motions to settle well into their designated trajectories or controlled states.

5.3.1 Benchmark scenarios – Collision without steering control inputs
Figure 5.1 shows a scenario with two vehicles of Model No.1 in a collision without steering control. Both vehicles depart from the original lane, defined as the condition when the center of gravity moves more than 0.9 meters from the center of the lane, within about 2 second after the initial impact. Similarly, the scenario depicted in Figure 5.2 with two vehicles of Model No. 2 also shows that the two vehicle move out of the desired lane.

5.3.2 Exemplar straight road scenarios – Collision with steering control inputs
Figure 5.3 shows a straight-road scenario with steering input, in contrast to that in Figure 5.1. This is a case where a control gain of 0.1 and a look-ahead distance of 10 m were used. The steering inputs were applied immediately after the collision and the trajectories of both vehicles quickly converge to the center of the designated lane. The lateral deviation, from the center of lane, of both vehicles did not exceed 0.9 m.

A scenario replicating that of Figure 5.2 but with steering inputs was depicted in Figure 5.4. This scenario also uses a control gain of 0.1 and a look-ahead distance of 10 m. The figure shows that the two vehicles converge to stay in their desired trajectories although the convergence rate is not as fast as that of Figure 5.3.
It can be noted here that the two vehicle models behave quite differently in the same set of collision conditions, as shown in Figures 5.1 and 5.2. Furthermore, when the same set of control parameters were applied, they respond in distinctly different manners as illustrated in Figures 5.3 and 5.4. The outcome should have been expected because the dynamic response and steering characteristics of the two vehicle models are different. System parameters should be normalized before meaningful comparisons can be made on control effectiveness between the two types of vehicles. Nevertheless, the fact that same controller stabilized both types of vehicles highlighted the underlined robustness of the controller.

One approach of adjusting system parameters can be accomplished through the imitation of similar vehicle response. Figure 5.5 shows the response of Model 2 vehicles under the same collision conditions of Figure 5.4, but the control gain is now set at 0.06 and the look-ahead distance at 20 in accordance to the design guidelines of Section 4. When compared to the motions of Model 1 vehicles in Figure 5.3, the data are better matched in Figure 5.5 than in Figure 5.4. However, since the vehicle inertia and steering characteristics are different, the dynamic behaviors are still not the same without involving more sophisticated frequency shaping in the controller. For example, there is less damping in the responses shown by Figure 5.5 than those in Figure 5.3.

Figures 5.6 shows a scenario with the same pre-impact conditions as in Figure 5.3 but the vehicles have sustained damage that caused the rear wheels of the leading vehicle and the front wheels of the trailing vehicle to deviate from the normal or desired angles. In this case, the wheels are offset by one degree (positive, or to the right) in the wheel angles. The controller was proven to be effective despite the damage bias on the steering wheels.

Similar exercises were conducted on both models of vehicles and the controller was equally effective although vehicle dynamics were different. For the following sections of discussions, only the results from the simulation cases of Vehicle Model No. 1 will be shown to avoid repetitive comments on similar outcome.

5.3.3 Exemplar curved road scenarios – Collision with steering control inputs
Figures 5.7(a) and 5.7(b) show a scenario in which the vehicles are expected to follow a curved road. The curved road starts with a straight section of 15 meters and then a circular arc curved to the right with a radius of 400 meters. A control gain of 0.1 and a look-ahead distance of 10 m were used. The steering inputs were applied at the beginning of the simulation.

It can be seen from the figures that the vehicles follow the curved trajectory successfully even though a collision occurs just as both vehicles enter the curved section. It can also be observed that the vehicles have a slight but consistent lateral position error in the later stage of the simulation. To reduce this error, a compensator as described in Section 5.2 was introduced into the controller and the results are shown in Figures 5.8(a) and 5.8(b). The results showed the lateral deviation was reduced.
Furthermore, an offset of the steering wheels due to collision damage was incorporated into the scenario. It was assumed that the collision caused a one-degree offset to the front wheels of the trailing vehicle and the rear wheels of the leading vehicle. The results are depicted in Figure 5.9 (a) and 5.9(b). Again, the controller was proven effective.

