Title

Platoon Collision Dynamics And Emergency Maneuvering IV: Intra-platoon Collision Behavior And A New Control Approach For Platoon Operation During Vehicle Exit/entry - Final Report

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California PATH Research Report

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PREFACE

This report is the final one in a series of four that document the findings of our research project - “Platoon Collision Dynamics and Emergency Maneuvering.” The first reports detailed how we constructed our vehicle models and simplified them so as to obtain accurate simulation capability with reasonable computation times. These simplifications were obtained by curve fitting to the actual vehicle responses. Inherent time delays of the system were retained. Although eliminating these delays would have further decreased computation time, this savings would have occurred at the expense of accuracy.

Both a pre-existing control approach as well as a newly designed one were utilized in the collision simulations. The new approach, one that takes account of more than just the preceding vehicles’ states, showed the capability of mitigating the severity of collisions to the overall platoon. This approach did not show an advantage in normal station-keeping operations, thus suggesting it would be reasonable as an emergency controller. The rest of the research project was devoted to investigations of how collisions propagate during emergency maneuvers and how they can be best mitigated.

Abstract

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This report examines platoon behavior during non-nominal operations, most especially due to emergency braking. Three main topics are discussed: multiple-collision wave propagation effects for homogeneous platoons with and without lead vehicle information, intra-platoon collision behavior of non-homogeneous platoons during emergency operations, and a new control approach for platoon operations during vehicle exit/entry.

The results regarding multiple-collision dynamics of homogeneous and non-homogeneous platoons during emergency braking were obtained by utilizing two of Desoer's linear controllers (with and without lead vehicle information). In the study of collision wave propagation effects for homogeneous platoons, the desired spacing and deceleration of the lead vehicle are used as the two control parameters. Quantitative results for a region of safety and a multiple-collision layer are presented. Qualitative results regarding the propagation of collision waves and impact severity measures are also discussed.

Non-homogeneity of the platoons was produced by varying the individual vehicle masses. The time of impact and the maximum absolute acceleration of the vehicles were used to characterize the overall platoon response to a multiple collision event. Deceleration of the lead vehicle was used as the control parameter in the simulations. The traction/mass ratio and the vehicle mass were shown to be important factors in influencing collision wave propagation and platoon collision severity. Details of the collision wave propagation behavior and the positioning of the most dangerous location for a vehicle within a platoon were also investigated.

Finally, a new platoon control concept was introduced, called Back Control, in which the controller of a given vehicle utilizes state information from the lead, preceding, and following vehicles, as well as the vehicle itself. Simulations were carried out on two non-steady state platoon operations -- vehicle entry and vehicle exit from a platoon. At this stage of the study, Desoer's controller was used as a reference to the proposed Back controller and a ride quality index (Mean Personal Rating) was used to assess passenger comfort in these simulations. It was shown that the Back controller had advantages over the reference controller in these two operations and that it was therefore worth examining as a candidate controller of vehicular platoons, especially in non-nominal operations.

1 EXECUTIVE SUMMARY

Several topics are addressed in this report, all of which have application to platooning design and safety. The general thrust of the work was to understand how platoons will react when faced with non-nominal (or emergency) situations. These situations range from abrupt acceleration/deceleration of the lead vehicle to unanticipated removal of vehicles from the platoon and greater than designed for merge velocities. Additionally, the effect of vehicular non-uniformity as well as inclusion/exclusion of sensor data was addressed.

The underlying rationale behind the investigation was to provide some answers to “what if’ kinds of questions. What if, due to a defective controller or actuator, a vehicle tries to merge too quickly? What will the consequences be? What if an important channel of information (in this case lead information) is lost? Will this significantly affect the platoon’s safety? What if controllers that were designed for known vehicular conditions, are used with vehicles for which the parameters have varied (heavily loaded vehicles, worn tires, additional aerodynamic loads due to carrier racks, etc.)? Will the overall platoon performance be seriously degraded or not? Although this report certainly does not claim to answer every question of this sort, it does answer a few and hopefully indicates areas in which further investigation is merited.

What was found in the study was that the exclusion of lead vehicle information is most important at tight spacings. When spacings are wider, the performance with or without lead is similar. Thus one immediate response to the loss of lead information would be to increase the nominal intra-vehicular spacing (for safety reasons) until such time as the vehicles can be removed from the platooning lane or lead information is restored.

Non-homogeneity seems to degrade performance - leading to more intra-vehicular collisions and/or more intense collisions. The position of the non-homogeneous vehicle within the platoon strongly affects the overall responses, indicating that some logic with regard to positioning within platoons, beyond that of “all new arrivals to to the rear” would be desirable.

Lastly, the idea of controllers that are designed for emergency situations appears to have merit. The Back Control concept, which gives each vehicle knowledge of preceding as well as trailing vehicles, allows each vehicle to position itself “between” vehicles more effectively. This distributes disturbances throughout the platoon, reducing the level of peak magnitudes. Thus, rather than large disturbances being felt by a few vehicles, all vehicles experience low level disturbances. It seems that such a trade-off might be desirable in the event of emergency situations.

Nomenclature

a_i	acceleration of car i
a_l	acceleration of lead vehicle
c_a	control gain for acceleration state error
c_{a1}	control gain of car 1 for acceleration state error
c_i	control law for car i
c_p	control gain for position state error
c_{p1}	control gain of car 1 for position state error
c_v	control gain for velocity state error
c_{v1}	control gain of car 1 for velocity state error
F_a	aerodynamic force
F_b	braking force
$F_{b,max}$	saturated braking force
F_c	impact force due to a collision
F_g	gravitational force caused by the road grade
F_r	rolling resistance force
F_{tf}	traction force
F_{tfm}	maximum traction force
f_r	rolling resistance coefficient
G_0	road roughness coefficient
g	acceleration of gravity
H	vehicle height
k_a	control gain for acceleration difference with lead vehicle
k_{a1}	control gain of car 1 for acceleration difference with lead vehicle
k_v	control gain for velocity difference with lead vehicle

k_{vl}	control gain of car 1 for velocity difference with lead vehicle
L	length of vehicle
M	vehicle mass
v	vehicle speed
v_0	steady-state value of the lead vehicle's velocity
v_i	velocity of car i
v_l	lead vehicle's velocity
x_i	position of car i
α	braking percentage
A	front spacing
Δ_i^f	front spacing error
Δ_i^r	rear spacing error
λ	road grade
ϕ	throttle angle
τ	engine response delay
τ_b	braking response delay
$sgn(\cdot)$	sign function

Table of Contents

List of Figures

2 INTRODUCTION

Platooning, a current topic of interest as a means of improving automotive travel, seeks to join several vehicles together electronically, the resultant train of vehicles being called a platoon. By maintaining small vehicle to vehicle spacings through onboard sensors and computer controllers, the overall vehicle throughput in a platooning lane will be increased over vehicles under manual control. In addition, the driver is freed from the immediate task of driving the vehicle once the computer has taken control.

In the past few years, a number of studies have focused on the tracking problem of platoon formation. However, only the nominal situation (which assumes that the platoon dynamics are slowly varying) has been investigated and those studies have concentrated primarily on the problem of controller design. The problems that will result from a serious platoon failure (large-scaled intra-platoon collisions) have yet to be investigated. The purpose of this investigation is to see how the platoon's responses are correlated to an emergency braking situation and to examine the question of platoon safety. Both homogeneous and non-homogeneous platoons are discussed. Two platoon models that utilize Tongue and Yang's reduced order vehicle model (Tongue et al. 1991, Tongue and Yang 1994) and two controllers (distinguished by whether they use lead vehicle information or not) (Sheikholeslam and Desoer 1990, Sheikholeslam and Desoer 1991) are used to examine the overall, nonlinear platoon dynamics.

In the simulations, the lead vehicle has been given a constant magnitude of deceleration. Non-homogeneity of the platoon is reflected in the varying vehicle masses and collision timing is used to illustrate collision wave propagation. The maximum absolute acceleration and approach velocity are used to assess impact severity.

In this study, a safe operating regime (one that guarantees a no-collision scenario) is constructed for homogeneous platoons and depends upon two parameters; desired spacing and deceleration of the lead vehicle. The boundary layer that defines when multiple-collisions occur is examined for the homogeneous platoons with lead vehicle information. To study collision wave propagation in the homogeneous platoons, three desired spacings have been simulated for both types of controller strategies by varying the deceleration of the lead vehicle.

It is found that intra-platoon multiple-collision wave propagation events depend strongly upon the implemented controller and the desired spacing and reflect the strong nonlinearities within the platoon. Moreover, this investigation also provides some insights into appropriate responses during emergency platoon operation. In addition, the importance of lead vehicle information is highlighted from the simulation results.

The rationale for studying intra-platoon collision behavior of non-homogeneous platoons is that, although closely similar vehicles can certainly be found in commercial operations, the reality of a viable platooning system for public use will undoubtedly involve vehicles that are not identical. It seems likely that the effect of non-homogeneity within a platoon would be to degrade its operation and the purpose of this study is to determine how great this degradation might be. Such mass non-homogeneities can occur due to varying loadings of the vehicles, both by passengers as well as cargo. Thus the drivetrain/brake systems will be considered to be identical while the masses will vary.

Details of the collision wave propagation effects and maximum impact force of individual vehicles are discussed for different non-homogeneous platoon formulations. It will be seen that the traction/mass ratio dominates the pattern of collision wave propagation and that the vehicle mass plays an important role in the impact severity.

In an attempt to develop a new control logic to suit the non-nominal platoon operations, a control concept, Back control, has been applied to two particular non-nominal operations: vehicle exit from the platoon and vehicle entry into the platoon. Both Sheikholeslam and Desoer's controller [2] and the Back controller, a controller that evaluates not only the states in front, but also those behind the controlled vehicle, have been used. To evaluate the performance of the controllers, a rider comfort index, the Mean Personal Rating value (Yang and Tongue 1994), has been utilized. It is shown that the Back controller has advantages in these two situations.

3 PLATOON COLLISION MODEL

The longitudinal dynamics of a vehicle can be simply expressed by Newton's second law:

$$\ddot{x}_i = \frac{1}{M_i}(F_{tf} - F_b - F_r - F_a - F_g + F_c) \tag{1}$$

where $\ddot{x}_i$ is the acceleration of vehicle i,

M_i is the vehicle mass,

F_{tf} is the traction force,

F_b is the braking force,

F_r is the rolling resistance force,

F_a is the aerodynamic force,

F_g is the gravitational force caused by the road grade, and

F_c is the force due to a collision,

Clearly, F_b, F_r,F_a, F_g, and F_c are external forces. F_b depends on the braking system and tire performance. F_r is a function of road roughness, vehicle speed, and tire properties. F_a is a flow-induced force, which depends on the vehicle profile, velocity, spacing between vehicles, and so on. F_g is the gravitational force caused by the longitudinal grades of highways. F_c is an impact force which depends on the vehicle's bumper characteristics and the impact severity of the collision. The only force that is dominated by the internal dynamics is F_{tf}, which involves the complicated engine dynamics, including the system's reaction lag.

3.1 Numerical Engine Model

In order to have a computationally tractable model for use in platoon simulations, a detailed (and pre-existing) engine/drivetrain model (Cho and Hedrick 1989, McMahon et al. 1990) was analyzed and approximated by a set of curve-fit equations (Tongue et al. 1991). The result of this reduction was the ability to characterize the engine response by the maximum traction, F_{tfm}, and the engine response delay, τ. These quantities are related as follows:

$$F_{tfm}(\phi, v) = a(1 - e^{-\beta\phi})^{\gamma} \tag{2}$$

$$\tau(\dot{\phi}) = 2.091\ \dot{\phi}^{-0.7033} \tag{3}$$

where

$$\alpha = 1.0 \times 10^{3}\ (-0.0053\ v + 2.74)$$

$$\beta = 1.0 \times 10^{-3}\ (0.061\ v + 101.9)$$

$$\gamma = 1.0 \times 10^{-3}\ (18.86\ v + 855.)$$

F_{tfm} is a function of throttle angle, ϕ, and vehicle velocity, v, and the engine response delay depends on throttle rate only. This time delay is quite critical since, without it, the engine would respond instantaneously when the controller requests accelerations, a rather unrealistic assumption, especially in view of the tight spacings that platoons are currently envisioned as having.

