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Author

Chan, Ching-yao

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Studies of Collisions in Vehicle Following Operations by Two-dimensional Simulation

Ching-Yao Chan

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Studies of Collisions in Vehicle Following Operations
by Two-Dimensional Simulation

Principal Investigator

Ching-Yao Chan

California PATH, Headquarters

University of California, Berkeley

Richmond Field Station, Bldg. 452, 1357 S. 46th Street, Richmond, CA 94804-4698, USA

Phone 510-231-5663, Fax 510-231-5600, cychan@uclink2.berkeley.edu

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ABSTRACT

In Automated Highway Systems (AHS), vehicles are equipped with automatic control systems to govern the accelerating, steering and braking functions in order to maintain an appropriate speed and spacing with respect to the surrounding vehicles. One concept of AHS suggests the implementation of vehicle platoons with small spacing between vehicles. With vehicles moving closely together in platoons, the hazards of “chain-reaction” collisions become a concern. The benefits of small delta-V need to be weighed against the number of collisions in such feared “chain-collision” scenarios.

This report discusses the effects of collisions in vehicle-following operations, especially for short-spacing scenarios. In this study, the collision analysis is conducted with a two-dimensional simulation program by which the translational and rotational movements of vehicles can be fully represented. For example, a greater delta-V of the initial collisions or a larger lateral offset between the vehicles can cause the greatest deviations from the specified path.

Also presented in this report are simulation scenarios where control actions are taken in post-impact conditions. Vehicle maneuvers in these simulations include steering and braking inputs to perform lane-following and lane changing. The potential implications and the effects of these maneuvers on the vehicle trajectories are discussed. The studies of these post-impact maneuvers offer a perspective on the possible actions for vehicles in automated modes. The current and future work of this study should provide insights for the evaluation of the safety hazards and control strategies in AHS.

KEY WORDS

Automated Highway Systems (AHS), Advanced Vehicle Control Systems (AVCS), Vehicle Collision, Simulation.

EXECUTIVE SUMMARY

In operations of automated vehicles or Automated Highway Systems (AHS), vehicles may be designed or commanded to travel with a small spacing between them. The automated vehicles should travel safely in normal operating conditions. If collisions occur as a result of failures or malfunctions, it is necessary to minimize the consequences of the collisions. This project report presents work conducted to understand the effects of operational variables on the outcome of collision in vehicle-following operations and the feasibility of controlling vehicle motions in collisions.

A two-dimensional simulation model is used in this study. The model allows translational movement on a horizontal plane and the rotational motion (yaw) about the vertical axis of a vehicle. A hard-braking failure scenario is simulated in this study with the leading vehicle decelerating while the following vehicle fails to brake accordingly. By using this model with a variety of initial conditions and vehicle parameters, the effects of offset, vehicle size, spacing and vehicle speed on the outcome of collisions are evaluated.

Several follow-up maneuvers by applying steering or braking inputs on the vehicles to respond to the failure event are also simulated to investigate the feasibility of control actions. Different approaches of follow-up actions are examined to discuss the hazards and benefits of these maneuvers. The work discussed in this paper represent a continuation of safety evaluation for AHS in various operating conditions and an initiation of a comprehensive model of collision analysis for future studies.

INTRODUCTION

In Automated Highway Systems (AHS), vehicles are equipped with automatic control systems to govern the accelerating, steering and braking functions in order to maintain an appropriate speed and spacing with respect to the surrounding vehicles. One concept of AHS suggests the implementation of vehicle platoons with small spacing between vehicles. [1,2] If implemented successfully, the density of vehicles on the roadway is higher and therefore the throughput can be increased. Furthermore, in the events of malfunctions or failures that lead to collisions between a leading vehicle and a following vehicle, the relative speed difference (ΔV) at impact is smaller.

With vehicles moving closely together in platoons, the hazards of “chain-reaction” collisions become a concern. The benefits of small ΔV need to be weighed against the number of collisions in such feared “chain-collision” scenarios. Hitchcock created a probabilistic model in which he included the statistical distribution of spacing, numbers of vehicle on a highway, vehicle weight, and the roadway friction coefficient to estimate the severity of collision and the probable Abbreviated Injury Scale (AIS) levels of the occupants. [3] His collision model is one-dimensional and plastic thus the vehicle masses are aggregated together once they are in a collision.