To account for the time delay embedded in the sensing and actuation cycle, a time delay was also introduced into the controller. A range of time delay was tested and the results of a case with 0.1 second time-delay are shown in Figure 5.10(a) and 5.10(b). The time delay resulted in a slight change in vehicle movements but not enough to render the control actions ineffective.

5.3.4 Discussions of simulation results and control parameters
A summary of observations from the simulation results is presented here to evaluate the effectiveness of lane-keeping control. The effectiveness referred to in these specific cases particularly focuses on whether departure from the original lane occurs after the impact.

Observations from the simulation results of Vehicle Model No. 1:
1. Variation of control gain
   Control gains were in the range of 0.01 to 0.20. In general, the higher the gain is, the more effective the control is. For cases tested with a look-ahead distance of 10 or 15 meters, the control is effective for the trailing vehicle with a gain in the range of 0.01 to 0.20 and for the leading vehicle in the range of 0.03 to 0.20.

2. Variation of look-ahead distance
   Look-ahead distance was varied in 3 increments: 5, 10, and 15 meters. The longer the look-ahead distance is, the more damping the closed-loop system is. Even though the outcome depends on other factors, a distance of 10 to 15 meters appears sufficient to successfully maneuver the vehicles.

3. Time Delay
   Time delay was varied in the range of 0.01 to 0.10 seconds. In general, the longer the delay is the wider the range of positions and yaw angles are. However, in most of the cases tested, the differences found were acceptable. It can be argued that the effect caused by time delay was not obvious in these cases because the look-ahead distance provides enough phase lead to compensate for the delay. Given the encouraging results with a built-in time delay, the system has the potential to offer an automated or a driver-assisting function that can be activated by crash sensors similar to those used in air bag restraint systems.

Similar exercises were conducted with Vehicle Model No. 2, but with a different set of control gains and look-ahead distances for reasons explained in the previous section.
Fig. 5.1 Vehicle No. 1, Straight Road without Control

Figure 5.2 Vehicle No. 2, Straight Road without Control
Figure 5.3 Vehicle No. 1, Straight Road with Control

Vehicle Model No. 1, Straight Road with Feedback Control
Gain=0.1, L=10 m, V1=10 m/sec, V2=30 m/sec

Figure 5.4 Vehicle No. 2, Straight Road with Control

Vehicle Model No. 2, Straight Road with Feedback Control
Gain=0.1, L=10 m, V1=10 m/sec, V2=30 m/sec
Fig. 5.5 Vehicle No. 2, Straight Road with Control

Vehicle Model No. 2, Straight Road with Feedback Control
Gain=0.06, L=20 m, V1=10 m/sec, V2=30 m/sec

Fig. 5.6 Vehicle No. 1, Control with Wheel Damage

Vehicle Model No. 2, Straight Road with Feedback Control and Wheel Damage Offset
G=0.1, L=10 m, V1=20 m/sec, V2=30 m/sec, Wheel Offset=1 deg
Fig. 5.7. Vehicle No. 1, Curved Road with Feedback Control
Fig. 5.8. Vehicle No. 1, Curved Road with Feedback Control and Gain Compensator

Curved Road with Feedback Control and Gain Compensator
Gain=0.1, L=10 m, V1=20 m/sec, V2=30 m/sec
Fig. 5.9. Vehicle No. 1, Curved Road with Feedback Control and Wheel Damage
Fig. 5.10. Vehicle No. 1, Curved Road with Feedback Control, Wheel Damage Offset, and Time Delay
In the specific cases examined here, the trailing vehicle, with the collision occurring to its front, was found to converge to its desired trajectory more quickly and more effectively than the leading vehicle that is impacted from its rear end. This phenomenon leads to a probable suggestion that the collision results in a disturbance more exaggerated from the rear for front-steering vehicles. Therefore, the leading vehicle may require greater efforts to be effectively controlled. This issue should be further investigated before a conclusion can be drawn.