3.2 Vehicle/Bumper Model

Based on the 1980 requirements for bumpers in 8 km/hr (5 mph) barrier impacts and impact experiments (Sharp et al. 1978, Johnke et al, 1984, Glance and Daroczy 1989), a realistic vehicle/bumper model has been developed. The requirement limits the damage that may be sustained to be less than 9.5 mm (3/8 in) for dents and to be less than 19 mm (3/4 in) for permanent large-scale deformations. This model considers both the bumper stiffness and the vehicular body stiffness, which are arranged in series. The bumper is assumed to be elasto-plastic, in which the energy dissipation for each collision cycle occurs through hysteresis in the bumper. The characteristics of this model are shown in figure 1. The value at point A in figure 1 is the point at which body rigidity comes into play. The enclosed area indicates the total energy absorbed due to the bumper.

3.3 Additional Forces

Other forces that are used in the vehicle model are defined as follows. The braking force is given by

$$F_b = \alpha\, F_{b,max}\, (1 - e^{-\frac{t}{\tau_b}}) \tag{4}$$

where	α	is the braking percentage,
	$F_{b,max}$	is the maximum braking force,
	t	is the braking time,
and	τ_b	is the time constant of the braking system.

Refering to ASTM STP884 (Lu 1985), the rolling resistance force can be expressed as follows.

$$F_r = M\ g\ f_r \cos(\lambda) \tag{5}$$

$$f_r = (0.4864 \times 10^{-3} G_0 - 0.0103 \times 10^{-6})\, v^3 +$$

$$
\begin{aligned}
&(-0.0952\ G_0 + 1.1425 \times 10^{-6})\, v^2 + \\
&(7.0982\ G_0 - 0.0310 \times 10^{-3})\, v + 0.01
\end{aligned}
\tag{6}
$$

where M is the vehicle mass,

g is the gravitational acceleration,

f_r is the rolling resistance coefficient,

λ is the road grade,

G_0 is the road roughness coefficient,

and $0.4050 \times 10^{-6} \leq G_0 \leq 6.400 \times 10^{-6}$, for highways.

A spacing-variant model of the drag coefficient (Tongue et al. 1991) has been applied to account for the behavior of the wake region between vehicles. The drag force is represented as

$$
F_a = \begin{cases} 0 & \text{if } A \leq .5H \\ 0.4\ \left(\frac{\Delta}{H} - .5\right) C_a v^2 & \text{if } .5H < A \leq\ 3H \\ C_a\, v^2 & \text{if } 3H < \Delta \end{cases}
\tag{7}
$$

where C_a is the aerodynamical coefficient, H is the height of the front vehicle, and A is the front spacing of the vehicle. Corresponding to different road slopes, the gravitational force can be expressed as

$$
F_g = M\ g\ \sin(X)
\tag{8}
$$

where λ is the grade of the road.

3.4 Longitudinal Control Laws

The longitudinal control laws proposed by Sheikholeslam and Desoer (1990), for platoons with lead vehicle information, are as follows.

$$\begin{aligned} c_1 &= c_{p1}\Delta_1^f(t) + c_{v1}\dot{\Delta}_1^f(t) + c_{a1}\ddot{\Delta}_1^f(t) + k_{v1}(v_l(t) - v_0) + k_{al}a_l(t) \qquad (9) \\ c_i &= c_p\Delta_i^f(t) + c_v\dot{\Delta}_i^f(t) + \mathrm{c}\&(\mathrm{t}) + k_v(v_l(t) - v_i(t)) \\ &+ k_a(a_l(t) - a_i(t)) \qquad (10) \end{aligned}$$

and

$$\begin{aligned} \Delta_i^f &= x_{i-1}(t) - x_i(t) - L \qquad (11) \\ \Delta_i^r &= x_i(t) - x_{i+1}(t) - L \qquad (12) \end{aligned}$$

where subscript i refers to Car i(l for the lead car), c_i is the control law for Car i, L is the desired headway spacing, $x_i(t)$ is the position of Car i, and $\Delta_i^f(t)$ and $\Delta_i^r(t)$ correspond to the front and rear state errors of Car i, respectively. Control gains are as shown in table 2.1

c_{p1}	c_{v1}	c_{a1}	k_{v1}	k_{a1}	c_p	c_v	c_a	k_v	k_a
120	74	15	-0.05	-3.03	120	49	5	25	10

Table 2.1 Control Gains for Platoon with Lead Vehicle Information

The longitudinal control laws proposed by Sheikholeslam and Desoer (1991), for platoons without lead vehicle information, are as follows.

$$c_i = c_p\Delta_i^f(t) + c\&(t) + c_a\ddot{\Delta}_i^f(t) + k_c a_{i-1}(t) \qquad (13)$$

and the control gains are shown in table 2.2

c_p	c_v	c_a	k_c
91.99	80.96	17.56	-5.15

Table 2.2 Control Gains for Platoon without Lead Vehicle Information

4 PERFORMANCE INDICES FOR PLATOON DYNAMICS

4.1 Rider Comfort: Mean Person Rating, MPR

When analyzing platoon operations during sudden maneuvers, one can consider two cases. The first would be the case of near or low severity impacts, such as might well occur in a tightly spaced platoon faced with sudden deceleration or acceleration commands. In this case, the vehicle damage would be slight or nonexistent but the passengers might well experience an unacceptably unpleasant ride. This would indicate the need for controller and/or spacing modifications. In the event of an energetic collision, (the second case), the question of vehicle and passenger damage becomes relevant. In order to assess both of these issues, three measures are considered: MPR, approach velocity, and maximum absolute acceleration.

Smith, McGehee, and Healey (1978) developed a measure of rider comfort based on the acceleration spectrum of the vehicle. In the present paper, their criterion is modified slightly so that increasing values of the comfort measure correspond to reduced levels of comfort (or increased discomfort). The measure, called the Mean Personal Rating (MPR) is given by

$$\mathrm{MPR} = 0.87 + 6.8\ \alpha_{40} \tag{14}$$

where α_{40} is the rms (the square root of the sum of squares of the acceleration spectrum) acceleration. The highest frequency used in this calculation is 40 Hz.

Figures 2 and 3 give a feel for what a given MPR value correponds to in a physical sense. In figure 2, we show an acceleration/deceleration profile which contains a positive acceleration for one second and an equal deceleration for one second. Figure 3 shows the corresponding

MPR index for different magnitudes of acceleration/deceleration and various time periods over which the analysis takes place. Several observations can be made from these figures. First, we see that MPR values scale linearly with the level of acceleration/deceleration, as we would expect. The second observation has to do with the time period used. In order to find the spectral components of the acceleration, a Fourier Transform is taken for the time varying input signal and a finite window is chosen over which to take the transform. For most physical systems, the vehicle's response to a disturbance will be a damped oscillation. Since the MPR rating looks at the transform of this damped oscillation, we have the problem of determining how much of the response to include. Most of the input occurs over a small time period but, due to the exponential nature of the response, it will continue to oscillate (at vanishingly small amplitudes), for a very long time. What figure 3 shows is a discrete approximation to this problem. The lowest period (1.5 seconds) doesn't include the entire acceleration/deceleration profile while at the other extreme (4 seconds) half the input is equal to zero. As one can see, using too large a window (period 2) doesn't affect the MPR value appreciably. The MPR rating doesn't very appreciably as the window is varied from 2 to 4 seconds. However, the effect of ignoring large amounts of data is significant, as shown by the sharply rising MPR at small periods. The overall conclusion is that ignoring the input profile after the response has become small (say five percent of the maximum) is a reasonable cut-off point and will not cause appreciable errors.

Finally, we can see what sort of MPR levels correspond to given levels of acceleration. Recall that the input is a constant acceleration for one second followed by a constant deceleration for one second. By looking at a particular g level, one can get a feel for how these comfort figures translate into what one would actually experience. For instance, th reader can imagine what it would feel like to be in a vehicle that accelerates for one second at .7g and then decelerates for an additional second at .7 g. .7 g's for both acceleration and deceleration are roughly the limiting values that can be obtained in high performance vehicles. Thus this maneuver would mean maximal acceleration and maximal braking. Such a maneuver would cause an MPR rating of around 90. Gentler inputs would produce correspondingly smaller MPR values.

4.2 Impact Criteria: Maximum Absolute Acceleration and Maximum Approach Velocity

Approach velocity refers to the difference in velocities between two vehicles just prior to a collision. Large approach velocities imply large momentum differences, leading to a large interchange of energy between the vehicles while maximum absolute acceleration refers to the maximal absolute value of acceleration that a vehicle will experience. This acceleration is directly related to the largest force the vehicle experiences.

A collision with a large approach velocity usually implies the occurrence of a major collision, which induces higher loss of property and physical injury (Shladover 1978). A large maximum absolute acceleration means that the occupants in the vehicle experience a large G-force. (Note that the force experienced by the vehicle is not the same as, but is proportional to, the one experienced by the occupants due to the isolation provided by the seat.) Determining a detailed map between accelerations, momentum transfers, and the ultimate injuries sustained by the passengers is a complex task and will not be explicitly addressed in this work.

4.3 Collision Wave Propagation Index: Collision Timing

In the following discussion, “collision timing” is equal to the duration measured from the time that the lead vehicle begins to decelerate to the onset time of an individual vehicle colliding with its preceding vehicle. This measure characterizes the collision wave propagation within a platoon. It should be noted that this timing for an individual vehicle only accounts for its first collision, and the vehicle may subsequently experience a series of collisions, either from the following or from the preceding vehicles, until it comes to rest.

