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INSTITUTE OF TRANSPORTATION STUDIES
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Brake Dynamics Effect on IVHS Lane Capacity

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**California PATH Working Paper
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Abstract

Highway automation is a topic of active research due to its promise of solving the congestion problem on the nation's highways. It is thus necessary to evaluate the benefits of such a system. One of the most important projected improvements is the increase in capacity and safety. This paper attempts to investigate the effects of brake system dynamics and inter-vehicle communication delays (microscopic characteristics) on the capacity of the system (macroscopic characteristics). Simulations were conducted to investigate the relationship between the microscopic and macroscopic characteristics. Recommendations were made regarding the maximum desired delays, intra-platoon and inter-platoon distances and platoon size in order to achieve the highest possible capacity while maintaining a high degree of safety.

Keywords: Automated Highway Systems Capacity, Brakes, ~~Car~~ Following, Intelligent Vehicle Highway Systems, Highway Capacity, Human Factors, Safety.

Executive Summary

Highway automation is a topic of active research due to its promise of solving the congestion problem on the nation's highways. It is thus necessary to evaluate the benefits of such a system. One of the most important projected improvements is the increase in capacity and safety. This paper attempts to investigate the effects of brake system dynamics and inter-vehicle communication delays (microscopic characteristics) on the capacity of the system (macroscopic characteristics).

A longitudinal vehicle model is used to simulate the vehicle behavior under braking. The Brake dynamics are simplified and assumed to be made up of a pure time delay followed by a first order response. In order to emphasize the benefits of the IVHS concept, a comparison is made between a human driver and an automatic controller. In the human driver case the pure time delay is caused by the perception of some external stimuli, reaction time to such stimuli, the foot transfer and the overcoming of any deadzones in the brake system. This pure time delay can range from 1.2 to 1.7 seconds. In the case of an intelligent vehicle, the pure time delay is associated with the delay in sensors, processing time, actuator lags and deadzones in the brake system. These delays can vary from 50 to 200 milliseconds.

The most critical parameter that these delays affect is the inter-vehicle spacing. As the delay increases, so does the spacing in order to ensure safety. As such, with human drivers, the maximum achievable capacity is about 2200 passenger-cars per hour per lane (pcphpl). In an IVHS platoon, as simulation shows, the achievable capacity approaches 6000 pcphpl, almost a three time increase over current capacity.

The investigation also shows that a small decrease in the delay can have an important effect on capacity. Recommendations are made regarding the ideal IVHS platoon size, inter-vehicle spacing and the desired maximum delay in order to obtain the highest capacity without compromising safety.

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1. Introduction

Over the last two decades the urban and suburban traffic in the United States has experienced a continued growth while there has been a slowdown in the construction of new highways and the expansion of the existing ones. The result of this situation is increased highway congestion and an associated increase in operating cost for shipping companies and increase in stress and fatigue for all drivers.

An obvious idea to reduce congestion would be to expand the existing highway system. However, in most urban areas this is not feasible due to lack of suitable land, increase in pollution and noise. As a result, the Federal Highway Administration (FHWA) and various state agencies and private companies have embarked on a research effort to better utilize the existing highway miles. The research area known as Intelligent Vehicle and Highway Systems (IVHS) proposes to use electronics, control and communication technologies to increase the efficiency of current highways.

A major component of the local IVHS agency, Partners for Advanced Transit and Highway (PATH), is to develop an Automated Highway System (AHS). In the present concept, an AHS would be able to increase the capacity of conventional highways by allowing vehicles to travel with very short spacings using automated control techniques.

One of the issues in AHS research is estimating the capacity increase in order to determine whether the IVHS concept is a cost-effective investment. Such an estimate must be based on theoretical vehicle models since the capacity increase must be estimated before an AHS is implemented and actual measurements are available. It is also important to know how the performance of each individual vehicle affects the capacity of the IVHS lane.

This study will concentrate on the effect of the brake performance on the capacity of the IVHS lane. The model is designed to take in account engine dynamics, engine brake, aerodynamic drag, rolling resistance and brake dynamics. Also taken into account is the effect of Anti-lock Brake System (ABS) and the road-tire interaction. To illustrate the fundamental principles, the model is used to analyze an emergency braking maneuver since such a condition will reveal the basic limitations of the system.

2. Longitudinal Vehicle Model

The powertrain model was adapted from Cho and Hedrick (1989) and McMahon, Hedrick and Shladover (1990). Since the emphasis of this study is brake control, a simplified model of the powertrain is used. The model is complete enough though to capture the dynamics of the vehicle.

A three state model was developed by Hedrick, McMahon and Swaroop (1993). For this model the following assumptions are made:

1. time delays associated with power generation in the engine are negligible
2. the torque converter is locked
3. no torsion of the drive axle
4. no slip at the wheels

Figure 2.1 shows a free body diagram of this simplified model.

