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CALIFORNIA PATH PROGRAM  
INSTITUTE OF TRANSPORTATION STUDIES  
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## **Low Speed Collision Dynamics and Control: Year One Report**

**Benson H. Tongue**  
**Ahrie Moon**

**California PATH Research Report**  
**UCB-ITS-PRR-95-25**

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# **Low Speed Collision Dynamics and Control: Year One Report**

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## **Abstract**

The primary aim of this project is to develop a program which will accurately determine platoon dynamics during both nominal and emergency situations on the road. Preliminary issues include collision detection between the vehicles within the platoon and determining the platoon's post-crash behavior. A two-dimensional vehicle model has been developed to address these issues. The overall simulation program includes individual modules that supply control input force, aerodynamic drag force, and road-tire interaction forces. Simplified models of these forces have been used for the simulations. The structure of the computer simulation code allows the use of upgraded modules as more refined controllers and system models are constructed. The platoon dynamical behavior resulting from the **simulation** program agrees qualitatively with physical intuition.

**Keywords:** Collision Dynamics, Intelligent Vehicle Highway Systems (IVHS), Safety, Traffic Platooning.

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## Nomenclature

$A_f$	frontal area of the car
$A_s$	reduction factor for the nominal friction coefficient
$C_d$	coefficient of aerodynamic resistance
$\delta_i$	steering angle input to vehicle $i$
$F_a$	aerodynamic drag force
$F_c$	control input force (combined traction and braking force)
$F_r$	force on the tire from the road (including sideslip force)
$I_i$	yaw moment of inertia of the vehicle
$m_i$	mass of vehicle $i$
$M_a$	moment on the vehicle due to aerodynamic forces
$M_c$	moment on the vehicle due to controller inputs
$M_r$	moment on the vehicle due to the road forces on the tires
$\mu$	modified coefficient of friction
$\mu_{nom}$	nominal coefficient of friction
$\vec{r}_i$	position vector of vehicle $i$
$\dot{\vec{r}}_i$	velocity vector of vehicle $i$
$\ddot{\vec{r}}_i$	acceleration vector of vehicle $i$
$\rho$	density of air
$\theta_i$	angular position of the vehicle $i$
$\dot{\theta}_i$	angular velocity of vehicle $i$
$\ddot{\theta}_i$	angular acceleration of vehicle $i$
$\dot{u}_i$	speed of vehicle $i$ in the direction along the car's longitudinal axis

# 1 Executive Summary

As PATH research heads towards physical implementation, issues of safety and comfort in platoons have become more pertinent concerns. To address these issues, it is necessary to study platoon dynamics during both nominal and non-nominal operations. This study requires more accurate models of vehicle interactions than models developed in previous platooning studies. The goal of this project is to develop a simulation program which will allow the study of platoon dynamics in both nominal and emergency scenarios.

The platoon concept poses a problem in multibody dynamics which has not yet been fully addressed in the existing literature. Most multibody dynamics research has been focused on constrained (or linked) multibodies. The intended application of the existing literature is for areas such as robotics, satellites, and biomechanics. There is relatively little literature on modeling the type of multibody system that is represented by the platoon paradigm used in the PATH project, i.e. a system consisting of multiple bodies which are not normally connected. (The only times connections occur for platoons are during collision. These connections will be complex, not simply pin joints.)

In platooning research to date, very simple vehicle models have been utilized in order to examine platoon dynamics. When used in longitudinal control development, the vehicles are essentially modeled as point masses. When a collision occurs within the platoon during longitudinal operation, it is assumed that the vehicles remain in a straight line [Hedrick et al. 1991, Sheikholeslam 1989, Shladover 1989]. In lateral control law research, the vehicle models are slightly more sophisticated in that they include the possibility of lateral translation and yawing motions [Peng 1991]. However, the models developed so far do not account for the complex interactions between vehicles during a collision. To realistically model platoon dynamics during a wide range of possible scenarios, it is necessary to investigate these complex interactions between vehicles. This is the aim of the current work.