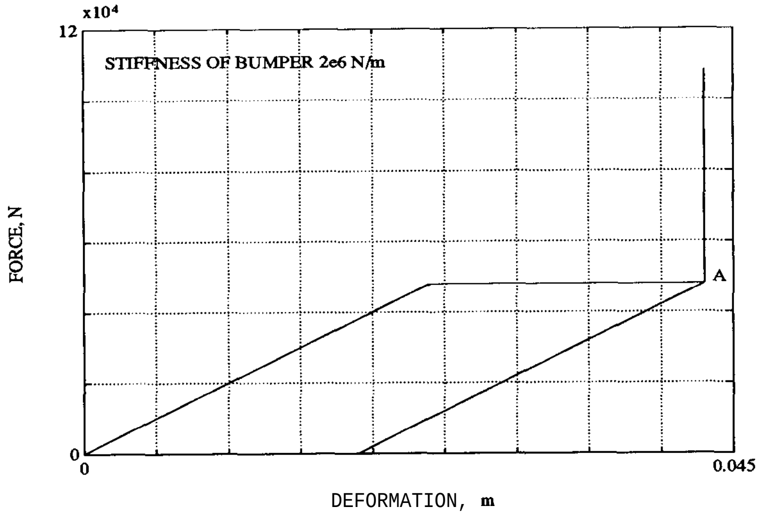


Figure 1: Characteristic of Vehicle/Bumper Model

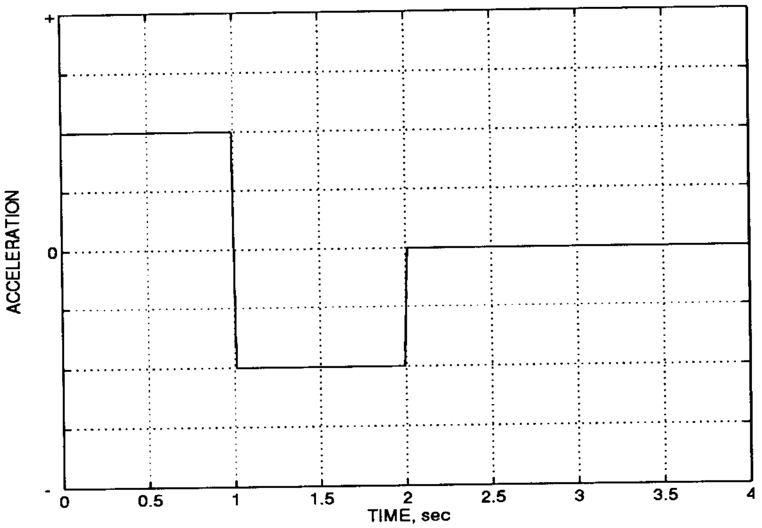


Figure 2: Acceleration/Deceleration Input Profile

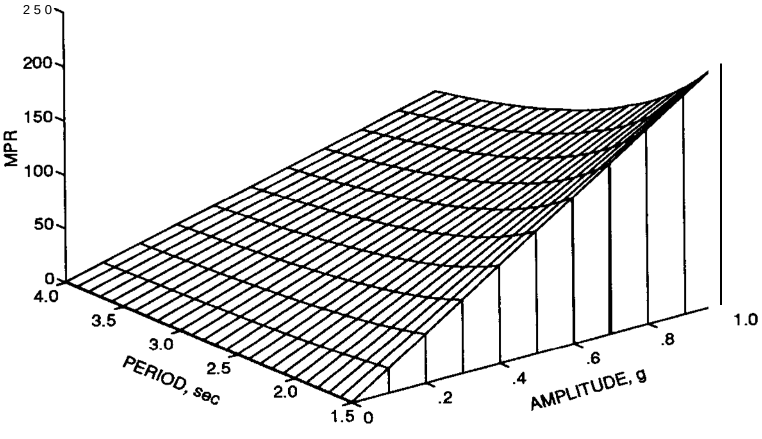


Figure 3: MPR Values for Varying Input Levels and Time Periods

5 INTRA-PLATOON COLLISION BEHAVIOR OF HOMOGENEOUS PLATOONS

In the following simulations, the lead vehicle behavior is assumed to consist of a constant deceleration. Each vehicle in the platoon was assumed to be identical. The power systems were assumed to exhibit response delay and saturation for both throttle and braking systems. Vehicle/bumper models were included in the front and the rear of the vehicles to account for vehicle collision forces. Aerodynamical forces and rolling resistance were also included. The parameters used in the simulations were as follows.

Vehicle mass	1,800 kg
Vehicle height	1.0 m
Bumper stiffness	2.0 MN/m
Vehicle body stiffness	6.0 MN/m
Maximum braking force	11,700 N
Aerodynamical Coefficient	0.43
Initial velocity	60 mph
Road grade	0 degree

In this work, all sensors and actuators were assumed to be functional, both before and after a collision. Clearly, an interesting later problem will be to consider the effect of limited control/sensor failure as a result of a collision.

5.1 Safety Operation Range for Emergency Braking

In an emergency braking situation, it is assumed that the platoon will decelerate to a stop. It seems reasonable that an intra-platoon collision will occur if the platoon decelerates too quickly or if the desired spacing is too small to sustain safe operations. The following simulation is carried out to construct a safe operation region within which one can be confident that collisions do not occur.

Figure 4 shows the maximum lead vehicle deceleration for which intra-platoon collisions do not occur (the maximum deceleration that vehicles can sustain is also shown in the plot). Below these limits, no collisions occur within the platoon. A minor collision occurs as the maximum deceleration limit is exceeded and severe collisions exist for the region far beyond the limits. It can be seen that, for both platoons, the magnitude of the deceleration limit increases as the desired spacing increases. Collisions do not occur for any vehicle if the desired spacing is larger than 4.6 meters.

It is interesting to note that the platoon utilizing lead vehicle information has a better ability to avoid intra-platoon collisions than one without lead vehicle information, as long as the desired spacing is less than 2.0 meters. This is due to the feed-forward effect that lead vehicle information provides. For platoons having lead information, the first collision always affects the first car of the platoon. What happens is that the vehicles know of the impending collision due to the lead vehicle's deceleration, and if the deceleration is large enough, the vehicle with the smallest room in which to maneuver will be the first to experience a collision. For this case, this vehicle is always the first car of the platoon. The following vehicles experience collisions in the order of the vehicle series number within the platoon.

In contrast, when the platoon doesn't utilize lead vehicle information (Sheikholeslam and Desoer 1991) the first intra-platoon collision occurs between Cars 9 and 10 for a desired spacing smaller than 1.6 meters and between Car 1 and the lead for a desired spacing greater than 2.0 meters. Thus, the way in which collision events begin depends strongly upon the intra-vehicular spacing. Above 2.0 meters, the vehicle spacings are enough to allow controlled deceleration, whether or not lead information is present. Below 1.6 meters, the lack of feed-forward information causes a disturbance wave to propagate down the platoon. This successively reduces the spacing between vehicles further down the platoon, thus causing the first collision to occur at the back of the platoon, rather than at the front.

In figure 5, the results of multiple-collision simulations are shown. To clarify these complicated phenomena, a new terminology (#-car collision) has been used. For instance, a 2-car collison means that there are two groups of intra-vehicle collisions; they might be the collisions among the lead, the first, and the second vehicles, or the collisions between the lead car and Car 1 and between Car 4 and Car 5. No special weighting has been put on how many collisions occur between two adjacent vehicles. Just as the first collision occurred at the front of the platoon when lead vehicle information is present, multiple collisions occur in the order of the vehicle serious number due to the feed-forward effect of including lead information.

Figure 5 shows the onset limits for multiple-collisions within the platoon having lead vehicle information. It can be seen that only the first four cars are involved in the intra-platoon collisions for a l-meter desired spacing if the lead vehicle saturates its braking capacities. Note that the situation right on the limit line is the occurrence of a minor collision for the last car involved in the multiple-collisions. For instance, for the 4-car collision case ($*$ line), Car 4 experiences a minor collision with Car 3, but Car 1 through Car 3 undergo major collisions with different degrees of severity. The no-collision region consists of those combinations of desired spacing and lead decelerations that lie beneath the solid line.

5.2 Collision Wave Propagation

As mentioned in Section 4.1, the collision characteristics change when lead vehicle information is **not** available and the desired spacing is less than 2.0 meters. Such a loss of lead information could come about by unanticipated failures in the communications system or in the lead vehicle's sensors. To illustrate these changes, two desired spacings (1.0 and 1.7 meters) are assigned to a platoon that lacks lead vehicle information. The case of a l-meter desired spacing for the platoon **with** lead vehicle information is also simulated as a baseline comparison for the case of multiple-collisions in which the first collision occurs between the lead vehicle and Car 1 and then propagates backwards to the rear of the platoon.

5.2.1 Platoons with Lead Vehicle Information

Figures 6, 7, and 8 illustrate the collision timing, maximum absolute acceleration, and maximum approach velocity, respectively. It is easy to see in figure 6 that the collision wave propagates backwards, car by car, as the deceleration magnitude of the lead vehicle increases. At a deceleration of .61 g, vehicle 1 has a collision timing other than zero. Thus the only vehicle to experience a collision is the first vehicle. At a deceleration of .75 g, the graph of collision timing versus vehicle series number increases monotonically, showing that first vehicle 1 experiences a collision, followed by vehicle 2, 3, etc. The first intra-platoon collision occurs around 1 second after the lead vehicle begins to decelerate. In line with intuition, the collisions occur sooner as a larger deceleration is applied to the lead vehicle. A zero collision timing means that no collision is observed.

From figure 7, it can be observed that the largest magnitude of the maximum absolute acceleration is not always associated with the car having the first intra-platoon collision (Car

1 in this simulation), but the car with the largest collision timing does exhibit the smallest maximum absolute acceleration among the colliding vehicles. Thus the accelerations vary during the collision interval as the controller tries to maintain order. There are three peak regions in this impact force related plot, one at Car 1, and the other two around Car **4** and Car 7. It should be noted that the maximum absolute acceleration increases rapidly as the lead car's deceleration increases. All these strong impacts are due to major intra-platoon collisions. The flat region in figure 7 is the collision-free region, the finite maximum absolute acceleration of which is due to braking saturation.

The trends seen for the maximum approach velocity (figure 8) are qualitatively similar to those of the maximum absolute acceleration (figure 7). Here we can see that the maximum approach velocity for the car with the first collision is not always (or even usually) the maximum of all the vehicles in the platoon. The later cars have to maneuver harder as they try to avoid a collision. Using Shladover's safety guidelines (Shladover 1978), the most dangerous locations are around Car 4 and Car 7 for severe platoon collisions and at Car 2 for lower decelerations, in which maximum approach velocities are larger.

5.2.2 Platoons without Lead Vehicle Information

Compared to the platoons having lead vehicle information, the behavior of the platoon without lead information is quite a bit less regular. Simulations are carried out by assuming desired spacings to 1.0 meter and 1.7 meters; the former one is in the region where the collision on the limit line in Figure 4 occurs between Car 9 and Car 10, and the latter one is in the transition region (between 1.6 to 2.0 meters desired spacing) that was mentioned in Section 4.1.

5.2.2.1 Desired Spacing of 1.0 m

Figure 9 shows the collision timing for 1 meter desired spacings. It can be observed that the first intra-platoon collision occurs between Car 9 and Car 10 if there is only one collision in the simulation, occurs between Car 8 and Car 9 if there are three cars involved in the collisions, and advances towards the middle of the platoon (and induces both forwards and backwards propagating collision waves) if a multiple-collision occurs. The deceleration magnitude necessary to induce multiple intra-platoon collisions is lower for this case than in the case of a platoon with lead vehicle information.

Figures 10 and 11 illustrate the maximum absolute acceleration and approach velocity for this simulation. In contrast with the previous case, the maximum absolute acceleration for the largest collision timing (Car 1 or Car 10) is not the smallest one among the colliding vehicles. Thus in this case, the last vehicle to collide had to deal with more involved intra-platoon dynamics, leading to high levels of acceleration. Generally speaking, both the maximum absolute accelerations and the maximum approach velocities increase as the collision wave propagates backwards and decrease as the collision wave propagates forwards. Moreover, at variance with the platoon having lead vehicle information, the most dangerous platoon operation locations are around Car 4 and Car 10.

5.2.2.2 Desired Spacing of 1.7 m

Figures 12 to 14 show what happens as the spacing tolerance is relaxed to 1.7 meters (which is close to the 2-meter junction point in figure 4). At the maximal deceleration, the collision timing variation versus vehicle series number resembles that of the case with lead information (figure 12). As the deceleration is reduced, we still have the trend of a backwards propagating collision wave, but the initiating vehicle isn't always Car 1. For instance, at a deceleration of .626 g, the first vehicle to collide is Car 2. From there, a collision wave propagates backwards, ending with a collision involving Car 6. For lower values of deceleration, this general trend breaks up and the overall response becomes quite unpredictable.

Again, the trends depend strongly on the magnitude of the lead deceleration. When all 10 cars experience collisions, the largest magnitude of accelerations and approach velocities are found at the rear of the platoon. But as the deceleration is reduced, the peak acceleration and approach velocities migrate towards the midpoint of the platoon.