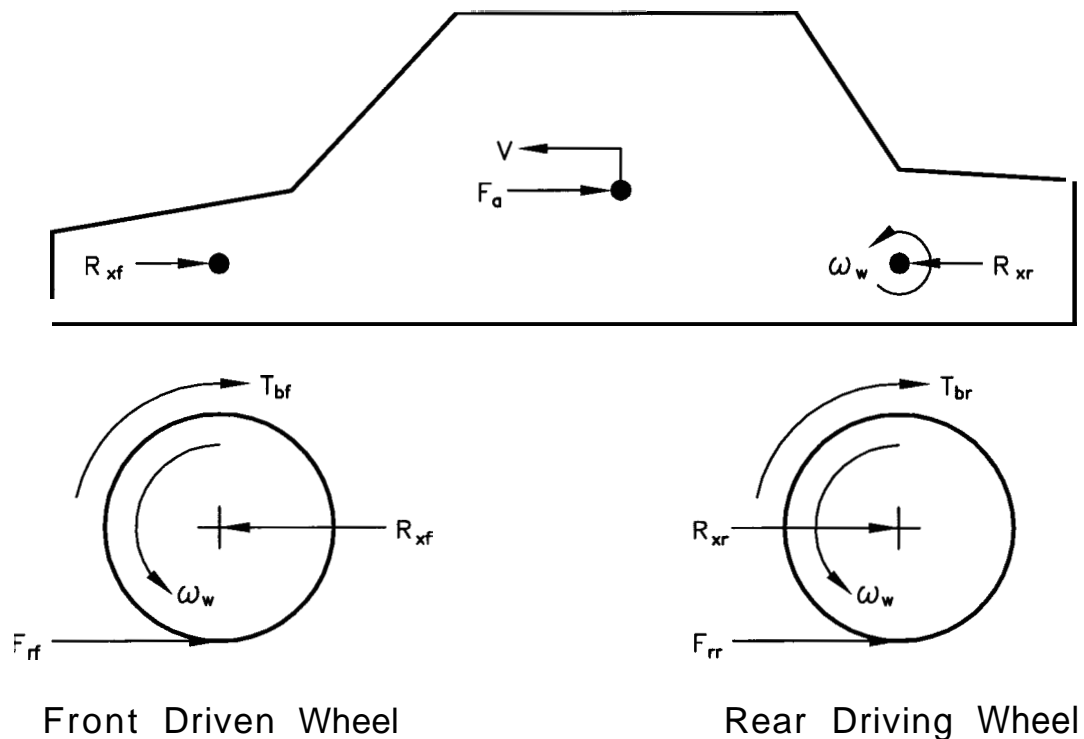


Figure 2.1. Vehicle Free Body Diagram

A simplified two state engine model was used. The engine state equations are:

$$\dot{m}_a = 0.6 \cdot TC(\alpha) - 0.0952 \cdot \omega_e m_a$$

$$\dot{\omega}_e = \frac{1}{J_e} (T_i - T_f - T_d - T_r - T_b)$$

where

m_a = mass of air in the intake manifold (kg)

ω_e = engine speed (rad / s)

$J_e = 36.42$ effective vehicle inertia (kg · m²)

$TC(\alpha)$ = throttle characteristic (function of throttle angle **a**)

$T_i = 47469.0 m_a$: engine indicated torque (Nm)

$T_f = 0.1056 \omega_e + 15.1$: engine friction torque (Nm)

$T_d = 0.0026 \omega_e^2$: aerodynamic drag torque (Nm)

$T_r = 215$: rolling resistance torque (Nm)

T_b = brake torque (Nm)

With the automatic transmission locked in overdrive, there is a linear relationship between engine speed (rad/s) and vehicle speed (Km/h):

$$v = 5.55 \omega_e$$

Due to this relationship it can be assumed that a change in the vehicle speed will be directly reflected in a change in engine speed. Therefore, a change in the throttle angle **a** will change the engine speed which in turn will change the vehicle speed, while a change in the brake torque T_b will change the vehicle speed which in turn will affect the engine speed.

Although the brake dynamics are complex, for this analysis it will be assumed that the brake torque dynamics is a pure time delay followed by a first order dynamic time response. A typical automatic brake response is shown in figure 2.2