This report discusses the issues investigated during the first phase of the project. A simple vehicle model has been developed for preliminary analysis, and a modular simulation



program has been written which utilizes this simple vehicle model. Section 2 describes the system models and preliminary issues which have been resolved using these system models. Section 3 documents the details of the simulation program which has been coded to allow for expansion and refinement of the vehicle model. Section 4 presents simulation results which are qualitatively representative of expected dynamics.

## **2 System Models**

Since the start of this project, a simplified vehicle model has been developed to resolve some preliminary issues involved in accurate platoon modeling. These issues are 1) how to detect contact/collision between two cars during simulation, and 2) how to determine the motion of these contact points after a collision occurs.

### **2.1 Features of the Current Model**

In this first stage of the work, the vehicle bodies are modeled as rectangles. The aerodynamic drag model is a modified version from the standard drag model for a car traveling on a straight road without any barriers in front of the vehicle. The tire model is a linear model which does not take into account many of the complexities involved in tire dynamics. Also, the controller implemented at this point does not exert control during and after the collision.

#### **2.1.1 Vehicle Body**

The vehicle bodies are represented by rectangles. The center of mass is assumed to be at the center of the rectangle. For now, the vehicle body is assumed to be a rigid body. The current model does not accurately account for deformation of the vehicles during a collision. Such deformations are accounted for only to the **extent** that the coefficient of restitution in the impulse-momentum formulation models this phenomena. Current work will extend this model so that the vehicle contains a rigid passenger compartment, front and rear crush zones and bumpers.

#### **2.1.2 Aerodynamic Drag Model**

A simplified aerodynamic drag model has been developed for preliminary simulations. This model is a modified version of the basic aerodynamic model for a car traveling on a straight

road:

$$F_a = (1/2)\rho C_d A_f \dot{u}_i^2 \quad (1)$$

where  $F_a$  is the aerodynamic force,  
 $\rho$  is the density of air (standard value =  $0.00238 \text{ kg/m}^3$ ),  
 $C_d$  is the coefficient of aerodynamic resistance,  
 $A_f$  is the frontal area of the car,  
 $\dot{u}_i$  is the vehicle speed in the direction along the longitudinal axis of the car.

This force is assumed to act in the direction opposite to velocity. In the present work, the frontal area of the car has been changed to the “effective area” perpendicular to the velocity vector, and  $\dot{u}_i$  has been changed to the magnitude of the velocity vector. (See figure 1.)

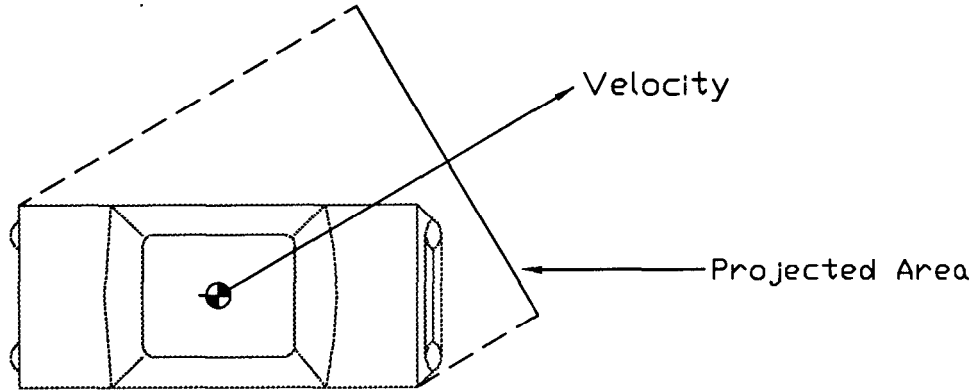


Figure 1: Aerodynamic Model Using “Effective Area”

This model does not account for the effect of other vehicles in the platoon which may alter the air flow and the aerodynamic forces of a given vehicle for which the calculation is being carried out.