Tongue and Young examined the consequences and effects of different control schemes in platoon collision dynamics in non-nominal conditions. [4,5,6] Vehicle bumper models were built into a one-dimensional platoon collision model. The effects of selected platoon parameter variations on the platoon response under various control algorithms were investigated. The control algorithms included forward and backward schemes, in which the control of individual vehicle depends on the dynamic information of the vehicles ahead and behind.

This report discusses the effects of collisions in vehicle-following operations, especially for short-spacing scenarios. In this study, the collision analysis is conducted with a two-dimensional simulation program by which the translational and rotational movements of vehicles can be fully represented. Some earlier work conducted by the author has identified certain parameters that are most influential on the post-impact vehicle trajectories. [7,8] For example, a greater ΔV of the initial collisions or a larger lateral offset between the vehicles can cause the greatest deviations from the specified path.

Also presented in this report are simulation scenarios where control actions are taken in post-impact conditions. Vehicle maneuvers in these simulations include steering and braking inputs to perform lane-following and lane changing. The potential implications and the effects of these maneuvers on the vehicle trajectories are discussed. The studies of these post-impact maneuvers offer a perspective on the possible actions for vehicles in automated modes. The current and future work of this study should provide insights for the evaluation of the safety hazards and control strategies in AHS.

SIMULATION MODEL

The analysis of vehicle collisions in this work is conducted with a simulation program developed by Engineering Dynamics Corporation (EDC). The software package, EDSMAC (Engineering Dynamics Corporation Simulation Model of Automobile Collisions), is used for the analysis of a single or two-vehicle accident. It is based on a program called SMAC [9-11], initially developed and validated by Calspan Corporation and subsequently improved by EDC [12-15]. EDSMAC uses a set of assumed or estimated initial conditions, including positions and velocities, and predicts the outcome of a collision. Researchers have found that the program yields reasonable results with sound input data [16-20].

In its vehicle model, EDSMAC allows the longitudinal and lateral movements as well as the rotational motion about the vertical axis of vehicles on a horizontal plane. If a contact between vehicles is detected, the collision phase is analyzed. The external forces can be applied either at the tire/road interface or between the vehicles. The vehicle exterior is assumed to have homogeneous stiffness.

EDSMAC allows the direct entry of vehicle data by users or the selection of default values. The vehicles are categorized by their wheelbase into several classes. Classes I and II are small passenger cars while Classes III to V are medium to large cars. In this paper, default values provided by EDSMAC are used in the simulation. [15]

Due to the limitations of the simulation models, the problem is formulated to analyze two-vehicle collisions only. The existing software does not allow a third vehicle or object in the collision process. The motions of the vehicles are restricted on a horizontal plane.

The source code of the original SMAC program developed by Calspan and NHTSA has been obtained and several publications related to the original development are given in the list of references. [21-24]

SIMULATION SCENARIOS, ASSUMPTIONS, AND PARAMETERS

In real-world accidents, vehicle crashes result in a wide range of post-impact behaviors. The post-impact motions of vehicles involved in a collision are functions of:

1. collision conditions, such as vehicle orientation and types of impacts;
2. vehicle parameters, such as size, weight and structural strength;
3. vehicle states, such as translational and rotational speed and acceleration;
4. roadway states, such as surface friction, curvature, grade, and roadside hazards;
5. driver input, such as throttle, braking, and steering;
6. tire-roadway interactions, such as friction coefficient, tire slip ratio, and tire slip angle.

In previous papers by the author [7,8,25-27], simulation results were discussed for the following scenario:

1. Two vehicles are proceeding in a straight lane with no steering inputs before, during, or after the impact;
2. The leading vehicle at time zero began braking with a constant 0.7 g deceleration and the following vehicle applied no braking; Throughout the simulation duration, the braking of the leading vehicle remains applied;
3. No other objects or vehicles come into contact or collisions with the two vehicles in question.

The simulation scenario was chosen to reflect one of the most critical failure conditions that might occur to cause collisions. Such scenarios might result from malfunctions or failures by:

1. a miscommunication from the leading vehicle to the following vehicle, and a failure in the range and range rate sensor on the following vehicle, or
2. a failure in brake actuation on the second vehicle.

The scenario above was simulated with a range of initial spacing, lateral offset between the longitudinal axes, initial speed and vehicle sizes. The outcomes of the simulations were evaluated by examining the vehicle trajectories, such as lateral displacement, angular rotation, and time to depart from a specified path. Further details and explanations of the simulation results can be found in other references. [25-27] In the discussion of simulation results shown in this report, the simulation is terminated four seconds after the initial collision.