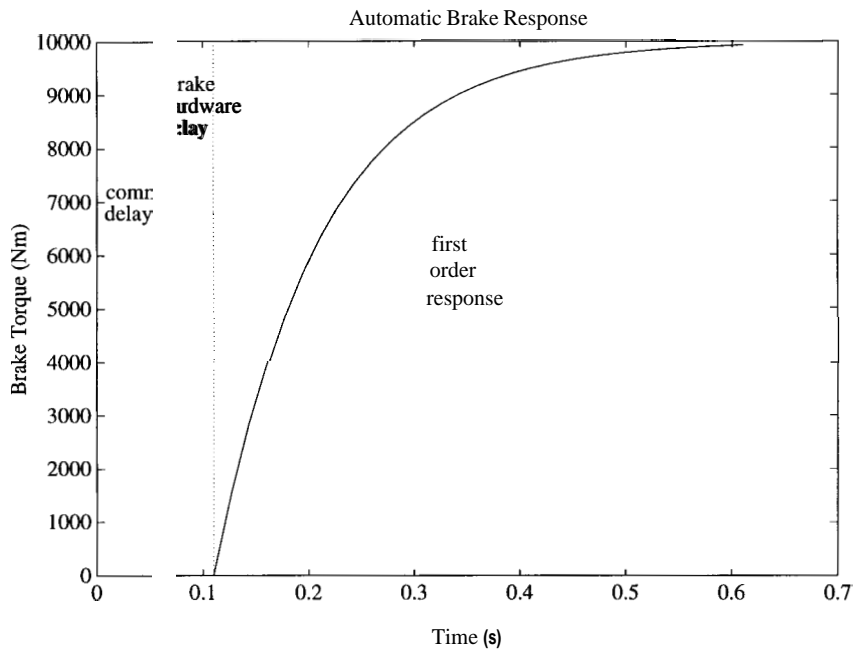


Figure 2.2 Typical Brake Dynamic Response

The maximum brake torque was limited to 10,000Nm to account for the capabilities of current brake systems. Furthermore, the deceleration is limited to 6.7 m/s^2 (0.7g). This is to account for the limitation of the tire-road interaction and the activation of the ABS.

3. IVHS and Human Drivers

In order to evaluate the efficiency of an AHS it is critical to determine the effect of vehicle dynamics on the capacity. In this paper the emphasis will be placed on the effects of brake dynamics during an emergency braking on the capacity of the AHS.

As illustrated in figure 2.2, an idealized brake dynamic response can be divided in two separate sections. The first one is the pure time delay. In turn, the pure time delay has two components. The first component is due to the recognition of the emergency brake mode which is dependent on the communication protocol and hardware. In the current system a token protocol involving a voting scheme is used making the pure time delay associated with the communication approach a duration of 60msec. The second component of the pure time delay is due to the delay in the brake hardware. It generally depends on the type of valves, hydraulic system and design of the brake system. The duration of this pure time delay can range from 10 to 100msec. Therefore, the lumped length of the pure time delay varies from 70 to 160msec.

The second component of the idealized brake dynamic response is the first order response. The critical element of this part is the time constant of the response. Again, the time constant varies with the brake hardware and it ranges from 10 to 100msec. In mathematical form, the dynamic brake response can be represented as:

$$\dot{T}(t + \Delta t) = \frac{T_d(t) - T(t)}{\tau}$$

where

T = brake torque

T_d = desired brake torque

Δt = pure time delay

τ = time constant

In order to have an understanding of these values, figure 3.1 shows the idealized brake response when a human driver is in control of the vehicle.

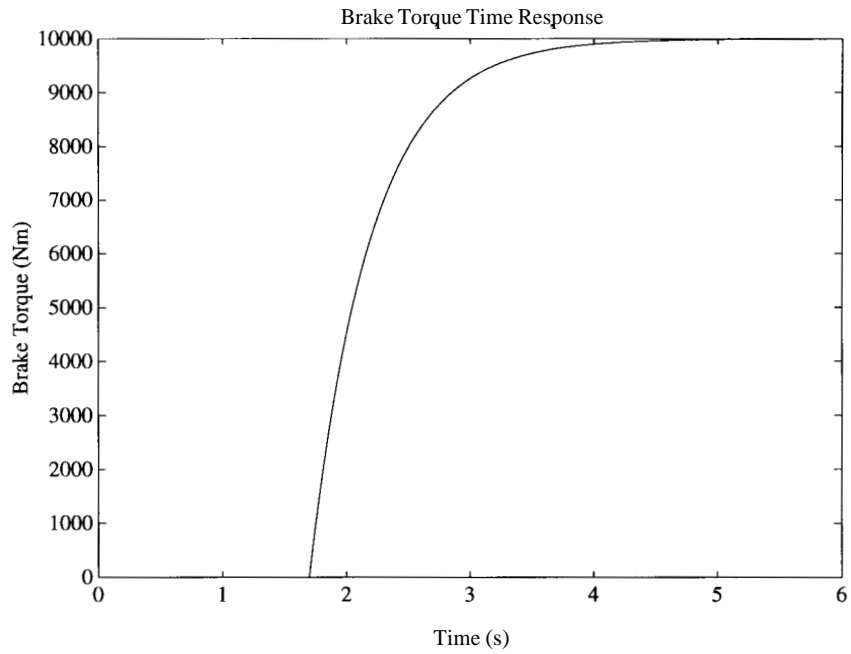


Figure 3.1 Brake Dynamic Response With Human Driver

The pure time delay is due to the perception of some external stimuli, the reaction time to such stimuli, the actual foot transfer and the overcoming of any deadzones in the brake system. In general, the pure delay for a human driver varies from 1.2 to 1.7 seconds (Bidwell, 1961). The first order response time constant is limited by the rate with which a human driver can depress the brake pedal and the bandwidth of any aids present in the brake system. These values range from 400 to 500msec..