### 2.1.3 Tire-Road Interaction Model

The tire-road interaction model developed in [Dugoff 1969] is being used at the present. The tire mechanics model allows for a combination of lateral and longitudinal slip and camber effects. The inputs to the vehicle are the steering angle, traction forces, and braking forces. The model accounts for various mechanical tire properties (cornering stiffness, camber

stiffness, rolling resistance) and the effect of vehicle speed on the friction between the road and the tires. The vehicle speed modifies the friction coefficient via the equation

$$\mu = \mu_{nom} (1 - A_s \dot{r}_i) \quad (2)$$

where  $\mu$  is the friction coefficient which accounts for the speed of the vehicle,  
 $\mu_{nom}$  is the nominal coefficient of friction,  
 $A_s$  is an empirical reduction factor,  
 $\dot{r}_i$  is the magnitude of the velocity vector  $\vec{r}_i$ .

The work in [Dugoff 1969] utilizes a three-dimensional vehicle model. For use in present work, the tire model has been adapted to the two-dimensional case. This reduced model still retains the lateral forces (sideslip) and longitudinal forces (road friction, rolling resistance) on the tires. It does not, however, account for camber effects. This is reasonable, since sideslip and longitudinal forces most strongly influence the effect on the directional response of the vehicle [Dugoff 1969].

Several other assumptions have been made to simplify the calculations. All tires are assumed to be identical, and so they all have the same empirical coefficients in the model. The forces *on* the front two tires are the same, and the forces on the rear two tires are the same. Also, the forces on the tires from the road are assumed to be directly transferred to the vehicle via the point where the tires are attached to the vehicle.

#### **2.1.4 Control Input Model**

The program has been designed such that the function that calculates the control input is modular. This feature allows the program to be utilized as a testbed for various controllers. The program can accept control inputs during emergency as well as nominal operating conditions.

In the simulations produced thus far, the controller is a simple one. During nominal operations, the control input only maintains the speed of the vehicle. It does not attempt to control the spacing between the vehicles. There is no control effort during and after a

collision. This simplicity is due to the fact that validation of the collision detection and response algorithms were the primary focus of the work.

## **2.2 Detecting Contact Between Vehicles**

To establish when contact between two vehicles occurs, the shape and the positions of the cars must be known at all times. In the current program, a collision is defined by observing when the areas of any of the cars intersect. Since the vehicle models are rectangles, determining when vehicles crash is more straightforward than will be the case for more realistic planforms.

When the shapes of the cars are allowed to take on more realistic forms, determining precise collision points will be quite a bit more difficult. Also, when a vehicle deforms, the vehicle body can take on complicated shapes, and the task of determining contact will be more formidable still. As a first step toward accounting for deformations, the cars will be allowed to deform in a controlled manner at the front and rear. Each crush zone (front and rear) will have two degrees of freedom, not including the bumper.

## **2.3 Determining the Motion of Contact Points**

The current model does not account fully for the deformation of vehicles during a collision, i.e. the shape of the vehicles do not change. The “deformation” is accounted for only to the extent that the coefficient of restitution in the impulse-momentum formulation models this phenomena. In the current program, post-collision simulation is almost identical to pre-collision simulation; the only exception is that there is no control input after the collision. Therefore, determining the motion of contact points after a collision is straightforward.

It is assumed that no friction forces are acting between the bumpers of the cars. When the model is upgraded to account for deformations that occur in a collision, friction forces will be essential to produce realistic simulations and will be included in the simulation code.

### 3 Simulation Program

The current version of the program is capable of simulating a platoon consisting of an arbitrary number of cars traveling along a straight road, and of simulating a platoon of two vehicles rounding a curve of constant curvature. One command within MATLAB will run every subprogram necessary to run the simulation sequence, from defining system constants and initial conditions to integrating the equations of motion. (All the code has been written inside MATLAB as m-files.) These are events that occur in a typical simulation:

- 1) The vehicles travel under nominal conditions with control inputs
- 2) Two of the vehicles collide and separate.
- 3) The vehicles travel without control inputs.
- 4) Steps (2) and (3) may be pa until the vehicles come to a stop.