One of the factors that should be mentioned here is the tire-roadway interaction issue. If the tire is skidding due to full braking (and without anti-lock braking capability), the directional stability of vehicle motion control is in jeopardy. When braking is not used (as in the failure vehicle) or only partially used, the steering function can be executed more effectively.

POST-COLLISION VEHICLE MANEUVERS

The simulation results from the previous studies demonstrated that control actions are necessary to correct or maintain the vehicle motion in its intended path. Without corrective actions, the vehicle can either travel out of its path to collide with other traffic or lose control with excessive translation and rotation. To examine the feasibility of such actions, several types of follow-up maneuvers are simulated in the scenario described in the previous section:

1. After the initial collision, the following vehicle makes a lane-change maneuver with steering input to avoid further impacts;
2. After failing to activate braking, the following vehicle initiates a lane-change attempt with steering input to avoid impacts or to minimize the collision magnitude;
3. After the initial failure, the following vehicle activates an emergency braking actuator with a delay to reduce its speed and to mitigate collision magnitude;

4. After the initial collision, the following vehicle uses steering input to maintain its own path in the original lane.

All of these scenarios assume that the vehicles are operable after the initial collision to the extent that the required actuation, braking or steering, are still functional. The implications and consequences of these scenarios are explained below. In assessing these simulation results, we are attempting to resolve the following main questions or concerns:

1. the feasibility of conducting steering functions for lane tracking or lane changing in a collision process;
2. the type of steering inputs needed to perform such functions;
3. the effectiveness of delayed emergency braking on the vehicle motions;
4. the comparison of vehicle trajectories and vehicle status in different follow-up scenarios.

In the previous section, the simulated scenario assumes two possible types of failure conditions. One of them involves a failure event in which the following vehicle fails to activate the braking function. If the event represents a total breakdown of the braking system, the following vehicle will continue to lack the braking ability in the following period. Therefore, the first two follow-on actions given above make an attempt to steer away from the decelerating leading vehicle before or after the first collision. The second maneuver scenario is a better alternative than the first if the collision can be avoided at all. However, both of these actions require a decision making process with the following considerations:

1. The steering function needs to be operable;
2. There is an adjacent lane that is open to accept the lane changing vehicle; and
3. The vehicle has the ability to detect or learn about such availability.

Note that the lane-changing vehicle has a brake failure and will continue to move at a considerable speed even after a successful maneuver. Some further actions or procedures, such as energy-absorbing soft barriers to stop the vehicle, are required.

The third follow-up maneuver scenario suggests that an “emergency” brake be applied after the initial collision with a time delay. This action represents a condition where the “physical capability of braking” is not lost but the decision making process has failed to activate. It can also imply a system in which a separate “switch” for the braking system is built into the vehicle. This switch is activated by a collision sensor.

The fourth follow-up maneuver scenario utilizes the steering input of the following vehicle to perform its “lane keeping” function. Further collisions with the leading vehicle are likely to occur but the magnitude of impact will continue to decrease as both vehicles slow down. This action can be seen as an alternative to utilize the stopping capability of the leading vehicle to stop the motions of both vehicles. This action avoids the concerns for lane changing indicated above but it still requires the ability of both vehicles to perform lane tracking in a collision process involving multiple impacts.

The risks of vehicle damage and occupant injuries in these follow-up actions may need to be evaluated on a case-by-case basis and appear difficult to be generalized. However, the follow-up actions involve the emergency handling logistics embedded in the design process of automated vehicles and they should be weighed carefully. For example, with Maneuvers One and Two, the attempt is made to move the failure vehicle away from the other vehicle and to bring it to a stop through other methods. On the other hand, Maneuver Four sacrifices the leading vehicle by utilizing its stopping capability to decelerate the failure vehicle. Such “unselfish” approach may be acceptable if the collision magnitude can be determined to be smaller than the alternatives.

The magnitude of steering angle and the timing of steering and braking inputs in these maneuvers are determined after a few iterations of simulation by an ad hoc approach. Efforts at modifying the current program to allow the implementation of closed-loop control strategies are underway. The values selected in these simulations are reasonable but they will ultimately depend on the design specifications of automated vehicles and control algorithms.