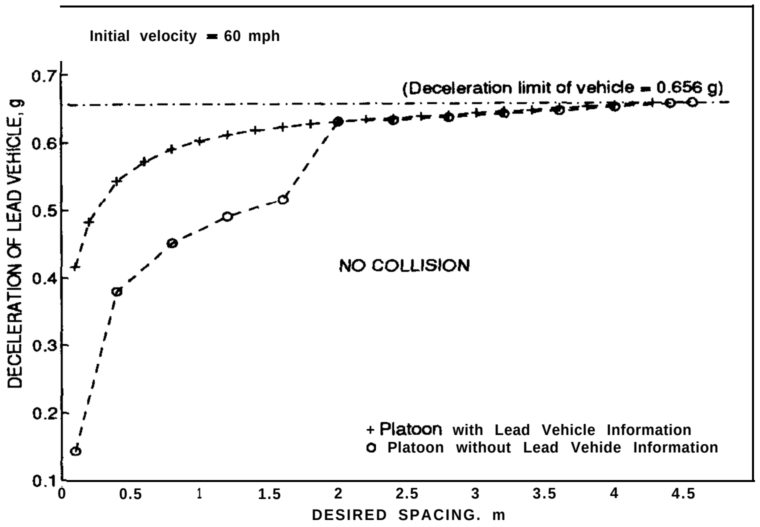


Figure 4: Safe Platoon Operation Region

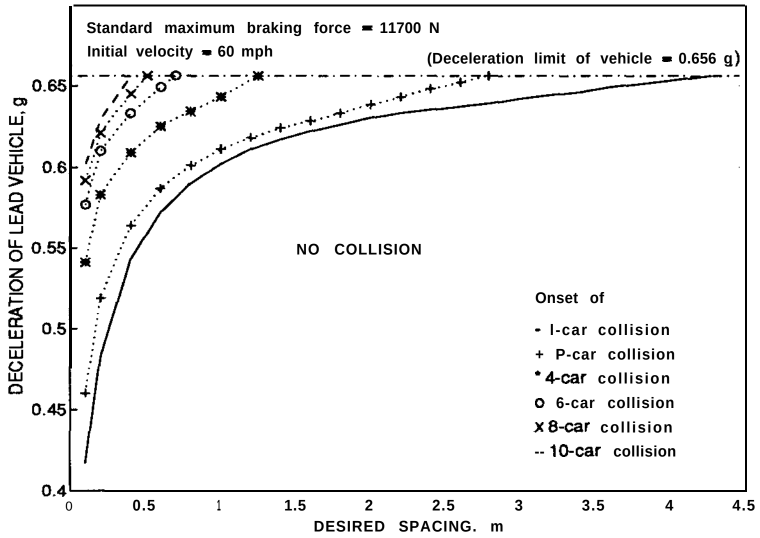


Figure 5: Multiple-Collision Limits for Platoon with Lead Vehicle Information

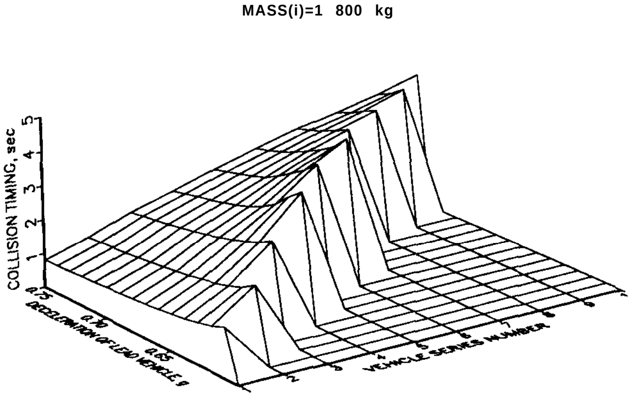


Figure 6: Collision Timing for Platoon with Lead Vehicle Information

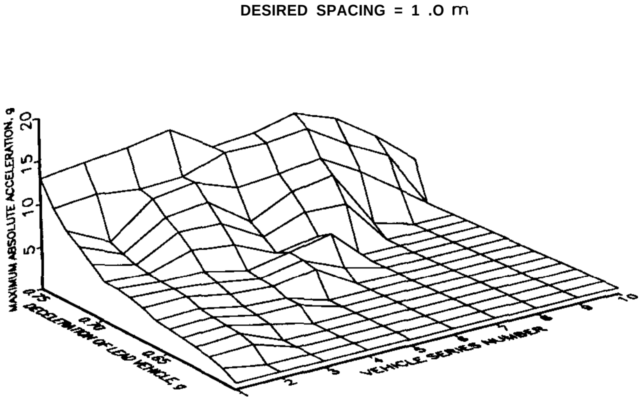
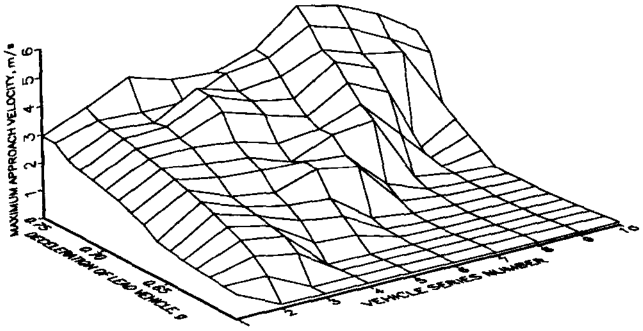


Figure 7: Maximum Absolute Acceleration for Platoon with Lead Vehicle Information



DESIRED SPACING = 1.0 m

Figure 8: Maximum Approach Velocity for Platoon with Lead Vehicle Information

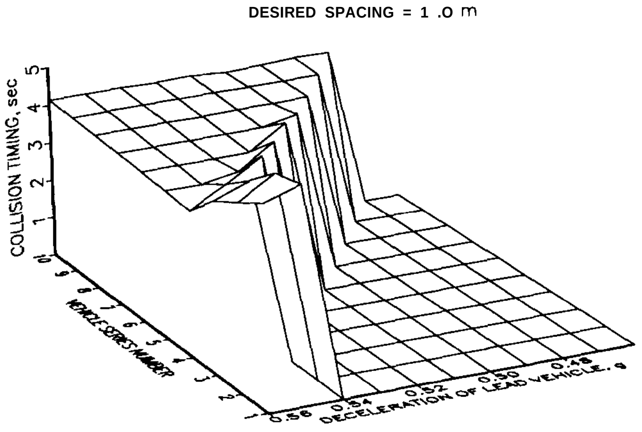


Figure 9: Collision Timing for Platoon without Lead Vehicle Information — 1 .O-meter Desired Spacing

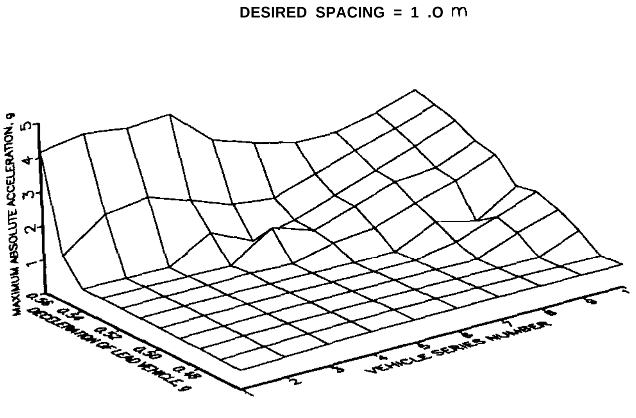


Figure 10: Maximum Absolute Acceleration for Platoon without Lead Vehicle Information — 1 .O-meter Desired Spacing

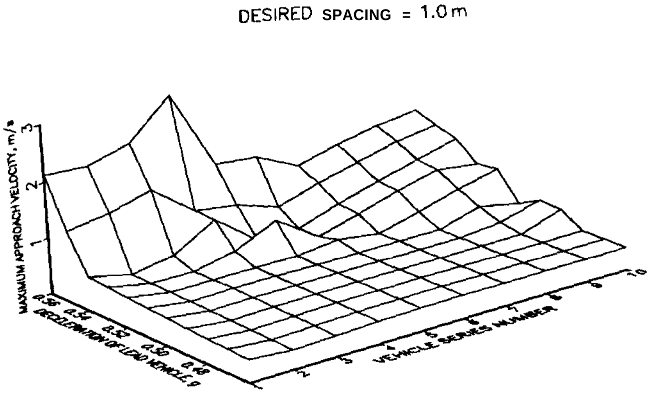


Figure 11: Maximum Approach Velocity for Platoon without Lead Vehicle Information – 1.0-meter Desired Spacing

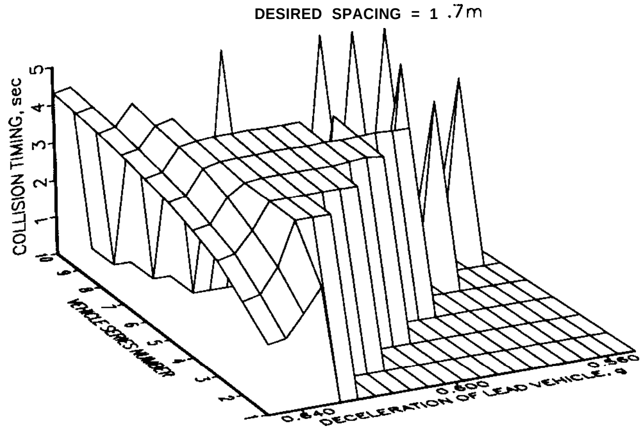


Figure 12: Collision Timing for Platoon without Lead Vehicle Information — 1.7-meter Desired Spacing

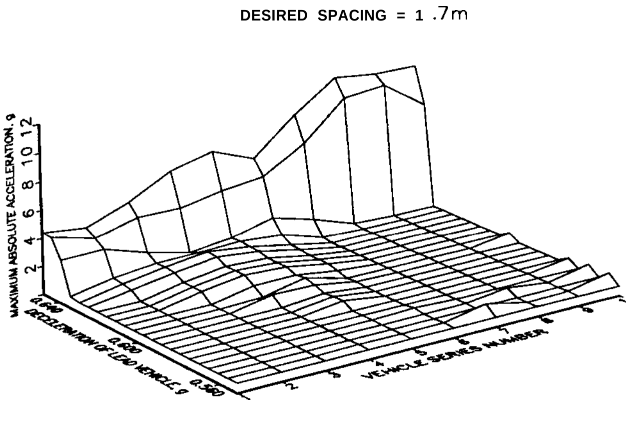


Figure 13: Maximum Absolute Acceleration for Platoon without Lead Vehicle Information — 1.7-meter Desired Spacing

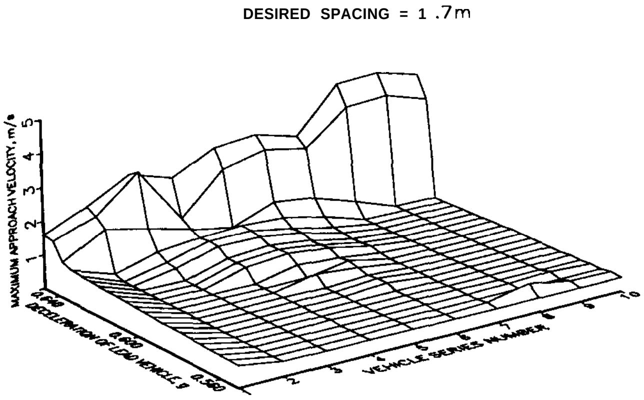


Figure 14: Maximum Approach Velocity for Platoon without Lead Vehicle Information — 1.7-meter Desired Spacing

6 INTRA-PLATOON COLLISION BEHAVIOR OF NON-HOMOGENEOUS PLATOONS

To mimic an emergency situation, a constant lead vehicle deceleration is applied at the start of the simulation. All the vehicles are assumed to have the same engine dynamics (both traction and braking) and physical characteristics, with the exception of the individual vehicle masses. The vehicle's bumper is assumed to be able to resume its function after a collision and all the sensors are presumed to be functional throughout the simulation. A homogeneous platoon, in which all vehicles have a standard mass of 1800 kg, is used as the baseline comparison. Simulations are carried out by varying the vehicle mass distribution (from 900 kg to 2700 kg) and the magnitude of the lead vehicle deceleration (from .60 g to .75 g). The parameter values used in the simulations are as follows.

Standard vehicle mass	1,800 kg
Vehicle height	1.0 m
Bumper stiffness	2.0 MN/m
Vehicle body stiffness	6.0 MN/m
Maximum braking force	11,700 N
Aerodynamical Coefficient	0.43
Desired Spacing	1 m
Initial velocity	60 mph
Road grade	0 degree

It is noted that performance of the braking system will be affected by additional loadings. Nevertheless, to simplify the complexity in the modelling, it is assumed that all the vehicle's braking systems are the same within a platoon, no matter what the vehicle's loading is.