It is therefore interesting to analyze the behavior of a platoon in which the vehicles are operated under human control in order to appreciate the benefits of an IVHS controlled platoon. In order to achieve 2000 passenger-cars per hour per lane (pcphpl) at 110 Km/h (70MPH) an average spacing of 50m must be maintained between vehicles. As figure 3.2 shows, this is a safe spacing since the final relative speed between vehicles during an emergency braking maneuver at this spacing is 0Km/h (i.e. no impact between vehicles occurs). It was assumed that the two vehicles are able to decelerate at the same rate of 6.7m/s^2 . The situation becomes more critical though when the two vehicles are not able to decelerate at the same rate. Figure 3.3 show how the collision speed varies with the initial spacing when the lead vehicle is able to decelerate at 6.7 m/s^2 while the following vehicle is able to decelerate only at 5.9 m/s^2 .

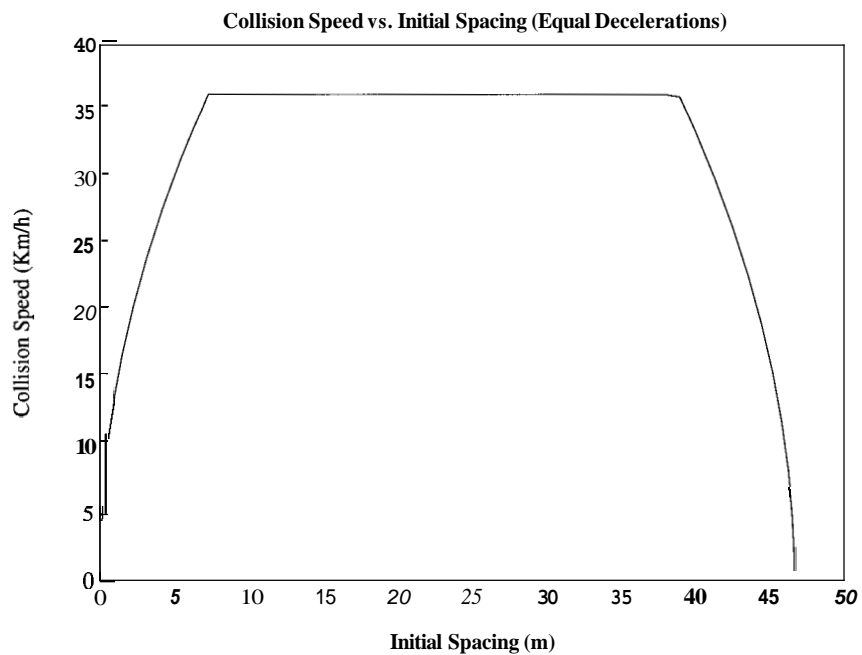


Figure 3.2 Collision Speed for Various Initial Spacings and Equal Decelerations

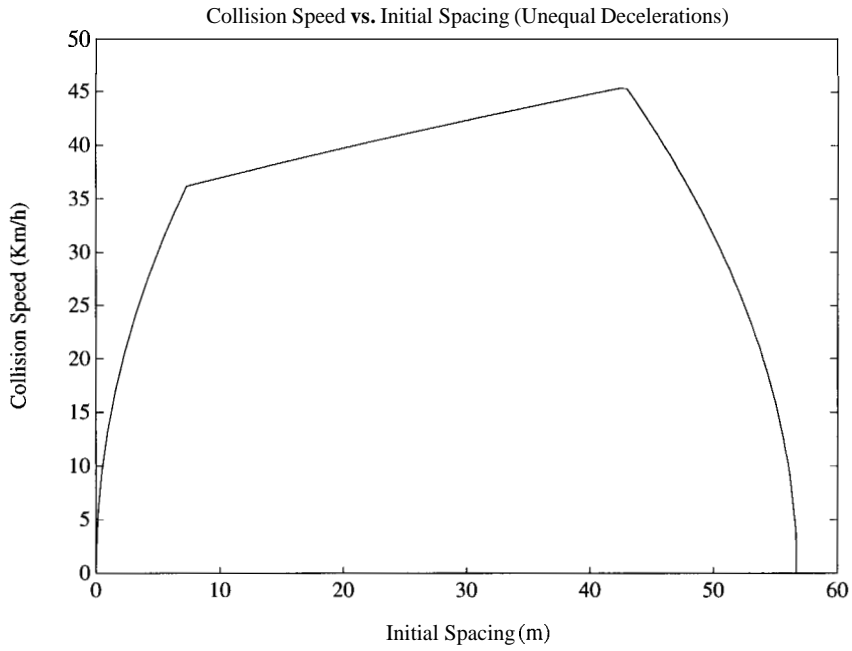


Figure 3.3 Collision Speed for Various Initial Spacings and Unequal Decelerations

However, maintaining an average 50m initial spacing between vehicles, figure 3.4 shows that the final spacing is also kept under 5m, the length of an average car.

