Title
Spacing And Capacity Evaluations For Different Ahs Concepts

Authors
Kanaris, Alexander
Ioannou, Petros
Ho, Fu-sheng

Publication Date
1996

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Spacing and Capacity Evaluations for Different AHS Concepts

Alexander Kanaris
Petros Ioannou
Fu-Sheng Ho
Universtiy of Southern California

California PATH Research Report
UCB-ITS-PRR-96-30

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

November 1996

ISSN 1055-1425

Spacing and Capacity Evaluations for different AHS Concepts

Alexander Kanaris, Petros Ioannou, Fu-Sheng Ho

Center for Advanced Transportation Technologies
University of Southern California
Los Angeles, CA 90089 - 2562

May 1996

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

Spacing and Capacity Evaluations for different AHS Concepts

Alexander Kanaris, Petros Ioannou, Fu-Sheng Ho

Abstract

In Automated Highway Systems (AHS), vehicles will be able to follow each other automatically by using their own sensing and control systems, effectively reducing the role of the human driver in the operation of the vehicle. Such systems are therefore capable of reducing one source of error, human error, that diminishes the potential capacity of the highways and in the worst case becomes the cause of accidents. The inter-vehicle separation during vehicle following is one of the most critical parameters of the AHS system, as it affects both safety and highway capacity. To achieve the goal of improved highway capacity, the inter-vehicle separation should be as small as possible. On the other hand, to achieve the goal of improved safety and elimination of rear end collisions, the inter-vehicle separation should be large enough that even under a worst case stopping scenario, no vehicle collisions will take place. These two requirements demand diametrically opposing solutions and they have to be traded off. Since safety cannot be compromised for the sake of capacity, it becomes a serious constraint in most AHS design decisions. The trade-off between capacity and safety gives rise to a variety of different AHS concepts and architectures.

In this study we consider a family of six AHS operational concepts. For each concept we calculate the minimum inter-vehicle spacing that could be used for collision-free vehicle following, under different road conditions. For architectures involving platoons we also use the alternative constraint of bounded energy collisions to calculate the spacing that can be applied if we allowed collisions at a limited relative velocity. In every case, the minimum spacing in turn, is used to calculate the maximum possible capacity that could be achieved for each operational concept.

Keywords: Automated Highway Systems, Vehicle Following, Vehicle Spacing, Highway Capacity, Highway Safety, Accident Avoidance, Collision Avoidance, Braking Scenarios, Brake Performance

Executive Summary

In this paper we analyze and evaluate the braking performance of different vehicle classes under six different Automated Highway Systems (AHS) operational concepts. For each operational concept we calculate the minimum inter-vehicle spacing that could be applied in order to achieve collision-free vehicle following under different road conditions such as wet and dry road surfaces. In addition to collision-free environments, for AHS architectures involving platoons, we also apply the alternative constraint of bounded energy collisions to calculate the spacing that can be applied if we wanted to allow collisions at a specific limit of relative velocity. In every case, the minimum spacing is used to calculate the maximum achievable capacity for each operational concept, thus opening the way for safety, risk, cost and performance tradeoff analysis of different AHS operational concepts.

The tools that were developed during this study allow users to parameterize and customize the vehicle braking scenario that will be considered as the worst case braking scenario because, obviously, different braking scenarios imply different spacing requirements and different capacity levels. To support our choice of parameters for the worst case braking scenario we have applied in each case, we considered and included in this paper tables of vehicle braking performance data derived from road tests performed by MHTSA and by the leading consumer magazines. Almost equal in importance to the deceleration performance potential of the vehicles involved is the timing of the braking command, which involves detection, communication and actuation delays. These delays vary depending on the AHS operational concept that will be chosen and the components that will be employed. Our choice of timing parameters was based on sensor-actuator-communication technology limitations and is supported by vehicle tests performed by the authors and by other researchers in the PATH program.

While the numerical results we obtained apply to nothing but the specific examples that we studied and the parameter choices we made, the methodology and tools we developed can easily be applied in order to evaluate the performance and limitations of any variant of these examples. Furthermore, by meticulously maintaining a level of consistency in the choice of parameters we made, we have obtained results that can be useful in ranking the relative merits of the different candidate AHS operational concepts.

Contents

List of Figures

List of Tables

1 INTRODUCTION

Urban highways in many major cities are congested and need additional capacity. Historically, capacity has been added by building additional lanes and new highways. Scarcity of land and escalating construction costs make it increasingly difficult to add capacity this way. One possible way to improve capacity is to use current highways more efficiently. The concept of Automated Highway Systems (AHS) was introduced to improve the capacity of the current transportation systems by using automation and intelligence.

Highway capacity depends on two variables: The velocity of the vehicles and the distance between them. Clearly, the higher the velocity of the vehicles, the higher the number of vehicles per lane per hour will be. But the vehicles need to maintain a certain amount of "safety distance" between them, to accommodate for the case that the flow of vehicles has to be slowed down or stopped, by applying the brakes. The moment that each vehicle starts applying its brakes typically involves a couple of seconds of delay in relation to the onset of braking of the vehicle in front, due to the fact that the human drivers need some time to process the information they perceive [22], plus an ,additional time delay to react and a delay for the mechanical and hydraulic systems of the vehicle to respond. During this time, the vehicle continues moving forward at practically the same speed and if there is not sufficient space between the leading and the following vehicle at the moment the leading vehicle applies the brakes and begins to decelerate, a collision would be inevitable. Even if the follower begins to apply its brakes at exactly the same time as the leader, the deceleration of the leading and the following vehicle may not match [9,10] and this generates the need for additional inter-vehicle distance during the cruising stage in order to accommodate for the difference in braking performance.