Before running the simulation, various physical parameters (such as mass and size of the cars) and initial conditions can be specified. For a two-car platoon, two different road-types can be chosen, straight or curved.

During nominal operations, numerical integration of the equations of motion and collision detection tests are performed simultaneously. The collision tests are conducted for pairs of vehicles. Control input forces, aerodynamic drag forces, and road-tire interaction forces are taken into account in the equations of motion. The translational dynamics of each vehicle are represented by the vector equations

$$m_i \ddot{\vec{r}}_i = F_c(\vec{r}_i, \dot{\vec{r}}_i, \ddot{\vec{r}}_i) + F_a(\dot{\vec{r}}_i) + F_r(m_i, \dot{\vec{r}}_i, \delta_i) \quad (3)$$

where  $m_i$  is the mass of vehicle  $i$ ,

$\vec{r}_i$  is the position vector of vehicle  $i$ ,

$\dot{\vec{r}}_i$  is the velocity vector of vehicle  $i$ ,

$\ddot{\vec{r}}_i$  is the acceleration vector of vehicle  $i$ ,

$\delta_i$  is the steering angle input to vehicle  $i$ ,

$F_c$  is the control input force (combined traction and braking force),

$F_a$  is the aerodynamic drag force,

$F_r$  is the force on the tire from the road (includes sideslip force).

The rotational dynamics are represented by the equations

$$I_i \ddot{\theta}_i = M_c + M_a + M_r \quad (4)$$

where  $I_i$  is the yaw moment of inertia of vehicle  $i$ ,

$\ddot{\theta}_i$  is the angular acceleration of vehicle  $i$ ,

$M_c$  is the moment on the vehicle due to controller inputs,

$M_a$  is the moment on the vehicle due to aerodynamic forces,

$M_r$  is the moment on the vehicle due to the road forces on the tires.

Once a collision is detected, a separate subroutine determines the impact dynamics for the interacting vehicles during the collision. This task is accomplished through the use of impulse-momentum equations and assuming a coefficient of restitution between the pair vehicles which are involved in the collision.

The state at the end of a collision is returned to a post-collision simulation program. The post-collision program integrates the equations of motion without the control input. Again, collision detection tests are performed at each step of the integration.

## 4 Simulation Results

Two illustrative simulation results are discussed here. In the first example, the platoon consists of five vehicles traveling along a straight road. In the second example, the platoon consists of two vehicles traveling around a road of constant curvature.

Table 1: Physical System Parameters

Parameter	Value
vehicle mass, $m_i$	1809 kg
vehicle yaw moment of inertia, $I_i$	<b>4068</b> kg-m <sup>2</sup>
vehicle length	<b>3.048</b> m
vehicle width	1.524 m
nominal friction coefficient, $\mu_{nom}$	1.05
reduction factor, $A$ ,	<b>0.00335</b>
coefficient of restitution	<b>0.8</b>

In each example, there are birds-eye view “snapshots” of the vehicles at specific instants in time. This is a quick visualization tool used to check the simulations. A fully animated computer graphics program has been independently developed to visualize the simulation in real time. Videotapes of the animation have been produced for two vehicles traveling around a curve and for a five-vehicle platoon traversing a straight road.

The physical system parameters used for both of these simulations are listed in table 1. These parameters are from reference [Dugoff 1969]. All the cars in these simulations are identical.



## 4.1 Five-Car Platoon on a Straight Road

For the five-car platoon, each car is initially traveling at a constant speed. For this simulation, the initial conditions of the vehicles are listed in table 2. The speed of vehicle 3 has been set lower than the speeds of the other vehicles so that a collision will occur in some finite time.