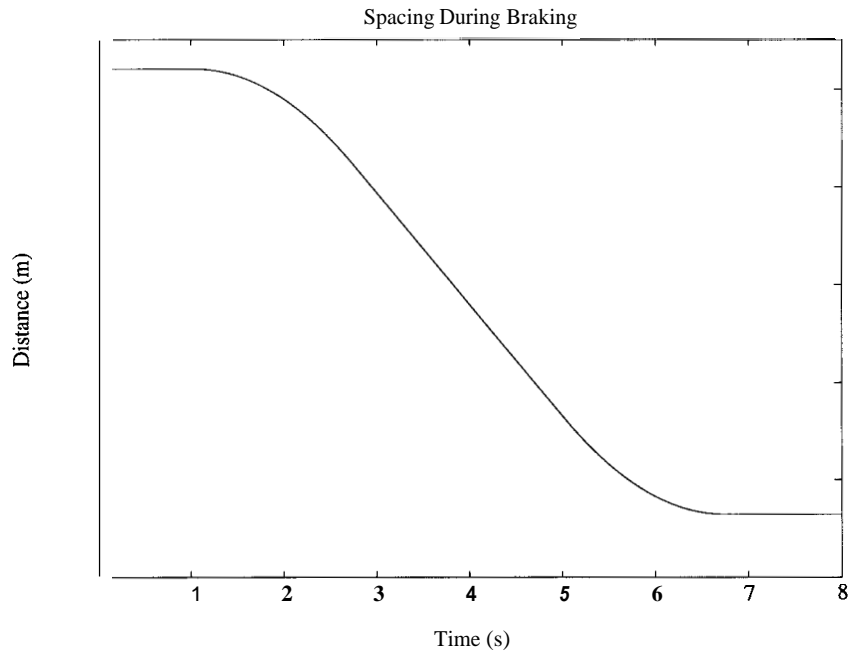


Figure 3.4 Spacing During Braking with Human Driver

However, without an adequate control scheme instabilities in the platoon will occur and most human drivers will not be able to maintain a spacing of exactly 50m, in order to be safe during an emergency. As a matter of fact, maintaining between 2 and 8 car lengths spacing proves to be the most dangerous situation since the relative speed between cars during a collision is upwards of 40Km/h (25MPH) as figure 3.2 shows.

The inability of a human driver to maintain the required spacing under heavy braking is illustrated in the t-x diagram shown in figure 3.5

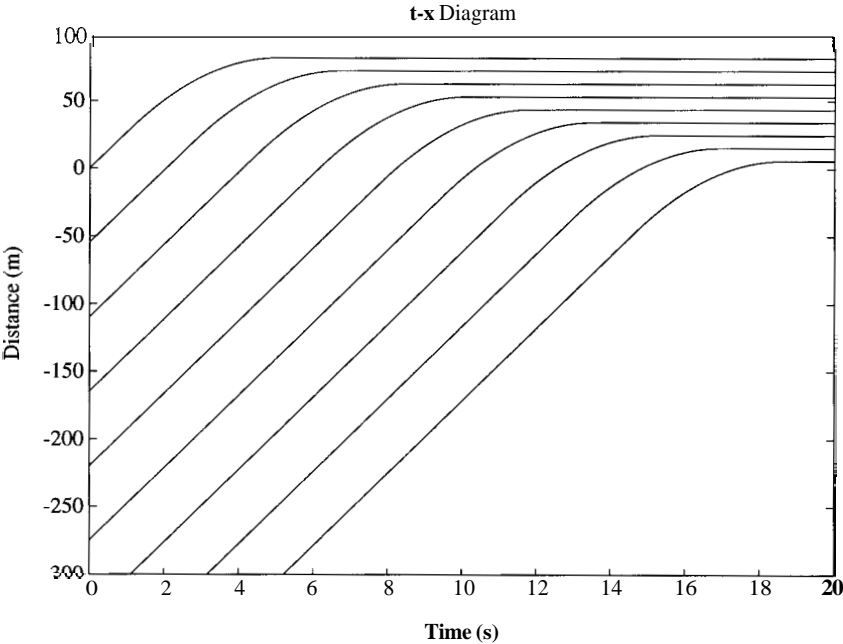


Figure 3.5 Platoon of Human Driven Vehicles Under Braking

The reduction in spacing over this short time interval is easy to notice, pointing out the instability of a platoon composed of human driven vehicles.

As figure 3.2 shows, there are two spacing values where the relative speed at impact is minimized. A low relative speed during an accident occurs at very small spacing between vehicles (0-5m) or very large (>50m). This idea drives the IVHS platoon concept.