5.4 Summary

We investigated by simulation the problem of applying steering control in vehicle-following collisions. The feasibility of maintaining vehicle trajectories following a collision was investigated with a vehicle collision model and a feedback controller. The collision controller design is formulated as an impulse disturbance rejection problem. A look-ahead steering controller is proposed based on the performance requirements of the steering control in collisions. The designed controller was proven effective in a variety of system conditions.

Included in the study was the complication of time delay of up to 0.1 second in sensing or actuation cycles. The effectiveness of a controller with a delay is significant because the steering function, as a driver-assistance or an automated function, can be potentially implemented after a collision was detected. Also, the controller was able to handle other complications, such as different vehicle steering characteristics, wheel angle offset due to collision damage, curved trajectories, and a range of collision conditions. The robustness of controller performance is extremely important in a safety-critical application.

6.0 DISCUSSIONS

We have established a solid understanding regarding vehicle dynamics and control strategies from a study of lane-keeping control in vehicle collisions. In particular, we explored the feasibility of maintaining the vehicle paths when an impact causes a strong disturbance to the motions of these vehicles. It was illustrated by the studies that steering control to stabilize vehicle trajectories is a feasible option.

In the course of the study, we developed a set of software programs, which allows us to analyze, simulate and animate vehicle motions in vehicle-following collisions. We also outlined a thorough analytical model that enables us to select proper control laws and associated gains based on the steering characteristics of the subject vehicles.

We applied a controller to the vehicle lane-tracking problems and determined that the controller can be effective if the key parameters were selected properly. The controller utilized in this study was a simple, yet robust, control law applicable to a wide range of system conditions. The result is significant because robustness is essential to such applications when a system is open to uncertainties and variations in operation parameters.
Included in the study are certain variations in implementation issues. Time delay was introduced to capture a potential delay in sensing and actuation cycles. Steering angle offset, which may be caused by damage suffered in collisions, is also incorporated into the examined scenarios. A compensation gain was introduced to reduce steady-state errors in lateral deviation.

6.1 Implementation Issues

While the analysis and simulation in the previous sections demonstrated the feasibility of steering control as a post-impact strategy, there are many issues that should be explored fully. The limitations of the proposed systems have been explained in Section 2. It is apparent that the system cannot be expected to perform beyond its physical constraints when the structural integrity cannot withstand a large impact or the post-impact conditions are too astray to overcome. Nevertheless, certain aspects for a realistic implementation of the suggested system as a driver-assistance function deserve more in-depth discussions.

6.1.1 Operating Conditions

The expected performance of a safety-critical system is confined by physical limits of its capacity and the operating environment. Operating conditions do not always allow effective outcomes in spite of control attempts. Before establishing the performance specifications of the target system, the physical limitations must be defined. In other words, the critical questions are:

(1) What operating conditions are not suitable for the use of the proposed function?

(2) In these conditions, are there side effects or undesired consequences if the system is activated?

The first question relates to the physical behaviors of vehicles in collisions, and the subsequent post-impact conditions. The vehicle may sustain substantial destruction to critical components and becomes inoperable, or the deviation in vehicle trajectories is excessive to an extent that cannot be practically corrected. The threshold of the performance limits and the related operating scenarios can only be established by an extensive study of vehicle dynamics through crash tests or extensive simulations.

The second question addresses the issue of proper deployment. On one hand, if the system is in state beyond control, the activation of the suggested system may still provide limited benefits. On the other hand, the activation of the steering control system may alter the paths of the subject vehicles into hazardous states. A balance must be sought between these two extremes so that the decision-making process of deployment can be properly implemented. A design specification on this issue will also affect the method of activation and the algorithm necessary for the distinction of various collision scenarios. Once the proper situations are established for control activation, it is potentially feasible to consider a sensing and processing procedure to “arm” the vehicle in a preparatory state before the actual use of steering control. In other words, when a vehicle senses an eminent crash, the control system will be ready for deployment, while the actual activation will occur once a crash is confirmed.
6.1.2 Equipment Requirements
The other set of constraints centers on the components or equipment required on a vehicle, including:

(1) Crash worthiness and structural integrity of the steering mechanism
Since characteristics of vehicle structures vary model by model, each platform will have its own limits in the crash threshold that will render the steering system inoperable.