Table 2: Initial Conditions for the Five-Car Platoon

Initial Condition	Car 5	Car 4	Car 3	Car 2	Car1
$x$ [m]	0	6.1	12.2	18.3	24.4
$y$ [m]	0	0	0	0	0
$\theta$ [rad]	0	0	0	0	0
$\dot{x}$ [m/s]	26.8	26.8	24.6	26.8	26.8
$\dot{y}$ [m/s]	0	0	0	0	0
$\dot{\theta}$ [rad/s]	0	0	0	0	0

At  $t = 1.36$  seconds, a collision occurs between vehicle 3 and 4. For these two vehicles, there are sudden changes (spikes and dips) in the plots of their velocities profiles at the time of the collision (figure 2). These points of change are marked with an x on figure 2. This is due to the momentum transfer from car 4 to car 3. The second plot on figure 3 shows a snapshot of all five vehicles at this time. The vehicles are traveling in the positive x-direction.

After the first collision, the vehicles all begin to decelerate since control inputs are terminated following a collision. At  $t = 2.86$  seconds another collision occurs, this time between car 4 and car 5. Once again, there are spikes and dips in the plots for the vehicle speeds for car 4 and car 5. These points are marked with an 'o' on the plots for cars 1 and 2 in figure 2. The third plot in figure 3 shows a snapshot of this collision.

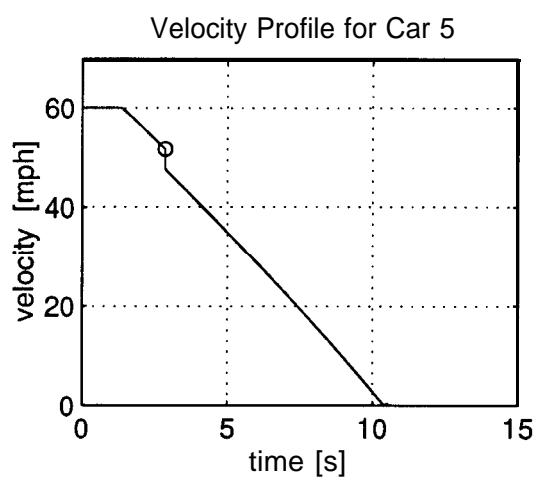
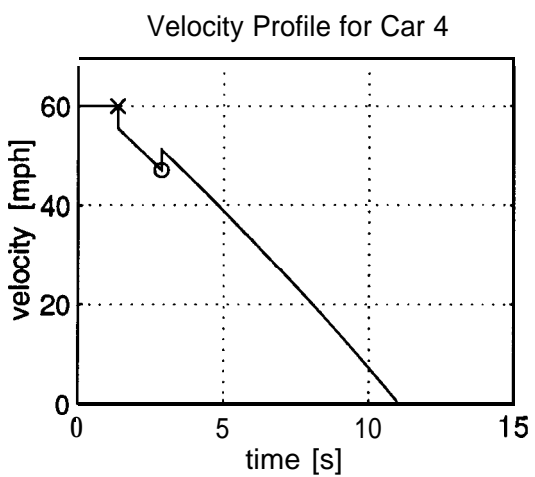
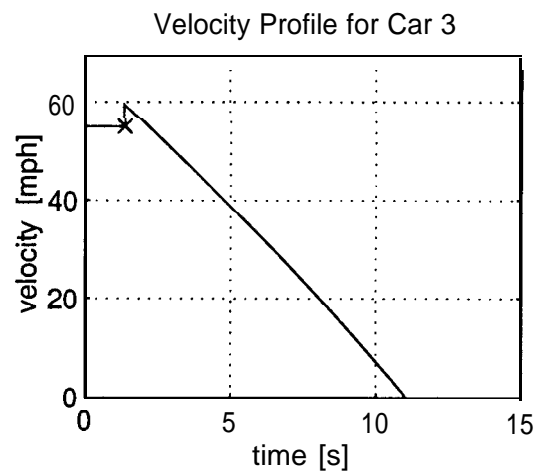
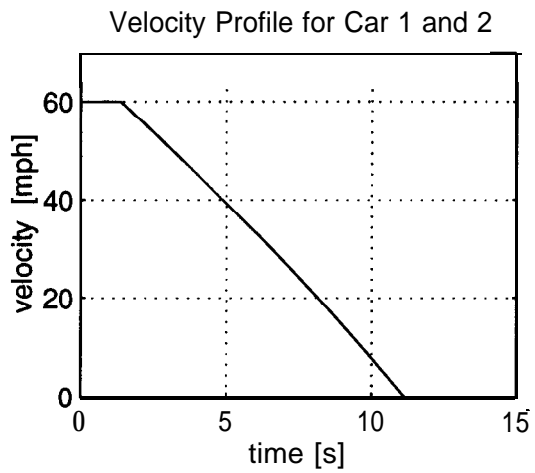