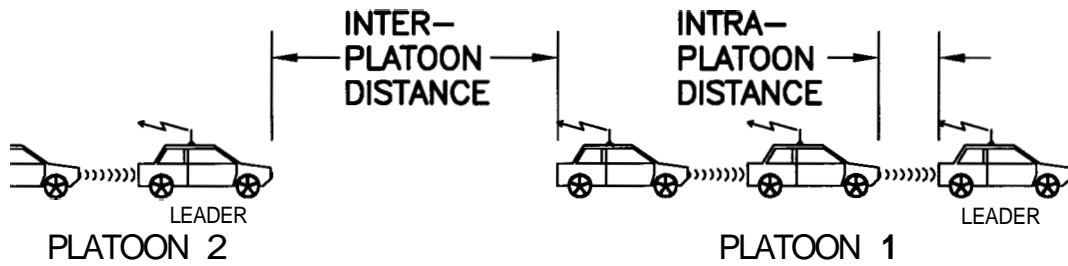


Figure 3.6 IVHS Platoon

Two different spacing values can be observed in the platoon schematic in figure 3.6. The intra-platoon distance is kept small enough so that the relative speed between vehicles during an accident is kept below 4Km/h. The 4Km/h value was chosen since the current federal regulations require that a bumper sustain a 4Km/h (2.5MPH) impact without damage. The inter-platoon distance is regulated by the “brick wall” safety concept. The idea behind this concept is that the second platoon has to come to a complete stop before touching the last vehicle in the first platoon even if that vehicle comes to a complete stop instantaneously.

4. IVHS Simulation Results

In order to investigate the full effect of the brake dynamics, the simulation was run for an emergency case. It is obvious that a platoon must perform safely under extreme conditions such as emergency braking. However, the constraints on the platoon are much more stringent under such conditions than under normal operation. The simulation was run using several brake dynamics and platoon sizes. From such simulations, several sets of information were obtained. One of the most important information was the capacity of the IVHS lane. This type of information will determine whether the increase in capacity warrants the cost of developing a brake system with more stringent dynamic constraints.

From a safety interest, the inter-platoon and intra-platoon distances were determined so that no impact occurs between the vehicles of a platoon or the leader and the last vehicle of two consecutive platoons, even though a 4Km/h impact is acceptable. The main reason for not allowing collisions to occur is that the dynamics of a multi-vehicle collision are complicated and beyond the purpose of this paper. Furthermore, by not allowing collisions to occur, the simulation will yield more conservative results and thus producing a “worst case” scenario.

4.1 Typical Results

A simulation run was performed using “typical” values of brake dynamics and platoon size. These values were chosen from the currently acceptable values in this research area. They are as follows:

Pure time delay:	50msec
Time constant:	50msec
Platoon size:	10veh
Initial speed:	110Km/h
Deceleration:	6.7m/s ²

The t-x diagram of such a platoon under emergency braking is shown in figure 4.1.

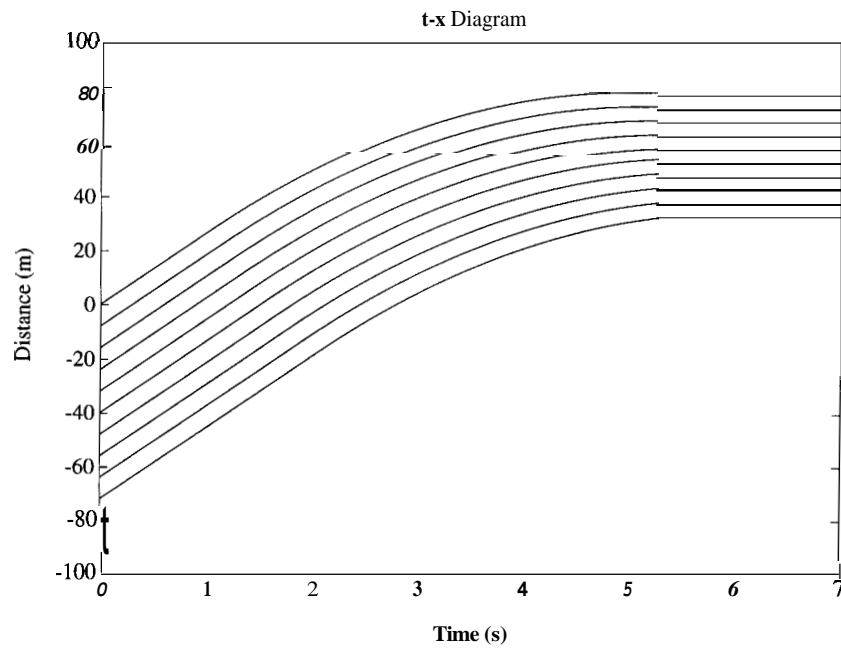


Figure 4.1 IVHS Platoon Under Emergency Braking

As it can be seen, the vehicles maintain a more constant spacing than the human driven platoon was able to maintain. The safety issue is also better addressed by the IVHS platoon. Figure 4.2 shows two such platoons and the fact that the second platoon was able to come to a complete stop under the “brick wall” safety concept.