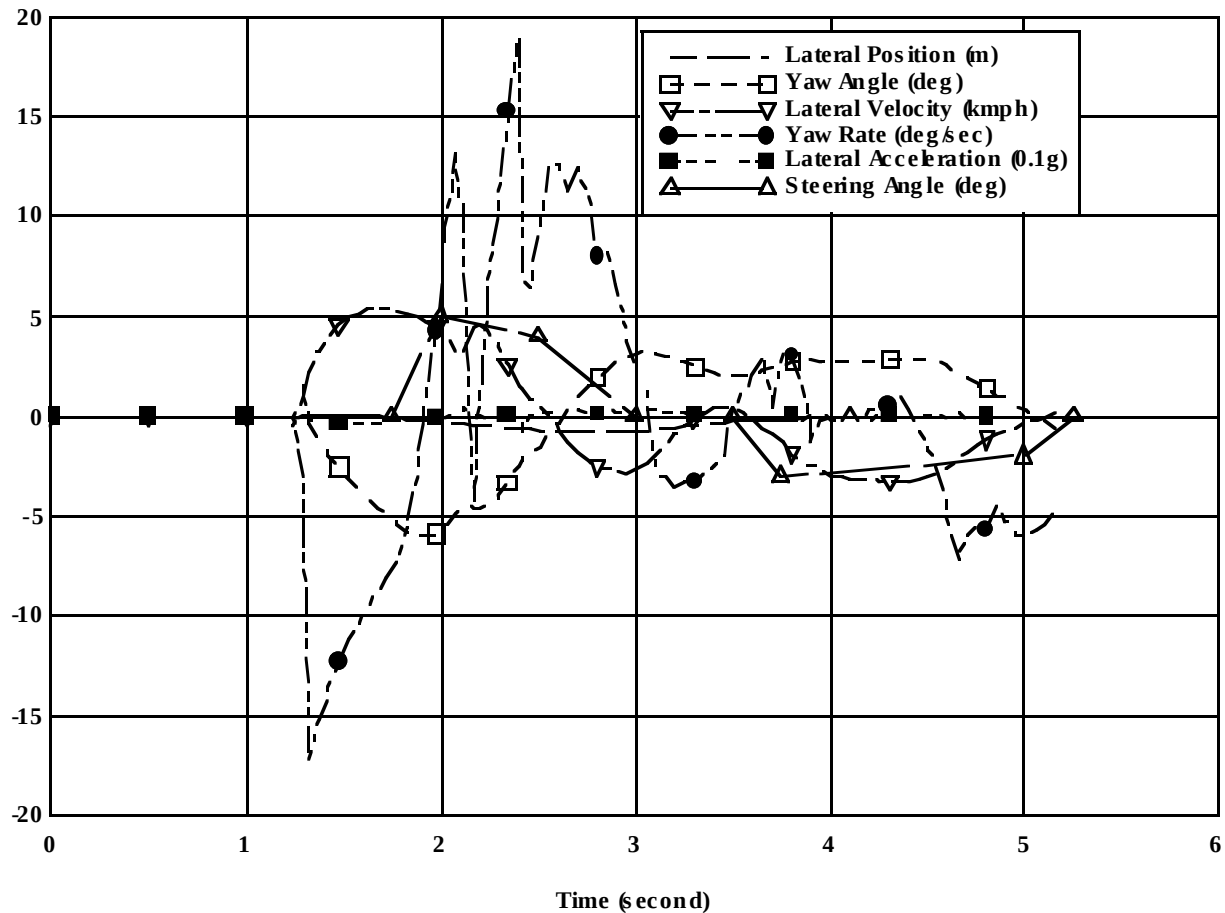


Figure 1. Motion variables of leading vehicle in a lane-keeping maneuver after a collision between a leading Class I vehicle and a following Class IV vehicle.

Note: Parameters in the simulation: initial speed = 105 kmph, lateral offset = 0.30 m, road surface friction coefficient = 0.875. The simulation begins with the leading vehicle braking at 0.7 g.

SIMULATION RESULTS

In the simulation of Maneuver One, the steering input to change lanes for the following vehicle is initiated at 1.71 seconds, about 0.5 seconds after the initial impact. In Maneuver Two, the steering action is activated at 0.5 seconds. Both of these scenarios assume that a time period of 0.5 seconds is needed for the decision making process to start the action. The steering angle inputs are selected to complete a 3.6 m (12 ft) lane change. During the lane change, subsequent contacts between vehicles continue to occur, therefore causing the steering inputs to be different from typical lane change maneuvers. In Maneuver Three, a deceleration of 0.7 g on the following vehicle is assumed to be initiated at 0.5 seconds, representing an emergency braking capability activated after the collision. No steering inputs are used in this scenario. In Maneuver Four, steering inputs are applied on both vehicles to maintain both vehicles in the lane but no braking is applied to the following vehicle. In all maneuver scenarios, the braking on the leading vehicle remains at 0.7 g throughout the simulation.