Figure 2: Velocity Profiles for the Five-Car Platoon

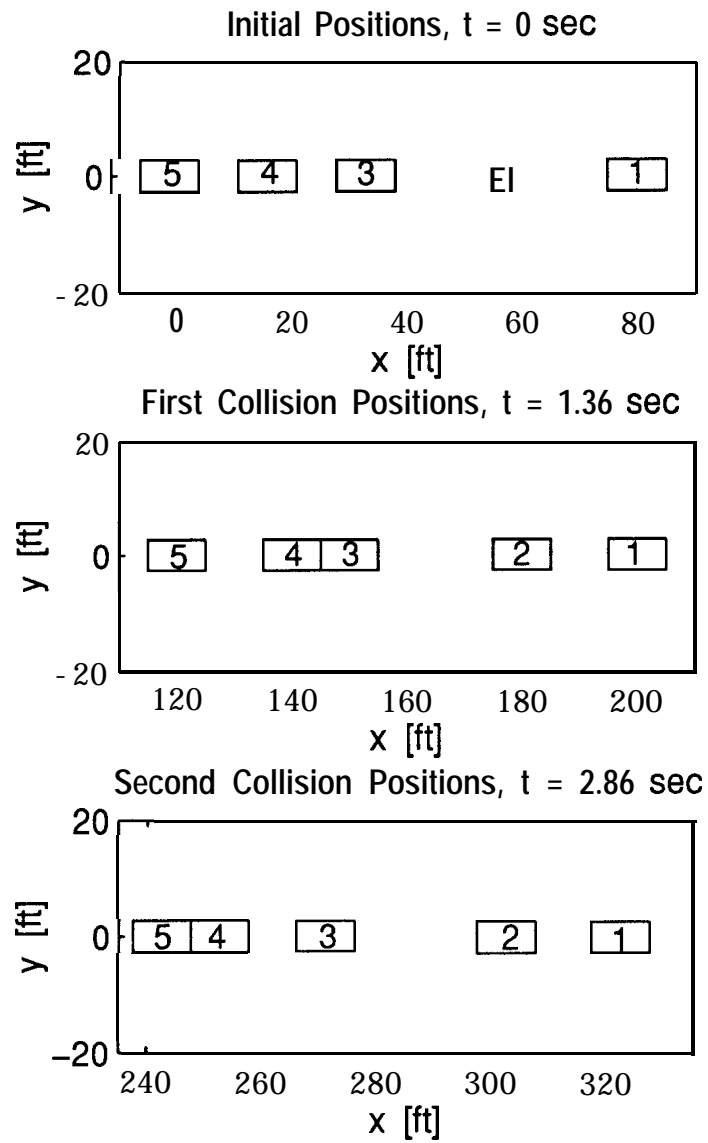


Figure 3: Snapshots of Vehicle Positions at Various Times (5-car platoon)

## 4.2 Two-Car Platoon on a Curved Road

The constant radius of curvature for the road is 30.48 meters for this simulation. The initial conditions for the two cars are listed in table 3. Note that initially,  $\theta$  represents the angular velocity necessary for the cars to negotiate the curve.

Table 3: Initial Conditions for the Two-Car Platoon

Initial Condition	Car 2	Car 1
$x$ [m]	0	6.1
$y$ [m]	0	0.61
$\theta$ [rad]	0	0.2
$\dot{x}$ [m/s]	.29.1	24.1
$\dot{y}$ [m/s]	0	4.9
$\dot{\theta}$ [rad/s]	0.65	0.55

Only one collision occurs during this simulation; this occurs at  $t = 0.67$  seconds. Note the sudden changes in the angular as well as the linear velocity profiles in figure 4. The points where the collision occurs is marked with an 'o' in the plots.