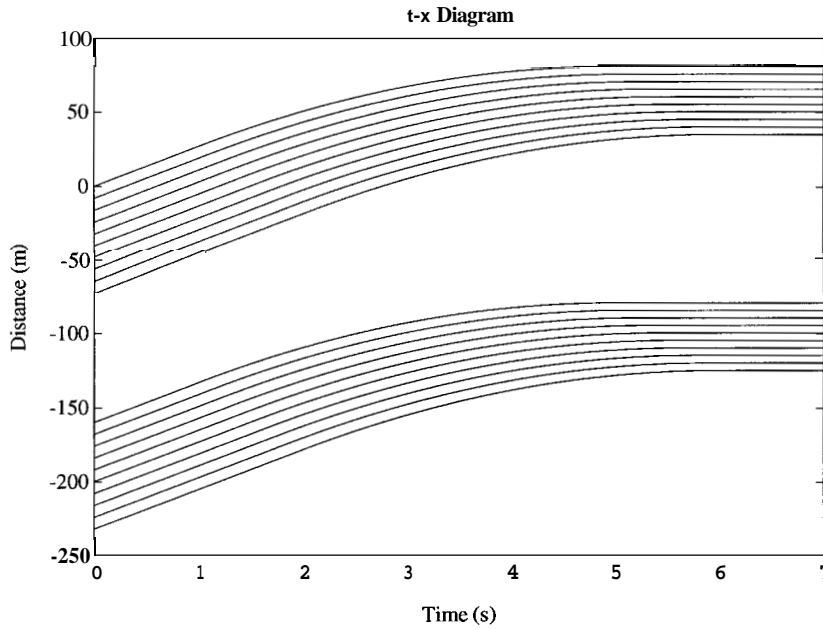


Figure 4.2 Inter-Platoon t-x Diagram

Even more important is the effect on the relative speed at impact. As in the human driven vehicles, two regions of low impact speed can be found. However, for the IVHS case, even the worst impact speed is below 1.5Km/h. Figure 4.3 shows these facts.

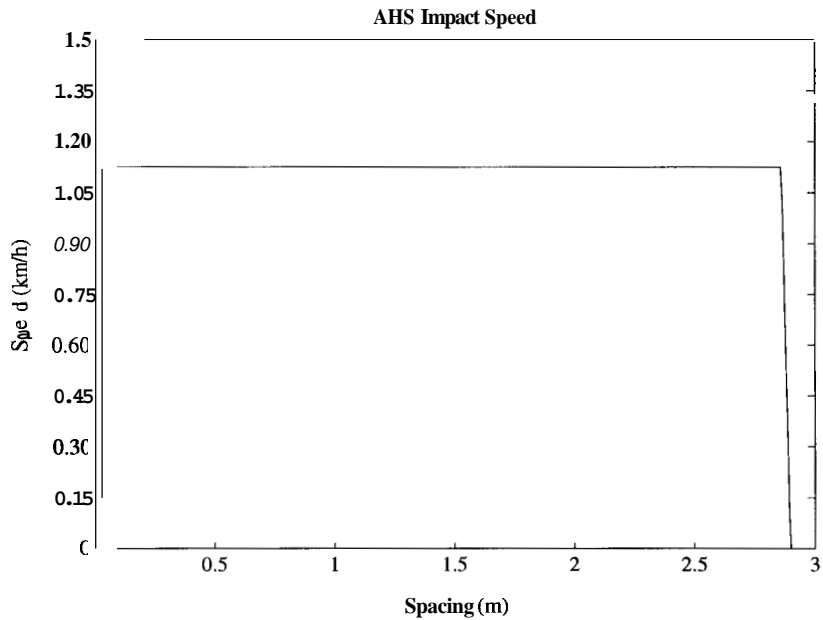


Figure 4.3 Collision Speed for Various Initial Spacings (IVHS Platoon)

4.2 Brake Dynamics Effect

The most relevant investigation involves the effect of the brake dynamics on the lane capacity. This type of information is necessary in developing required specifications for the next generation of automatic brake systems. The cost of developing a system with very stringent requirements must be weighted against the improvement in capacity. Early research has shown that from a control issue, a very short pure time delay is desired but the cost to develop such a system is too high using the current technology.

The simulation was therefore run with pure time delay and time constant values ranging from 10 to 100msec for the brake system hardware, or from “ideal” to “currently available.” Additionally, a 60msec pure time delay was added to account for communication delay. The initial speed was 70MPH. The results are summarized in Table 4.1 along with intra-platoon and inter-platoon distances.

Table 4.1 Brake Dynamics Effect on Capacity

$\tau \rightarrow$	10 msec			50 msec			100 msec		
Δt (msec)	Capacity (pcphpl)	Intra- (m)	Inter- (m)	Capacity (pcphpl)	Intra- (m)	Inter- (m)	Capacity (pcphpl)	Intra- (m)	Inter- (m)
100	4707	4.3	83.4	4706	4.3	83.5	4700	4.3	83.7
50	5060	3.0	81.9	5059	3.0	82.0	5053	3.0	82.2
25	5305	2.2	81.1	5304	2.2	81.2	5297	2.2	81.4
10	5403	1.9	80.6	5402	1.9	80.7	5394	1.9	80.8

Several conclusions can be drawn from the above table. First, the time constant has a minimal effect on the capacity. The pure time delay however, has an important effect on the capacity. Furthermore, the capacity increases almost linearly with the decrease in the pure time delay, as figure 4.4 shows.