Table 1 and 2 show the vehicle status and positions of the leading and the following vehicles in different maneuvers. Table 1 contains the results from a case of a large vehicle following a small vehicle, and Table 2 from a case of a small vehicle following a large vehicle. It should be noted here that although in Maneuver 2 the following vehicle makes a lane-change attempt, a collision still occurs before the lane change is completed. This collision involves a front corner of the following vehicle and a rear corner of the leading vehicle and results in a lowest delta-V impact among all maneuvers. As a result, the following vehicle has the highest speed and travels the longest distance at the termination of the simulation, as indicated in both tables. Maneuver 4, with steering inputs from both vehicles, is most efficient in keeping both vehicles in the original lane. If the braking capability in the following vehicle is lost (as in Maneuvers 1, 2, and 4), Maneuver 4 appears to be a reasonable approach to slow down both vehicles while maintaining vehicles in the original lane. With an emergency braking capability, Maneuver 3 is able to bring the speeds of both vehicles to a much lower level.

Figure 1 and 2 depict several variables representing the motions of the leading vehicle and the following vehicle respectively in Maneuver 4, Table 1. In these figures, the lateral position and speed, yaw angle and yaw rate, lateral acceleration and steering angle at the front wheel are plotted. In this case, a leading small vehicle and a following large vehicle are both traveling at 105 kmph with an initial spacing of 5 m and a lateral offset of 0.3 m. At time 0, the leading vehicle begins braking at a deceleration of 0.7 g and at 1.21 seconds the first collision occurs. Roughly 0.5 seconds after the first impact, steering actions are taken on both vehicles in an attempt to maintain both vehicles within a lane. The maneuvers in this case demonstrate successful attempts to minimize the deviations of vehicle trajectories.

A comparison of vehicles in all maneuvers shows that Maneuver 3 brings the final speeds down to the lowest levels because the braking of the following vehicle is activated after the first impact. Maneuver 2 yields the highest speed of the following vehicle because the lane change maneuver is initiated before the first collision occurs. It is noteworthy that delta-V in subsequent collisions in Maneuver 4 gradually decreases. This is significant because the strategy deployed in Maneuver 4 is only sensible when the subsequent collisions cause less severe damage to vehicles and injuries to occupants in subsequent impacts.

Using the initial and final speeds of both vehicles for calculation, the “equivalent” stopping decelerations are 0.25g and 0.46g respectively for Maneuver 4 in tables 1 and 2. This “equivalent” deceleration represents the effective braking capability of both vehicles without braking power in the following vehicle. The difference in the deceleration in both cases is caused by the vehicle weight differential. In the simulation program, a Class I vehicle has a default weight of 1000 kgs (2202 lbs) and Class IV a weight of 1928 kgs (4247 lbs).

One issue that is not discussed in this report is the effects of operational variables and vehicle maneuvers on vehicle damage. It should be noted that vehicle damage or structural deformation is not linear or additive in multiple collisions. For example, two collisions of 10 kmph delta-V on the same region of a vehicle are not likely to generate the same degree of damage when compared to a single 20 kmph collision. Sophisticated modeling and reliable crush measurement data are needed for accurate estimates of vehicle damage in multiple collisions. A thorough investigation into this problem may lead to certain guidelines of structural requirements and the effects of collisions on the integrity of control systems and vehicle operability.