The positions of the two vehicles at various times is shown in figure 5. The snapshots are of the initial condition ( $t = 0$  s), at the time of the collision ( $t = 0.67$  s), and 0.6 seconds after the collision ( $t = 1.27$  s). Because the collision occurs at an angle, the cars rotate afterwards. Car 1 rotates more than car 2 does.

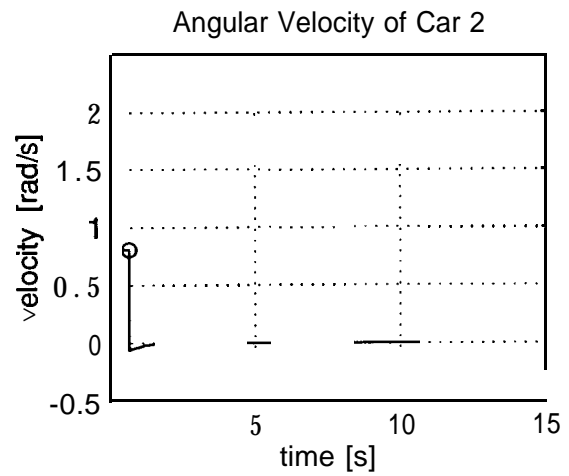
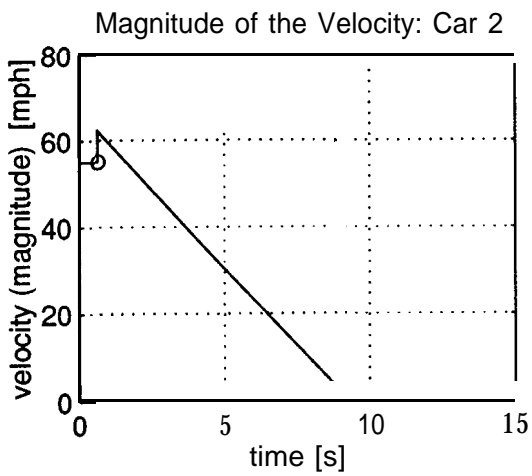
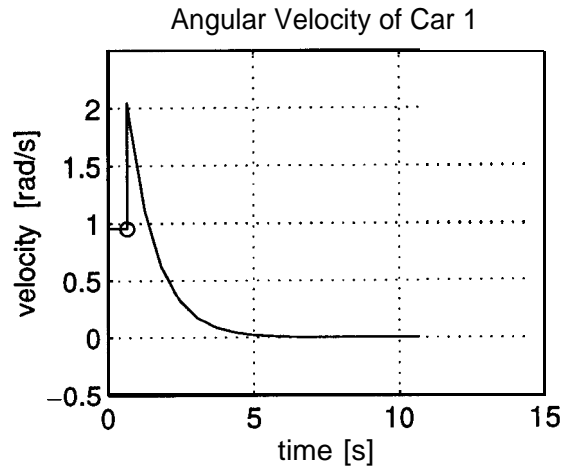
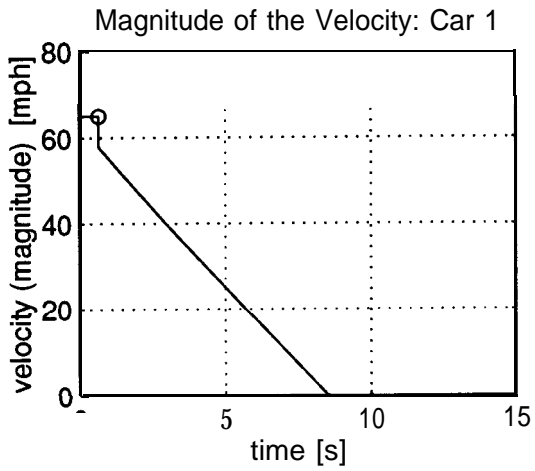