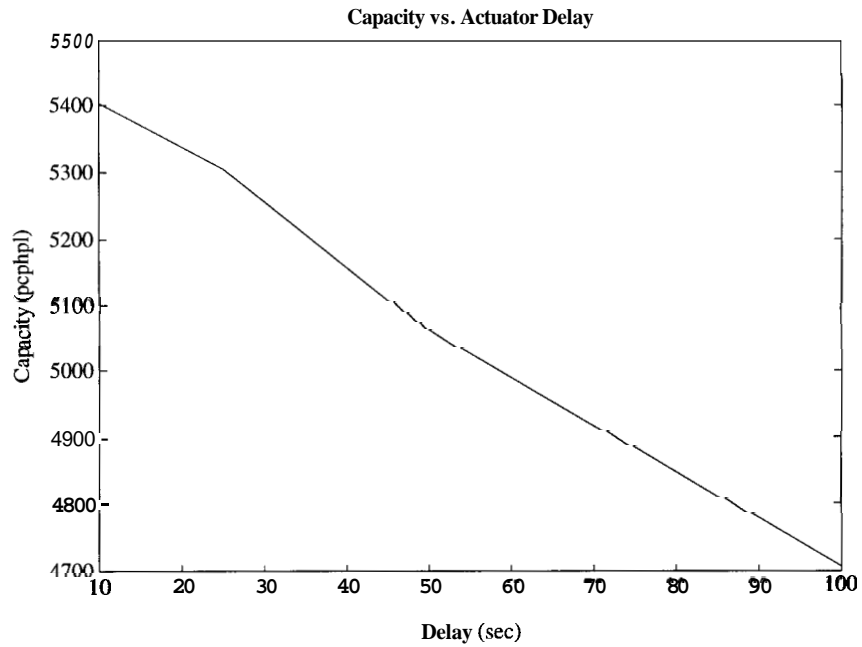


Figure 4.4 Pure Delay Effect on Capacity

It is also interesting to notice that even with a brake system pure delay of 10msec the minimum intra-platoon distance is 1.9m instead of the hypothesized distance of 1.0m. This is due to the pure time delay of 60msec caused by the communication protocol and hardware. If the 1.0m intra-platoon distance is the critical parameter in design, the following values must be achieved.

Table 4.2 Requirements for 1.0m Intra-Platoon Distance

Total delay	Time constant	Capacity	Inter-platoon dist.
40 msec	25 msec	5716 pcphpl	79.7 m

It is interesting to notice that with a total pure time delay of 40msec the achievable capacity is 5716 pcphpl, or about three (3) times the present capacity.

Since decreasing the communication delay is one way to increase capacity, methods must be found to achieve this goal. The present communication system uses a token protocol, where each vehicle takes its turn in transmitting while the rest are receiving. Therefore, one way to reduce the communication delay is to use smaller platoons. This issue will be investigated in the next section.

4.3 Platooning Strategies

One problem with using smaller platoons is that there will be more larger inter-platoon spacings which will reduce the total capacity. The problem with larger platoons is that the communication delay increases linearly with the size of the platoon but there are less inter-platoon spacings. The effect of the platoon length was investigated in this section.

Platoon lengths from 5 to 20 vehicles were used in simulation. A larger platoon was considered unachievable due to the possibility of spacing error propagation along the length of the platoon. The brake system pure time delay was kept at 50msec in order to have an even comparison basis. The results are summarized in Table 4.3

Table 4.3 Platoon Size Effect on Capacity

	Platoon Size		
	5 veh	10 veh	20 veh
Capacity	3307 pcphpl	5059 pcphpl	6343 pcphpl
Intra. Dist.	2.2 m	3.0 m	4.6 m

It is clear from the above table that the maximum capacity can be achieved with a large platoon size. The platoon size will be however limited by control, communication and logistical issues. The capacity can be further increased if the communication delay is improved by technological advances.

Conclusion

An attempt was made to investigate the effect of brake system dynamic characteristics and platooning strategy on the capacity of an IVHS lane. These results should help create realistic goals regarding the specifications of the brake system hardware, communication hardware, lane capacity and safety.

It was shown that a small decrease in the hardware pure time delay can have **an** important effect on the capacity. Also, a larger capacity can be achieved by using as large as possible platoons. The combination of these two factors should be able to raise the capacity of an IVHS lane to 3 to 3.5 times the currently achievable capacity.

According to these preliminary results, the following recommendations can be made. Maintain a platoon size of 20 vehicles. Reduce the total pure time delay to 40msec. This can be achieved by a combination of reduced communication delay and brake system pure time delay. Maintain an intra-platoon distance of 1m and an inter-platoon distance of 80m. These distances will guarantee safe operation even during emergency maneuvers. They will also yield an IVHS lane capacity of 6000 pcphpl, or about three times the current capacity.

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