6.1 Multiple Collisions of Uniform Heavier/Lighter Platoons

Three platoons are used in the simulations. The lighter-vehicle platoon (LP) contains 1620 kg vehicles; the heavier-vehicle platoon (HP) contains 1980 kg vehicles; and the standard platoon (SP) contains 1800 kg vehicles. It is assumed that all the vehicles have the same engine and braking capacities. Figures 15 and 16 illustrate the collision timings and maximum absolute accelerations of these three platoons, respectively.

One can see from figure 15 that the pattern of collision timings is similar for all three platoons (collision timings for the LP, SP, and HP are arranged from top to bottom, respectively). The first collision within the platoons occurs between Car 1 and the lead vehicle, and then the collision wave propagates backwards. The main differences in the plots shown in figure 15 relate to the number of vehicles involved in the collsions. It can be seen that the HP experiences a denser multiple collision pattern. At .68 g deceleration of the lead vehicle, the HP generates lo-car collisions, the SP generates 6-car collisions, and the LP only experiences 2-car collisions. At the same deceleration, the rear part of the LP has a higher possibility of avoiding intra-platoon collisions due to the higher traction/mass ratio in the LP (which implies a higher saturation limit).

Figure 16 shows the maximum absolute accelerations corresponding to figure 15. Note the severe impact levels of the HP, which are about double those found for the SP. It can be seen that the LP experiences far less severe collision impact forces than those platoons having heavier vehicles, under the same range of the lead vehicle decelerations. In a multiple intra-platoon collision situation, peak accelerations are felt at Cars 1, 4 and 7, implying that these are the most dangerous vehicles to be in.

6.2 Multiple Collisions of Distributed-Mass Platoons

Having seen what the general effect of a uniformly changing vehicle mass is, we now move to the case of nonuniform mass distributions. In these simulations, two platoon formulations are used; one having an increasing mass distribution and the other with a decreasing mass distribution. The difference between adjacent vehicles is always 90 kg and Car 5 represents the nominal case for both platoons. Figures 17 and 18 show the response of both platoons as well as that for a uniform nominal mass platoon.

Figure 17 displays the collision timings for the increasing-mass platoon (IMP), standard platoon (SP), and decreasing-mass platoon (DMP), labeled a), b) and c), respectively. It can be seen that the involvement sequence of intra-platoon collisions is quite different for the DMP than for the IMP. At .60 g deceleration of the lead vehicle, the IMP's first collision occurs between Car 5 and Car 6, at which point the collision wave propagates in both the forward and backward directions to all the vehicles in the platoon. In contrast, the DMP's first collision occurs between Car 1 and the lead vehicle, followed by a collision wave that propagates backwards to Car 4. Interestingly, the SP does not experience any collisions. Thus the nonuniformity of the mass distribution has clearly led to a degradation of the platoon's operations.

As the deceleration of the lead vehicle increases, the position of first collision in the IMP moves forward within the platoon, and the subsequent collision events maintain the same qualitative behavior. It can also be seen that the propagation speed is larger in the backward direction (the direction of increasing mass). In the DMP, the collision wave propagates further backwards with increasing deceleration levels, and at a deceleration of 0.75 g, 7 vehicles are involved in the multiple collisions incident.

The collision severity of this simulation is shown in Figure 18. The average of the maximum absolute accelerations of the IMP is about three times those found in the SP and DMP. The magnitude of the impact each vehicle experiences does not vary greatly within each platoon. However, the consequences for the individual vehicles will be quite different due to the difference in their masses. According to Evans and Frick (1993), the driver in the lighter car will have a higher fatality risk in two-vehicle crashes. Thus the possibility of fatality increases as the vehicle series number rises for both the IMP and DMP in the case of multiple collisions, while at the same deceleration levels, the vehicles in the IMP have a higher injury risk than those in the DMP.

6.3 Multiple Collisions of Platoons with an Odd Mass at Car 5

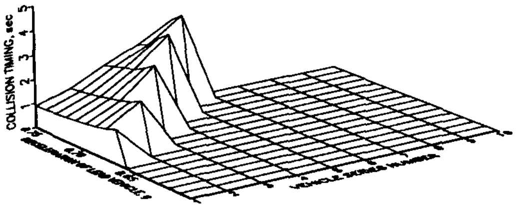
To further examine the effect of mass variation, platoons with an odd mass at Car 5 have been constructed: Car 5 has a mass of 2700 kg while the others remain at 1800 kg for one platoon (H5P), while for the other (L5P) the fifth car has a mass of 900 kg. The response of the standard platoon (SP) is listed as a baseline comparison for all figures. This is a very large mass difference and is used to accentuate the effect of mass variations on the overall platoon performance.

Figure 19 shows the collision timings for the L5P, SP, and H5P, labeled a), b), and c), respectively. In the SP, it is clear that Car 1 initiates the collision wave, which then propagates backwards. This regular propagation is altered for the H5P and L5P. In the H5P, there are actually two initiation points in the platoon: one is Car 1 and the other is Car 5. The collision wave originating at Car 5 propagates both forwards and backwards. The first collision for a deceleration of .60 g occurs between Car 5 and Car 4 whereas for .75 g decelerations the initial collision affects Car 1. In both cases, Car 5 is a collision wave initiator. In the L5P, Car 1 and Car 6 (the car directly following the light car in the platoon), are the two initiation points from which the collision waves propagate. Unlike the case of the H5P, for the L5P, the collision wave that originates at Car 1 propagates backwards and is retarded by Car 5. However, due to the response of Car 5, Car 6 hits Car 5 and generates another backward collision wave. Although Car 5 cannot prevent the following vehicles from experiencing a collision, it still reduces the number of vehicles involved in a multiple collisions situation, which can be seen from the fact that an 8-car collision occurs for decelerations of .75 g while the SP and H5P have IO-car collisions for the same deceleration.

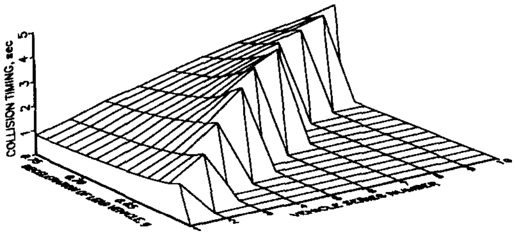
Figure 20 shows the maximum absolute accelerations for this simulation. It can be seen that a heavier car in a platoon does jeopardize the entire platoon, an observation that is reflected in the higher magnitudes of maximum absolute acceleration for the H5P. The most dangerous positions for the H5P are Car 4 and Car 6 (the preceding and the following vehicles of a massive vehicle), which are seen to have higher peak acceleration values in figure 20 as well as having an adverse mass ratios with respect to Car 5 (Evans and Frick 1993). For the L5P, it is clear that Car 5, the lighter car, is the most dangerous one to be in during a multiple collision situation, not only for the high impact forces it experiences, but also for its relative low mass ratio to Car 4 and Car 6. Lastly, one can see that the vehicles preceding the light one (Car 1 - Car 4) for the L5P are not affected by vehicle 5.

In summary, the existence of individual higher mass vehicles in a platoon tends to degrade the platoon's operation. Also, a higher number of vehicular collisions implies a greater degree of risk with respect to personal and property damage. A platoon design strategy is suggested from the results, namely that one should arrange vehicles in order of decreasing mass in order to maximize safety. Of course, one has to know the masses of the vehicles in order to do this. If such information is available, then one could also directly modify the individual vehicle's control laws to reflect these mass differences. An investigation of both possibilities will be addressed in future work. An alternative strategy which merits investigation is to to increase the desired spacing of the platoon in order to provide more response space and time for the heavier vehicles.

(a) LP : MASS(i)=1800*0.9 kg



(b) SP : MASS(i)=1800 kg



(c) HP : MASS(i)=1800*1.1kg

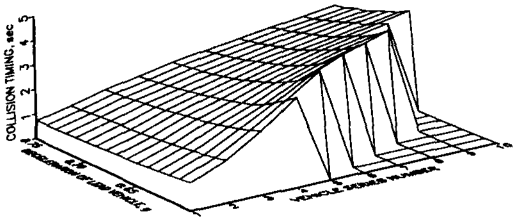
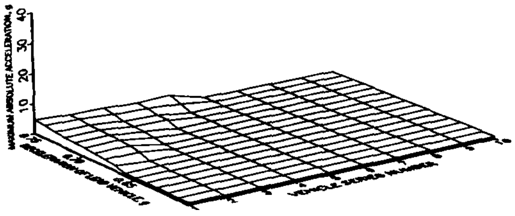
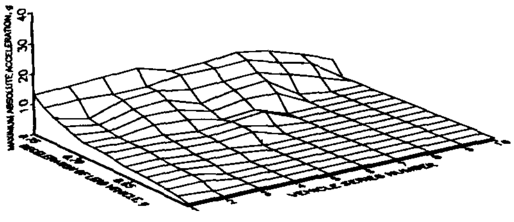


Figure 15: Collision Timings of Platoons with Uniform Heavier/Lighter Vehicles

(a) LP : MASS(i)=1800*0.9 kg



(b) SP : MASS(i)= 1800 kg



(c) HP : MASS(i)=1800*1.1 kg

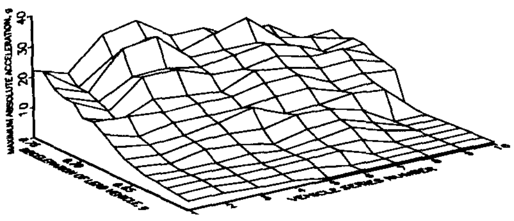
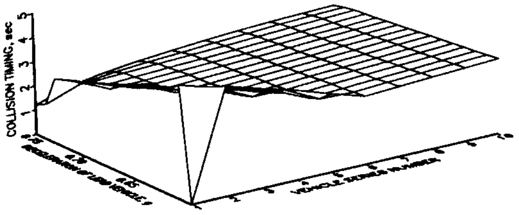
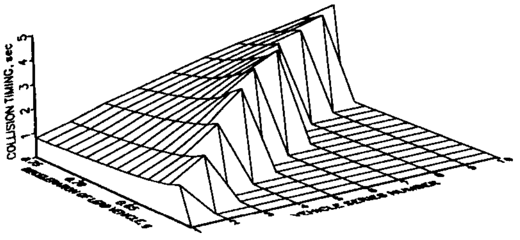


Figure 16: Maximum Absolute Accelerations of Platoons with Uniform Heavier/Lighter Vehicles

(a) IMP : MASS(i)=1800(0.05i+0.75) kg



(b) SP : MASS(i)=1800 kg



(c) DMP : MASS(i)=1800(−0.05i+1.25) kg

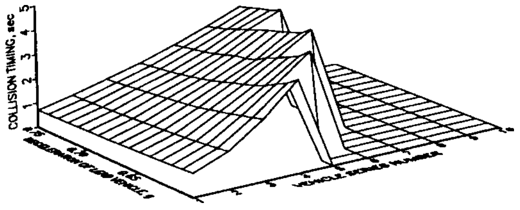
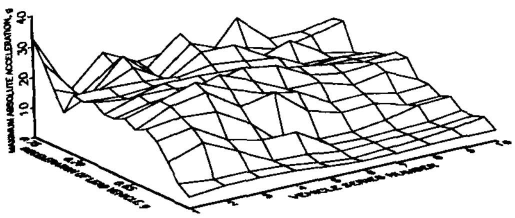
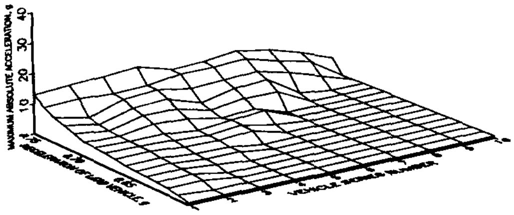


Figure 17: Collision Timings of Platoons with Monotonous Increasing/Decreasing Mass Vehicles