(2) Steering actuator
The required performance of a steering actuator as implied by the exemplar cases demands no more than the capabilities available on advanced experimental vehicles [17], thus should not become an obstacle of development.

(3) System activation by rash triggering
As pointed out in the previous section, the system performs satisfactorily with a time delay, which implies that the system can be activated by a crash-sensing device. For example, air bags or seat-belt pre-tensioners are activated by electromechanical devices or acceleration-based electronic sensors within 10 to 50 milliseconds from the onset of a collision. For the system in question, a simple acceleration-based sensor can be used for activation as a stand-alone device or an add-on feature of the existing crash sensor.

(4) Position and orientation sensing
Based on the controller design, the steering command is determined by feedback information of lateral position and heading angle errors. The success of a feedback controller depends fully on the availability and accuracy of the sensing inputs. The implementation of the proposed system thus requires a secure means of measuring these two inputs and a robust source of backup information when the primary source is lost. This subject should be examined closely and thoroughly.

6.1.3 Position and Orientation Sensing
Although the design of the selected controller is formulated as a feedback controller with a position and a yaw angle input, it does not necessarily demand the direct measurements of those two variables. In recent years, a magnetic marker sensing system has been used extensively for real-world vehicle control experiments with great success [3]. This sensing system provides a highly accurate and reliable position measurement with readings of magnetic fields by magnetometers from a series of magnetic marker installed just under the road surface. The magnetic markers are usually spaced at one-meter interval. Researchers at PATH (Partners for Advanced Transit and Highways) developed a breakthrough technique to use the downward-looking sensing system for the adoption of the look-ahead control structure. By installing sensors at both the front and rear ends of a vehicle, the positioning errors can be processed to estimate the heading angle deviation. The position measurement at the back end of the vehicle is projected forward by $L$ (the look-ahead distance in the controller), which practically constitutes a virtual forward-looking sensor. Similarly for control of a rearward motion, the front sensor measurement can be projected backward to forecast the heading angle in the reverse direction.
Even though the magnetic marker system provides excellent and reliable results, it is not the only choice for feedback sensing in steering control systems. Other potential candidates that have been validated in real-world experimentation include computer vision [29,30], magnetic tape [231,32], and DGPS-Inertia systems [33,34]. The key questions for any of these systems are

1. Whether the sensing system can withstand the shocks or impacts in a collision and continue to provide accurate information, or
2. If the sensing system is partially disabled, what types of backup devices or algorithms can be used to supply information with sufficient integrity.

Take the magnetic-marker system as an example, the front or rear sensors are likely to be damaged in a moderate collision, thus removing half of sensor measurements. In the absence of partial sensing information, the control system either needs to switch to a controller that relies on other information or the system must reconstruct the information from other sensing devices. For example, if the vehicle is equipped with an inertia navigation system that contains acceleration and yaw rate information, those data must be integrated in a dead-reckoning process to provide continual estimates of vehicle states as inputs to the controller. Since the controller is required to work within a tiny fraction of second (in the order of 0.1 second), the backup sensing system must have latencies smaller than the required time frame and the data must be sampled frequently to yield meaningful updated information. For instance, a GDP-based system that is updated every one second will not be adequate for this application. An inertia navigation system is a promising candidate as a backup unit.

6.3 Future Work

The following two areas need to be further explored:

(a) Establishment of operating limits and performance requirements
(b) Design and integration of sensing devices to provide reliable and continual information in a collision incident.

Certain issues associated with the problem have not been fully addressed to date. A generic look-ahead controller was proven to be effective in the case studies examined in this study. However, alternative control algorithms may provide equal or better performances. Steering control is only one of the possible damage-mitigation strategies. A combined use of steering and braking is necessary in many collision situations. Strategies using individual wheel steering or differential braking may result in additional benefits if these advanced vehicle technologies are available. Also, the effects of sensing noises and actuator dynamics with respect to system performance will be a challenging topic. These areas along with the aforementioned two subjects remain topics of future studies.
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