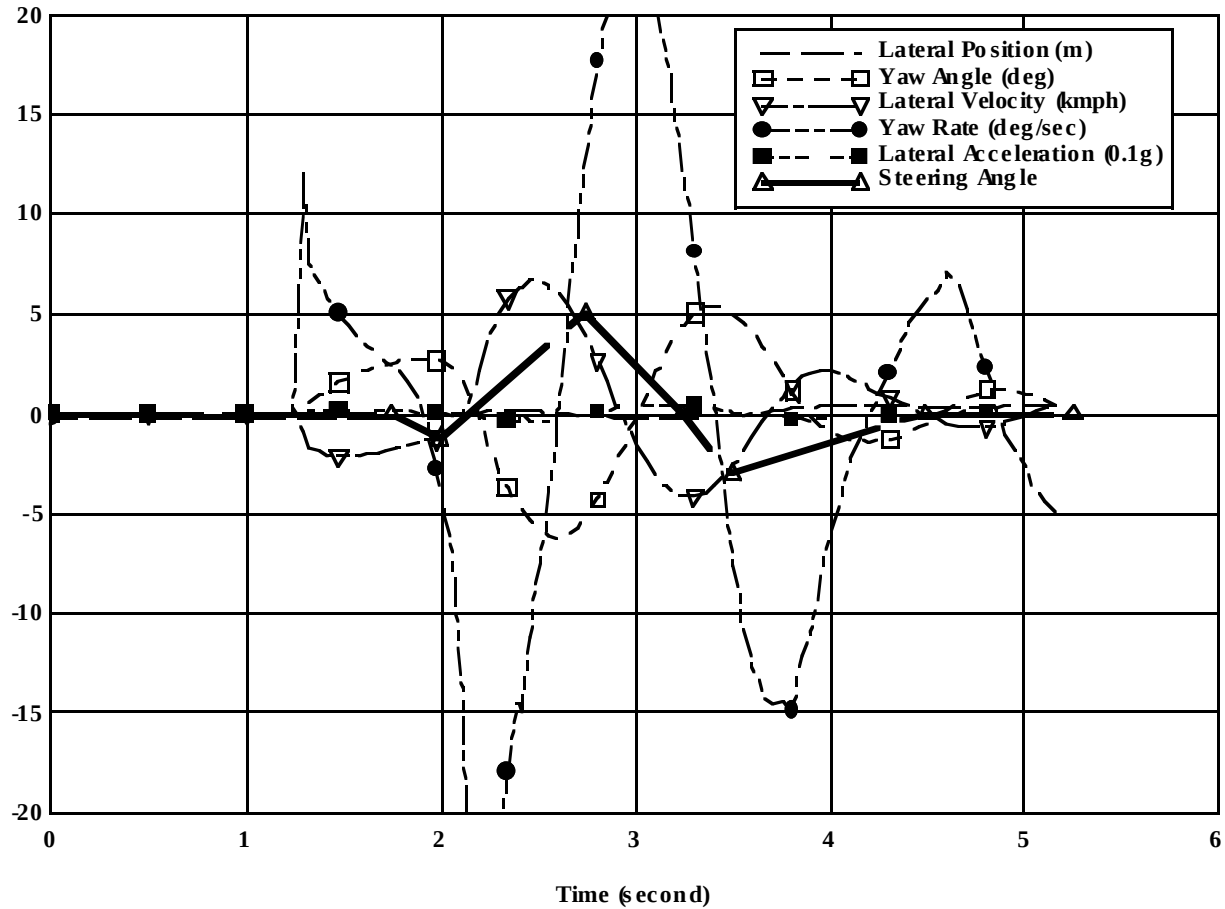


Figure 2. Motion variables of following vehicle in a lane-keeping maneuver after a collision between a leading Class I vehicle and a following Class IV vehicle.

Note: Parameters of the simulation: initial speed = 105 kmph, lateral offset = 0.30 m, road surface friction coefficient = 0.875. The simulation begins with the leading vehicle braking at 0.7 g

SUMMARY AND FUTURE WORK

This report reviews the effects of certain operational parameters on the post-impact vehicle trajectories. Simulations of vehicle-following collisions show that large lateral offset and large initial spacing can result in significant path deviations or vehicle rotation and cause quick departure from the original traveling lane. [25,26] The speed-differential or delta-V in collision appears to be a significant factor of the collision outcome in typical highway operations, as reflected in the large initial-spacing cases. The results also indicate that without control actions, the vehicles involved in a collision can be out of their lanes within 1 to 3 seconds.

Several maneuvers are proposed to examine the feasibility of controlling vehicle motions during or after collisions. These maneuvers involve the use of steering and/or braking inputs on one or both vehicles. The simulation results demonstrate lane-change or lane-keeping functions can be accomplished in the representative scenarios. An emergency braking function, if implemented, will be desirable to reduce the vehicle speed and their distance.