(a) IMP : MASS(i)=1800(0.05i+0.75) kg



(b) SP : MASS(i)= 1800 kg



(c) DMP : MASS(i)=1800(−0.05i+1.25) kg

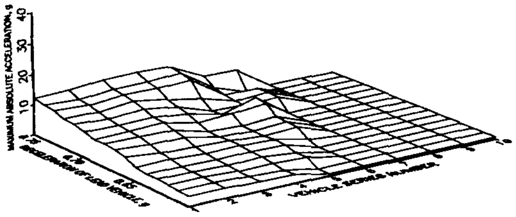
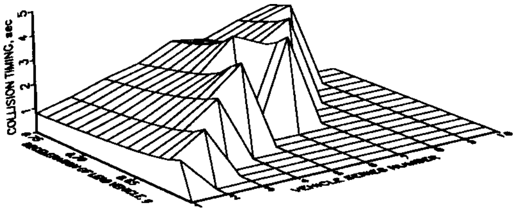
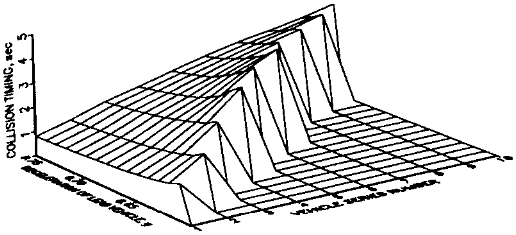


Figure 18: Maximum Absolute Accelerations of Platoons with Monotonous Increasing/Decreasing Mass Vehicles

(a) L5P : MASS(5)=1800*0.5 kg



(b) SP : MASS(i)=1800 kg



(c) H5P : MASS(5)=1800*1.5 kg

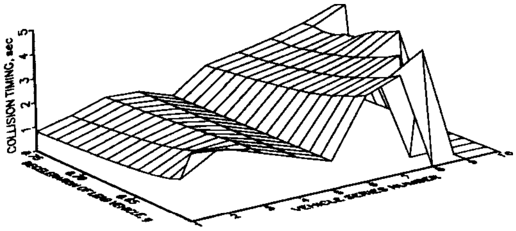
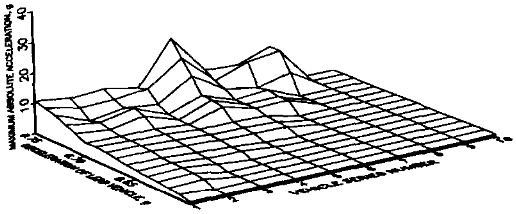
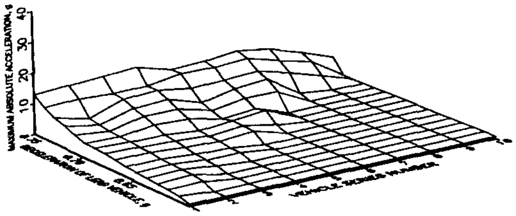


Figure 19: Collision Timings of Platoons with Odd Mass at Vehicle 5

(a) L5P : MASS(5)=1800*0.5 kg



(b) SP : MASS(l)- 1 BOO kg



(c) H5P : MASS(5)=1800*1.5 kg

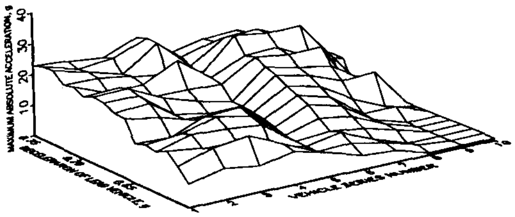


Figure 20: Maximum Absolute Accelerations of Platoons with Odd Mass at Vehicle 5

7 A NEW CONTROL APPROACH FOR PLATOON OPERATIONS DURING VEHICLE EXIT/ENTRY

In pursuit of an automated highway system, many researchers have centered their attention on the vehicle tracking problem, focusing either on longitudinal or lateral control. A basic assumption of these investigations has been that velocities vary slowly, i.e. the system is in a "normal" operating condition, traveling along the highway. Only the states of the lead, the preceding, and the vehicle itself were used to evaluate the control efforts. This means that controllers are never "aware" of what is happening behind them. Thus, a given vehicle would take no evasive action, even if a vehicle to its rear was approaching quickly and a collision was imminent.

The purpose of this study is to explore the question of how the platoon might react when something other than just translation down the highway is taking place. Attention will be focused on two particular operations: vehicle exit from the platoon and vehicle entry into the platoon. Both Sheikholeslam and Desoer's controller (Sheikholeslam and Desoer 1990) and the Back controller, a controller that evaluates not only the states in front, but also those behind the controlled vehicle, have been used. To evaluate the performance of the controllers, the rider comfort index, the MPR value (section 3.1), has been utilized. It is shown that the Back controller has advantages in these two situations.

7.1 Controller Development

For computational reasons, the individual vehicle internal dynamics are represented by a set of curve-fit equations, in which the engine force is a function of throttle input and vehicle speed (section 2.1). The longitudinal dynamical equations of a vehicle are expressed through Newton's second law and include a rolling resistance force, an aerodynamic force, a gravitational force, and a force due to vehicular collisions. The rolling resistance force is a function of velocity and road roughness and the aerodynamic force depends upon the vehicle profile and spacing with respect to the preceding vehicle (thus the drafting effect of closely spaced vehicles is included in the model).

The key idea behind Back Control is to mimic the way in which human drivers react to impending collisions. A normal response to an impending collision is to look both ahead and behind and blend braking and throttle to keep one's vehicle midway between the following and preceding cars. Given sufficient maneuvering room, this strategy will keep the controlled car from striking either the trailing vehicle or the preceding one. A controller has been developed based on this behavior that weights the state of the following vehicle as well as the preceding one in emergency operations and ignores the states of the following vehicle when in normal (station keeping) operations. One potential disadvantage to this approach is that it fully couples the system, producing a dynamical system that resembles a series of mass/spring elements. Although this may simplify analytical analyses, it allows disturbances to propagate both forward and backward within the platoon. The primary advantage is that by positioning the vehicle midway between two others, one can presumably best avoid vehicle contacts.

To apply this concept, scheduled control gain surfaces have been constructed. Figure 21 illustrates the control gain surface as a function of the spacing errors. When a vehicle is exactly between two other vehicles, the Back controller is inoperative. During nominal operations, the control gain only depends upon the forward spacing error. The same approach is also used to define the velocity and acceleration control gain surfaces. It should be noted that no attempt was made at this point for optimality, beyond some basic gain modifications based on good judgement. Since developing an optimal formulation is quite time intensive, it was decided to first look at a reasonable design and determine if the basic approach has merit.

7.2 Back-Controlled Platoon Formulation

Two platoon models were simulated. Each platoon consisted of ten vehicles, excluding the lead car (whose dynamics were presumed to be known). The power systems were assumed to exhibit response delay and saturation for both throttle and braking systems (Tongue et al. 1991). Aerodynamical forces and rolling resistance were also included. No communication delay (delay in data transmission from one vehicle to another) was assumed. Since controllers are integral to the platoon concept, a choice had to be made as to the specific controller to be utilized. It was decided to adopt Sheikholeslam and Desoer's controller (S&D controller) to serve as a basis for the simulations and provide a baseline comparison for the Back controller as it has been shown previously to exhibit very good regulation characteristics.

Finally, it was assumed for both controllers that lead information was available, i.e. the controller for each vehicle had the state of the lead vehicle available to it for control purposes. In previous work (Sheikholeslama and Desoer 1991), the inclusion of lead information has led to increased platoon performance, as reflected in faster settling times and a reduced magnitude of disturbance propagation within the platoon.

To better understand how Back control differs from previous controllers, some background on the S&D controller approach is now given. Sheikholeslam and Desoer first eliminated system nonlinearities by means of exact linearization. The information used in the feedback path were the differences in position, velocity, and acceleration between the controlled vehicle and the preceding one, as well as the velocity and acceleration of the lead vehicle. By balancing these, the authors tried to obtain a well damped response to perturbations from the preceding vehicle as well as have some preview effect (due to the lead information). Although the referenced work did not derive an optimal controller, the controller gains were adjusted to yield an acceptable performance. The Back control approach contains additional feedback terms — the states of the following vehicle. Three control gain surfaces, one for the position error, one for the velocity error, and one for the acceleration error, are used to carry out the Back Control concept.

Similar to the longitudinal control laws proposed by Sheikholeslam and Desoer, the Back control laws are given by

$$\begin{aligned} c_1 &= \Gamma_{1p}(\Delta_1^f, \Delta_1^r, t) + \Gamma_{1v}(\dot{\Delta}_1^f, \dot{\Delta}_1^r, t) + \Gamma_{1a}(\ddot{\Delta}_1^f, \ddot{\Delta}_1^r, t) + k_{v1}(v_l(t) - v_0) + k_{al}a_l(t) && (15) \\ c_i &= \Gamma_p(\Delta_i^f, \Delta_i^r, t) + \Gamma_v(\dot{\Delta}_i^f, \dot{\Delta}_i^r, t) + \Gamma_a(\ddot{\Delta}_i^f, \ddot{\Delta}_i^r, t) + k_v(v_l(t) - v_i(t)) \\ &+ k_a(a_l(t) - a_i(t)) && (16) \end{aligned}$$

where

$$\begin{aligned} \Delta_i^f &= x_{i-1}(t) - x_i(t) - L && (17) \\ \Delta_i^r &= x_i(t) - x_{i+1}(t) - L && (18) \\ \Gamma_{1p}(\Delta_1^f, \mathrm{A};, t) &= c_{p1}(1 - \frac{2}{2 + \varphi_1(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \varphi_1(t)}))) && (19) \\ \Gamma_{1v}(\dot{\Delta}_1^f, \dot{\Delta}_1^r, t) &= c_{v1}(1 - \frac{2}{2 + \dot{\varphi}_1(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \dot{\varphi}_1(t)}))) && (20) \\ \Gamma_{1a}(\ddot{\Delta}_1^f, \ddot{\Delta}_1^r, t) &= c_{a1}(1 - \frac{2}{2 + \ddot{\varphi}_1(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \ddot{\varphi}_1(t)}))) && (21) \\ \Gamma_p(\Delta_i^f, \Delta_i^r, t) &= c_p(1 - \frac{2}{2 + \varphi_i(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \varphi_i(t)}))) && (22) \\ \Gamma_v(\dot{\Delta}_i^f, \dot{\Delta}_i^r, t) &= c_v(1 - \frac{2}{2 + \dot{\varphi}_i(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \dot{\varphi}_i(t)}))) && (23) \\ \Gamma_a(\ddot{\Delta}_i^f, \ddot{\Delta}_i^r, t) &= c_a(1 - \frac{2}{2 + \ddot{\varphi}_i(t)})(1 + 2(1 - sgn(1 - \frac{2}{2 + \ddot{\varphi}_i(t)}))) && (24) \end{aligned}$$

and

$$\begin{aligned}
\varphi_i(t) &= \Delta_i^f - .5\Delta_i^r(1 - sgn(\Delta_i^r)) && (25)\\
\dot{\varphi}_i(t) &= \dot{\Delta}_i^f - .5\dot{\Delta}_i^r(1 - sgn(\dot{\Delta}_i^r)) && (26)\\
\ddot{\varphi}_i(t) &= \ddot{\Delta}_i^f - .5\ddot{\Delta}_i^r(1 - sgn(\ddot{\Delta}_i^r)). && (27)
\end{aligned}$$

In the above, the subscript i refers to Car $i(l$ for the lead car), c_i is the control law for Car i, L is the desired headway spacing, $x_i(t)$ is the position of Car i, and A{(t) and $\Delta_i^r(t)$ correspond to the front and rear state errors of Car i, respectively.