Figure 4: Velocity Profiles for Two-Car Platoon

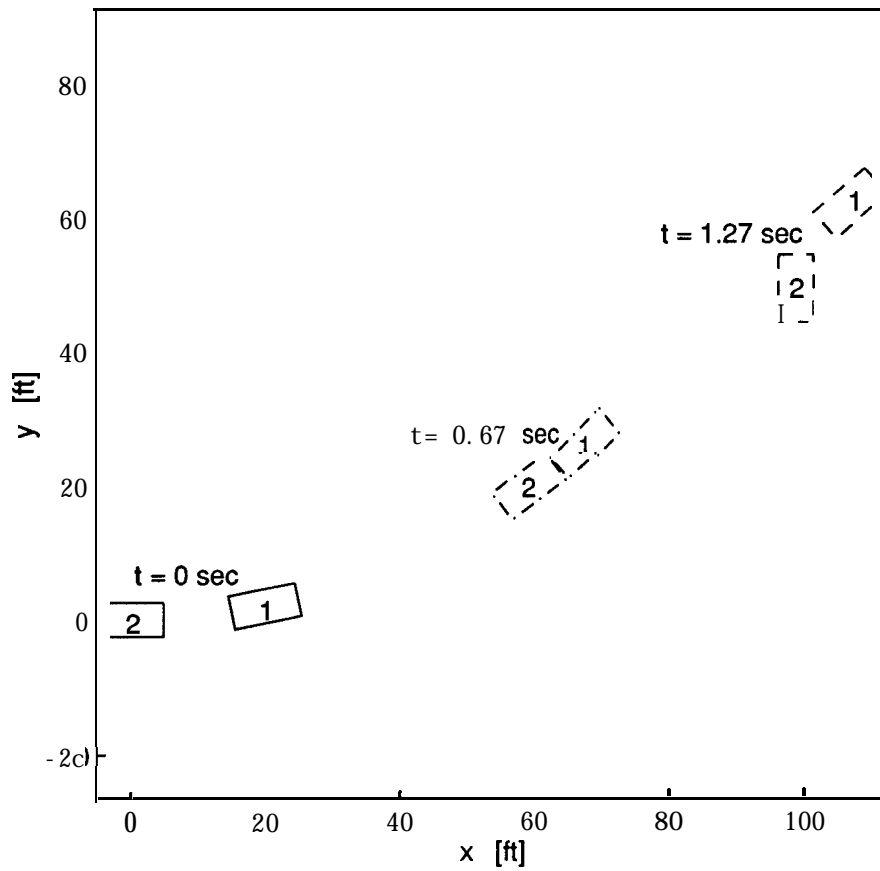


Figure 5: Snapshots of Vehicle Positions at Various Times (2-car platoon)

## 5 Conclusion

The results from the simulations reflect reality in a qualitative sense. The vehicles collide and transfer momentum to each other. The aerodynamic drag and forces on the tires from the road act to slow down the vehicles after a collision. When the vehicles are traveling around a curve, the onset of a collision induces the individual vehicles to spin about their own center of mass in addition to translating across the road. Thus it seems that the important collision detection logic and numerical simulation parts of the code are working. The next step will be to include more realistic crush capabilities in the vehicle models as well as upgraded force components to more accurately reflect real world vehicle behavior.

To carry this work forward, there is still some work to be done on the two-dimensional model. More information must be gathered on the aerodynamics in a platoon and steering system dynamics. To accurately model collisions, the deformation of bumpers and vehicles must be researched and analyzed.

After refinement of the two-dimensional model, the vehicle model will be upgraded to three-dimensions. This will require research into suspension characteristics of vehicles to incorporate pitch and roll effects in vehicles. Also, the model for deforming vehicles dynamics will need to include more details due to the added physical dimension.

Finally, to streamline the code, the features of the model which dominate the observed behavior of an actual system will be retained while unimportant modeling components will be deleted.

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