The understanding of vehicle motions in collisions is an important step in evaluating the safety hazards and benefits of automated vehicles. The use of two-dimensional crash models allows the examination of lateral and rotational movement. These simulations enable the assessment of operational parameters as well as the control inputs in crash conditions. A continuation of this work should include the implementation of a closed-loop control model with the crash and dynamic models. Efforts in developing a model with similar features for multiple vehicle collisions are also considered.

ACKNOWLEDGMENTS

This work was performed as part of the California PATH Program of the University of California in cooperation with the state of California Business, Transportation, and Housing Agency, Department of Transportation.

The contents of this paper reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

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A commercial version of EDSMAC was provided by Engineering Dynamics Corporation (EDC) of Beaverton, Oregon, to PATH at no cost. Thanks should go to Terry Day, who offered the program and provided helpful instructions.

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Table 1

Comparisons of vehicle trajectories with different follow-up maneuvers: a leading Class I vehicle and a following Class IV vehicle, initial speed = 105 kmph, lateral offset = 0.30 m, road surface friction coefficient = 0.875. The simulation begins with the leading vehicle braking at 0.7 g. Column 2 shows the range of lateral position, and Column 3 the range of yaw angle; Column 4, 5, and 6 indicate the vehicle speed, the yaw angle, and the coordinates at the end of the simulation.

Leading Vehicle

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (kmph)	Final Yaw Angle (deg)	Final Position (m)
No Action	-8.55, 0.06	-192.29, 0.00	15.372	-192.29	98.91, -8.55
Maneuver 1	-4.12, 0.06	-142.99, 0.00	0.08	-142.78	87.42, -4.12
Maneuver 2	-0.00, 0.47	0.00, 0.88	0.00	0.27	64.70, 0.46
Maneuver 3	-5.29, 0.06	-8.47, 0.00	3.89	-8.47	87.80, -5.29
Maneuver 4	-0.74, 0.06	-6.04, 3.20	59.71	-0.58	114.33, -0.02

Following Vehicle with an initial offset of 0.30 m

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (m/sec)	Final Yaw Angle (deg)	Final Position (m)
No Action	-6.75, 0.25	-9.39, 2.92	76.30	-7.92	114.91, -6.75
Maneuver 1	-0.32, 3.76	-1.69, 7.97	85.23	0.32	120.57, 3.60
Maneuver 2	-4.19, -0.31	-10.89, 3.39	101.01	-0.23	136.70, -3.72
Maneuver 3	-0.32, 2.09	0.00, 3.33	5.16	3.33	84.57, 2.09
Maneuver 4	-0.32, 0.40	-6.20, 5.41	60.00	0.42	110.21, 0.40

Table 2

Comparisons of vehicle trajectories with different follow-up maneuvers: a leading Class IV vehicle and a following Class I vehicle, initial speed = 105 kmph, lateral offset = 0.30 m, road surface friction coefficient = 0.875. The simulation begins with the leading vehicle braking at 0.7 g. Column 2 shows the range of lateral position, and Column 3 the range of yaw angle; Column 4, 5, and 6 indicate the vehicle speed, the yaw angle, and the coordinates at the end of the simulation.

Leading Vehicle

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (kmph)	Final Yaw Angle (deg)	Final Position (m)
No Action	0.00, 0.88	0.00, 1.48	0.00	1.21	75.46, 0.88
Maneuver 1	0.00, 0.95	0.00, 1.60	0.00	1.60	74.64, 0.94
Maneuver 2	-0.63, 0.02	-1.75, 0.00	0.00	-1.75	62.54, -0.63
Maneuver 3	0.00, 0.91	0.00, 1.47	3.68	1.47	74.50, 0.91
Maneuver 4	0.00, 0.98	-5.01, 4.48	19.40	4.48	87.20, 0.82

Following Vehicle with an initial offset of 0.30 m

	Lateral Position Range (m)	Yaw Angle Range (deg)	Final Total Speed (m/sec)	Final Yaw Angle (deg)	Final Position (m)
No Action	-5.64, -0.31	-4.41, 0.01	74.26	-4.41	107.77, -5.64
Maneuver 1	-3.57, -0.31	-8.39, 0.01	75.90	-0.04	109.86, -3.57
Maneuver 2	-3.81, -0.31	-9.92, 0.76	100.95	0.13	136.35, -3.66
Maneuver 3	-1.39, -0.31	-6.10, 0.01	0.00	-6.10	63.63, -1.39
Maneuver 4	-0.98, 0.41	-3.32, 11.14	19.53	1.29	82.97, -0.15