The gains for the Back controller are as follows.

c_{p1}	c_{v1}	c_{a1}	k_{v1}	k_{a1}	c_p	c_v	c_a	k_v	k_a
120	74	15	-0.05	-3.03	120	49	5	25	10

Table 6.1 Back Control Gains for Platoon with Lead Vehicle Information

7.3 Vehicle Exit from a Platoon

In this simulation, it is assumed that a 4-meter spacing is generated at $t = 0$ sec between Cars 5 and 6 due to the exit of a vehicle. Figures 22 and 23 show the acceleration responses of the vehicles for the S&D controller and the Back controller, respectively. Figure 24 shows the overall ride quality and figure 25 illustrates the maximum absolute acceleration magnitudes.

As can be seen in figure 22, only Cars 6 through 10 are affected by the disturbance in the S&D-controlled platoon, in which the state of the following vehicle are not taken into consideration. Engine saturation is also observed in figure 22 for the first 3 seconds. Figure 23 shows that all the vehicles in the Back-controlled platoon are affected by the disturbance generated within the platoon. No engine saturation occurred for this platoon. In addition, the overall acceleration levels are reduced by the Back controller. It acts to spread disturbance out among all platoon participants and, in so doing, reduces the peak disturbance magnitudes.

Figure 24 shows the MPR values for both platoons. (As stated in section 3.1, Mean Personal Rating is a comfort scale – the higher the MPR is, the less comfort the passengers experience.) It can be seen that the overall rider comfort for Cars 6 through 10 in the Back-controlled platoon is better than that of the S&D controller (reflected in smaller MPR values). Although the MPR's for Cars 1 through 5 are higher in the Back-controlled platoon, the difference is quite small and the reductions for the other vehicles are quite appreciable. These characteristics are mirrored in figure 25, where the maximum absolute acceleration indicates the maximum instantaneous acceleration experienced by the vehicle (this term is correlated to the force exerted on the vehicle body and on occupants in the vehicle). It is noted from figures 22 and 25 that the maximum absolute accelerations of Car 6 to Car 10 in the S&D-controlled platoon are caused by decelerations, but those in the Back-controlled platoon are caused by accelerations of the vehicles. What roughly happens is that the trailing cars in the S&D controller, sensing the large gap caused by the vehicle exit, accelerate quickly to close the gap and then jam on their brakes to hold their spacing. This large braking is absent in the Back controller as all vehicles jockey back and forth, closing the gap while at the same time maintaining the maximum safety margin between vehicles.

In summary, it is seen that the Back Control algorithm can distribute the disturbance to all vehicles within the platoon and thus increases the ride quality of the platoon by reducing the severity of the vehicle's motion.

7.4 Entry of a Vehicle

For a normal vehicle entry operations, it is currently thought that the entering vehicle will join the platoon from the rear and accelerate to the desired state. Therefore, the response of both platoons will be the same because the joining vehicle always has a headway spacing greater than 1 meter (for which the Back controller won't be active).

However, it is possible that the vehicle link-up might not always work as smoothly as desired. Consider the case for which the joining vehicle accelerates too strongly and has a headway spacing less than 1 meter. Car 10 (the joining vehicle) passes the desired location at $t = 2$ sec, and has the acceleration profile shown in figure 26. The dynamics of Car 1 through Car 9 won't be affected in the S&D-controlled platoon (figure 26). However, the dynamics of the vehicles in the Back-controlled platoon do change, corresponding to the hazard posed by the approaching Car 10 (Figure 27).

Figure 28 shows the minimum vehicle to vehicle spacings for all platoon members. It can be seen that the closest spacing for the S&D-controlled platoon is 0.1 meter and is 0.5437 meter for the Back-controlled platoon. Thus the S&D-controlled platoon is on the verge of a collision, while the Back controlled vehicles are all maintained a safe separation distance. Although the minimum spacings for Car 1 through Car 9 are reduced, the overall possibility of a collision is seen to decrease in the Back-controlled platoon. The trade-off for avoiding a collision in the Back-controlled platoon is the rider comfort, which is shown in figures 29 and 30. Thus the comfort level of all members of the Back-controlled platoon is reduced in order to preclude a collision within the platoon.

Figures 31 and 32 show the results for a more severe case, in which Car 10 approaches the platoon quickly enough that a collision actually occurs between Car 9 and Car 10 in the

S&D controlled platoon (Figure 31). As expected, figure 32 shows that the Back controller avoids an internal collision for this abnormal approach scenario.

(Δ^f, Δ^r) = (Front spacing ~~error~~, Rear spacing ~~error~~)

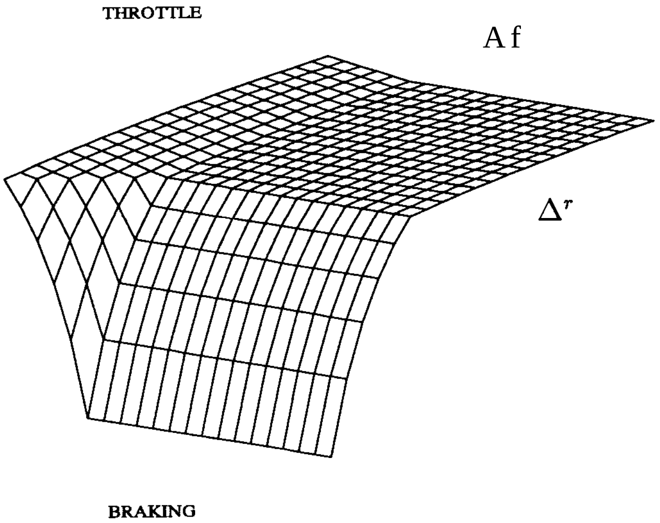


Figure 21: Control Gain Surface for Spacing Error

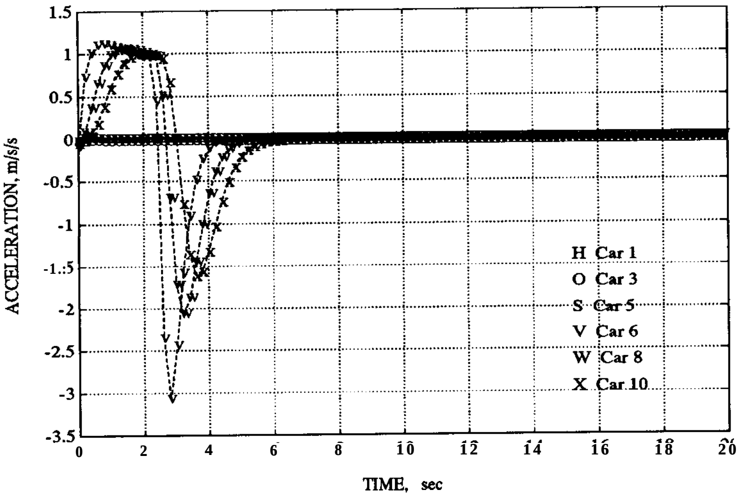


Figure 22: Vehicle Exit Simulation on the S&D-controlled Platoon — Acceleration vs. Time

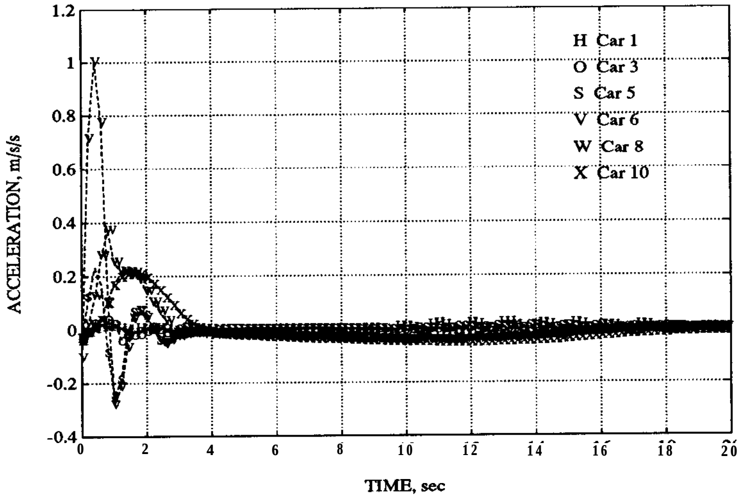


Figure 23: Vehicle Exit Simulation on the Back-controlled Platoon — Acceleration vs. Time

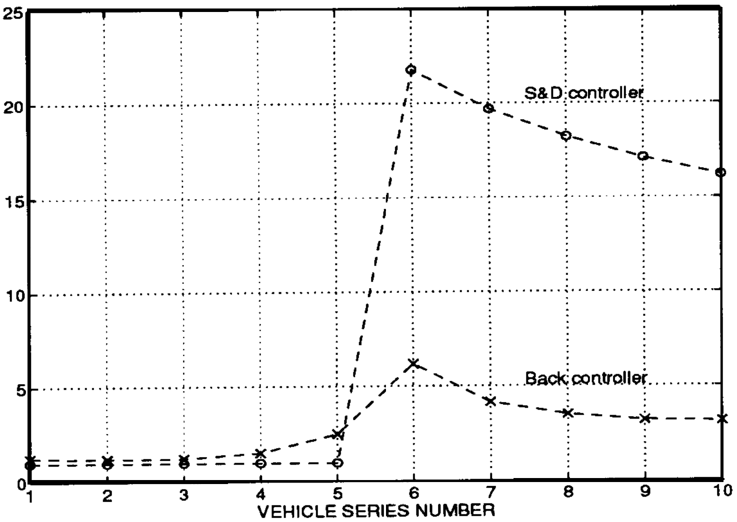


Figure 24: Vehicle Exit Simulation MPR vs. Vehicle Series Number

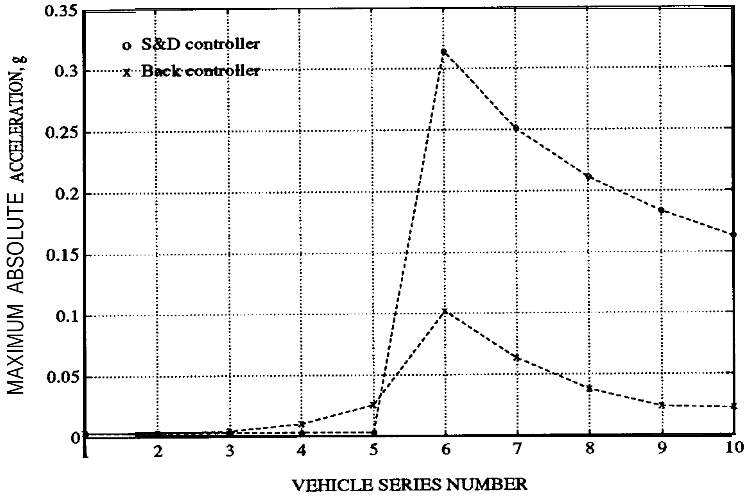


Figure 25: Vehicle Exit Simulation — Maximum Absolute Acceleration vs Vehicle Series Number

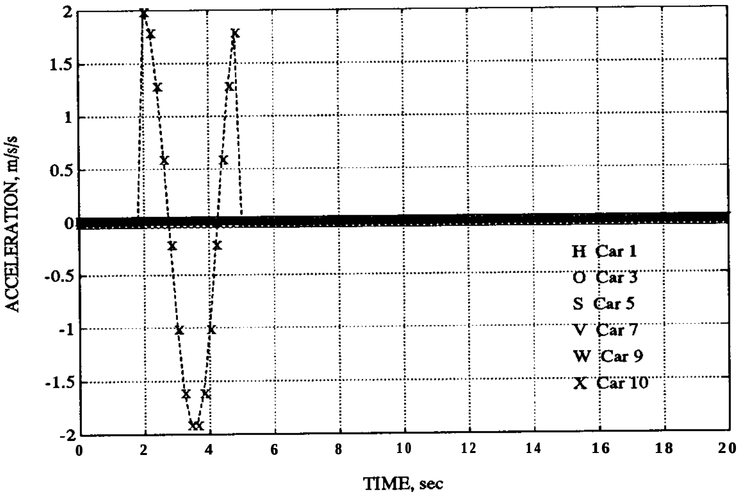


Figure 26: Vehicle Entry Simulation on the S&D-controlled Platoon — Acceleration vs. Time

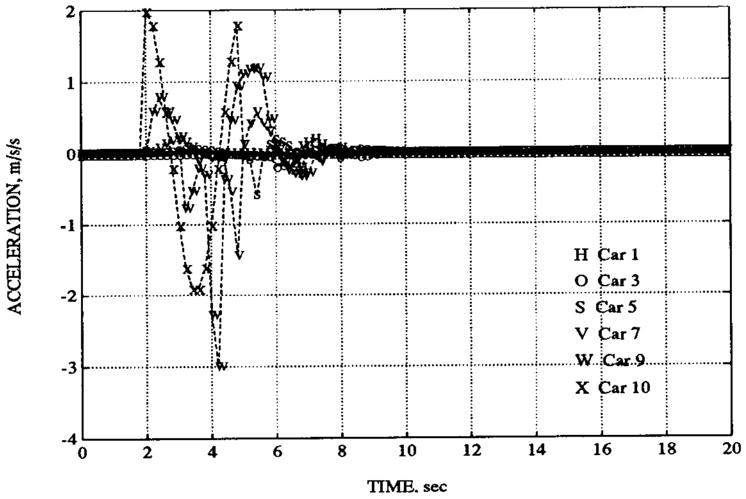


Figure 27: Vehicle Entry Simulation on the Back-controlled Platoon — Acceleration vs. Time

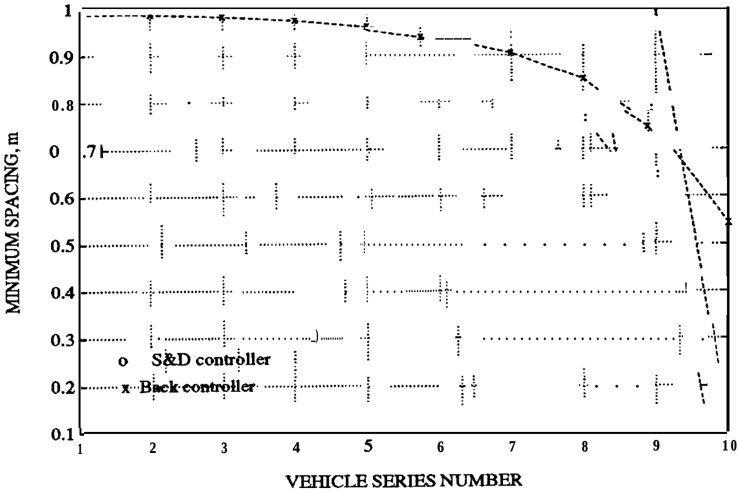


Figure 28: Vehicle Entry Simulation — Minimum Spacing vs. Vehicle Series Number

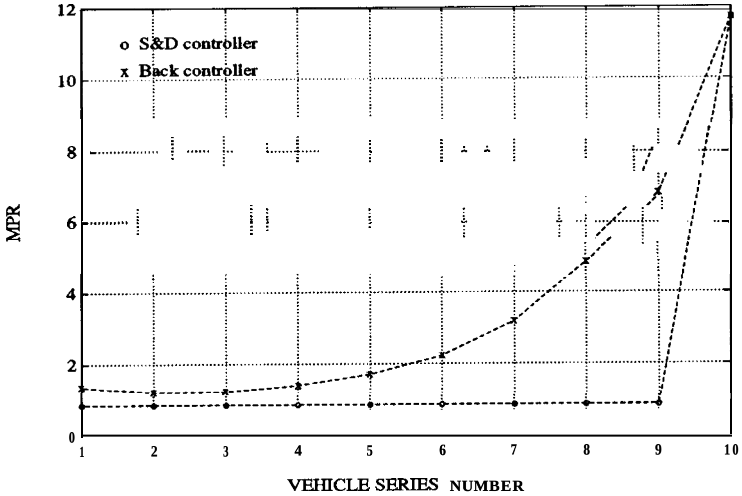


Figure 29: Vehicle Entry Simulation — MPR vs. Vehicle Series Number

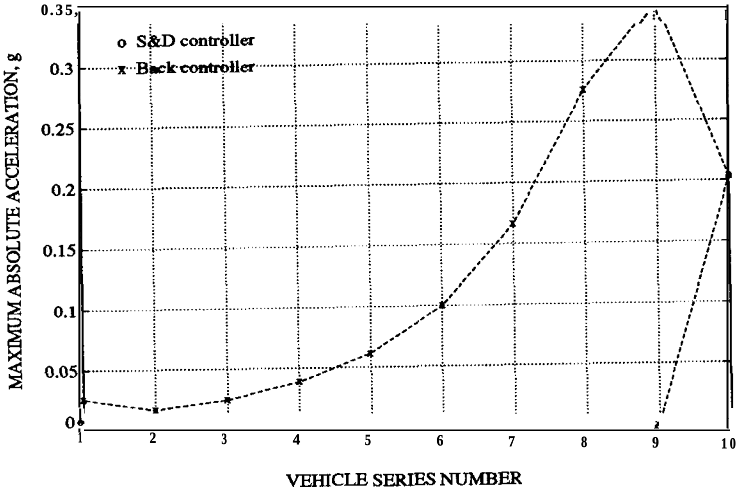


Figure 30: Vehicle Entry Simulation — Maximum Absolute Acceleration vs. Vehicle Series Number

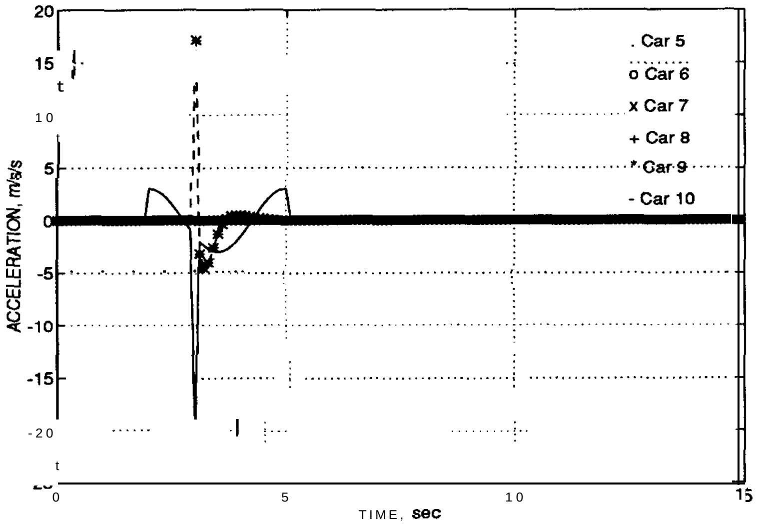


Figure 31: Vehicle Entry Simulation on the S&D-controlled Platoon — Acceleration vs. Time

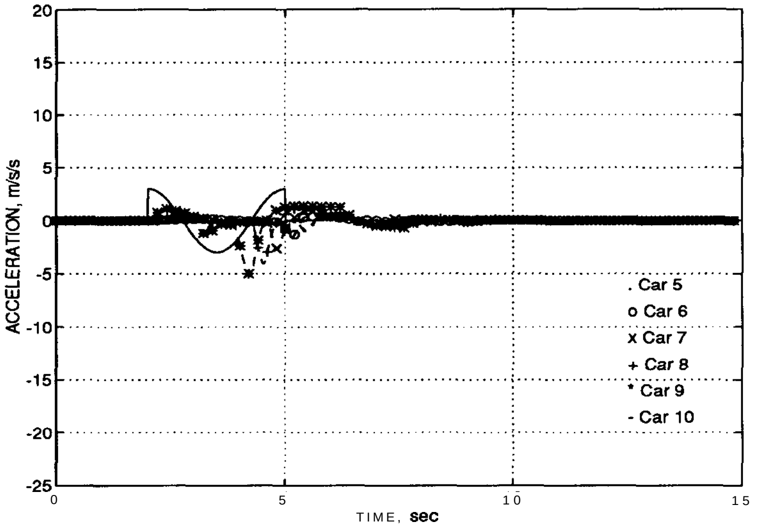


Figure 32: Vehicle Entry Simulation on the Back-controlled Platoon — Acceleration vs. Time

8 CONCLUSIONS

The inclusion of lead vehicle information has been widely perceived as an effective way to increase a platoon's tracking ability and a means to reduce the chance of a collision. Section 4 has shown that lead information is also beneficial **during** collision sequences. One advantage of lead information in understanding collision behavior is the regularity of the collision events when lead information is present. Also, the lead data causes a marked increase in the maximal lead vehicle decelerations that can be withstood without the occurrence of collisions. The extra computational costs associated with lead information inclusion would seem to be worthwhile in view of the increased performance they allow. If lead information is not utilized, due to processing limitations or a system's failure, then the platoon's collision behavior becomes less regular and the maximum approach velocities and accelerations increase. This degradation in performance implies that the controllers might be well advised to enter an "emergency" situation when sensor loss is detected. An immediate increase in intra-vehicular spacing and rapid removal of the underperforming vehicle would seem to be reasonable actions, given the degree to which the entire platoon's performance can be degraded when vehicles lose critical spacing/preview data.

Multiple intra-platoon collisions of non-homogeneous platoons have been characterized by the collision timings and maximum absolute accelerations, which correspond to the pattern of collision wave propagation and impact severity, respectively. Based on the simulation results in section 5, it is seen that multiple collisions that involve larger numbers of vehicles always imply more severe impact crashes. It has also been shown that the traction/mass ratio plays an important role in the propagation of collision waves and that the mass of the vehicle has a strong influence on vehicle safety. The fact that parametric variations of mass can influence the platoon's behavior to a significant degree suggests that a careful analysis of how general parametric variations affect platoon safety and performance. Since vehicles will certainly vary within platoons, it is worth thinking about what quantities could be defined that would be in some sense invariant. For instance, given the maximum acceleration/deceleration capabilities of a vehicle, we could define a buffer zone ahead and behind the vehicle within which the vehicle can brake and accelerate. The vehicles could then be put together in platoons, not with a fixed one meter spacing, but with intra-vehicular spacings that are defined by the individual vehicle's buffer zones. This implies a non-uniform spacing strategy. It may well be that this strategy would lead to the best operation in terms of safety; a situation in which each vehicle has the amount of spacing it needs, given it's own individual capabilities in terms of braking and acceleration. A further result of this kind of study would be recommendations of how platoons should be ordered. As seen in this work, the position of the heaviest/lightest vehicle has direct implications as to the severity of any collisions. It may well be that, for safety reasons, simply letting vehicles join up as they enter the platoon stream is not optimal, and that some placement strategy that explicitly considers their performance characteristics would be preferable.

It has been shown in section 6 that the Back Control concept is relevant to platoon operations of vehicle exit and entry. In the current simulations, the Back controller has shown the capability of providing a better ride quality and reduced the possibility of an intra-platoon collision. The fact that the Back Controller allows the entire platoon to react to disturbances means that the peak magnitude of the disruption is reduced by “smearing” the activity over the entire platoon rather than localizing it at a small number of vehicles. This can have a significant impact on safety. For instance, if a vehicle approaches the platoon too quickly (due to a faulty controller, frozen accelerator, etc.), the traditionally controlled platoon will ignore this approach, with the result that a strong collision will occur between this vehicle and the back end of the platoon. If a Back Controller had been active, the platoon would accelerate away from the approaching vehicle. This would reduce the severity of the collision for the vehicle at the platoon's end and might also induce small collisions within the platoon. However, the existance of several small magnitude collisions might well be considered to be preferable to one or two collisions of high magnitude, collisions which would lead to a large degree of damage to both the vehicles and occupants. It is concluded that the Back control approach merits further investigation as it may provide an enhanced safety level for platoon operations. It should also be noted that this controller does not require additional sensors; the rearward vehicle states could be transmitted via the same network that carries the lead vehicle information. However, additional sensors would certainly have attractive aspects, as they would add some redundency to the sensor system. In the event of a forward facing sensor's failure, the rear sensors could take over. This, and controller optimalization, would be fruitful venues for further study.

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