Heavy vehicles travel a significantly longer distance from the moment they apply their brakes until they come to a complete stop. This has to be accommodated for by allowing a significantly larger inter-vehicle spacing. On the other hand, when a light vehicle follows a heavy vehicle, the braking distance is not the limiting factor because typically the light vehicle will be able to come to a stop in a much shorter time and distance. In this case, the limiting factors are the initial conditions and the total delay between the time that the leader starts decelerating and the time that the follower starts decelerating at the maximum possible deceleration.

The delay in detecting and in reacting to the leading vehicle's deceleration can be reduced significantly, by taking the human driver out of the "control loop" [1,12,13,16]. With advances in technology and vehicle electronics, systems that were previously considered impossible to implement or too costly are becoming feasible and available. One such system is a functional extension of the classic cruise control [12]. The cruise control which is widely available on luxury cars today, is a controller that controls a throttle actuator in order to maintain constant vehicle speed. The next step in functionality, is a controller that uses a sensor to measure the relative distance and the relative speed to any vehicle ahead and controls a throttle and a brake actuator in order to follow at the same speed and maintain a fixed relative distance [12,14,15]. Such vehicles can follow each other in the same lane automatically by relying on their own sensors and controls. Vehicles that rely on their own sensors, controls and intelligence to operate in a highway environment are referred to as autonomous vehicles.

Advances in communications made it possible for vehicles to communicate with each other exchanging information about braking intentions and capabilities, acceleration, lane changing etc. The infrastructure may also support vehicle following and maneuvers by providing desired speed and spacing commands in addition to traveler information. This distribution of intelligence gives rise to the operating concept referred to as infrastructure supported free agent.

When the infrastructure becomes actively involved by sending braking commands for emergency stops and lane changing maneuvers, we have an operating concept referred to as infrastructure managed free agent.

Another concept is to organize vehicles in platoons of a certain size where the intra-platoon spacing is very small and the inter-platoon spacing could be larger for safety purposes. In this case each platoon appears to the infrastructure as a single unit and therefore can be managed more efficiently. Each platoon is now responsible for the control of its vehicles.

If the inter-vehicle separation becomes very small, the laws of physics dictate that collisions between vehicles may be inevitable. In the interest of safety and avoidance of vehicle damage it will be of paramount importance that the energy dissipated during the collision be constrained. Since safety cannot be compromised for the sake of capacity, it becomes a serious constraint in most AHS design decisions.

In this study we consider a family of AHS platooning concepts. For each concept we calculate the minimum inter-vehicle spacing that would be required to guarantee either collision free following or bounded energy dissipation. in the event of a collision. We will be assuming that if the collisions are relatively rare events, are always very minor and cause no permanent damage to the vehicles, the public might be willing to accept the fact that collisions may happen. Allowing for collisions to happen can reduce the minimum headway requirements for a platoon based AHS architecture.

Finally, in a slightly different operational concept, a high level of synchronization is introduced where each vehicle is allocated a slot in time and space. The infrastructure manages the slot distribution by issuing the appropriate commands for each vehicle.

The degree of infrastructure involvement and distribution of intelligence lead to different operational concepts and architectures for AHS. The purpose of this section is to study the Minimum Safety Spacing (MSS) for a number of different AHS concepts and architectures and to obtain capacity estimates.

2 SAFE INTERVEHICLE SPACING ANALYSIS

Inter-vehicle spacing during vehicle following is a very critical parameter of highway traffic. Insufficient spacing is usually the cause of rear-end collisions. In principle, the possibility of having a rear-end collision can be reduced by increasing the inter-vehicle spacing. However, the spacing that guarantees collision-free vehicle following can be characterized only when the braking scenario is known and well defined.

A braking scenario, which describes exactly how the vehicles brake, is usually specified by the deceleration profiles of the vehicles as a function of time. For each scenario there is a minimum spacing which must be maintained during steady state traffic flow, if collision-free vehicle following must be guaranteed. In this section we develop the basic equations that can be used to calculate the minimum spacing for collision free vehicle following, given the deceleration response information for both the leading and the following vehicle.

2.1 Minimum spacing for collision avoidance

Consider two vehicles following each other, as shown in figure 1. Assume that at t = 0 the leading vehicle begins to brake according to the deceleration profile defined by al(t) and the following vehicle brakes according to the deceleration profile defined by a,(t). Assume that L_l and L_f are the lengths of the leading and following vehicles respectively. At t=0 the leading vehicle has a velocity $V_l(0)=V_{l0}$ and a position $S_l(0)=S_{l0}$ and the following vehicle has a velocity $V_f(0)=V_{f0}$ and a position $S_f(0)=S_{f0}$. If the spacing between the two vehicles. at t=0, $S_r(0) = S_{l0} - S_{f0} - L_l$ is large enough, then there would be no collision during braking maneuvers.

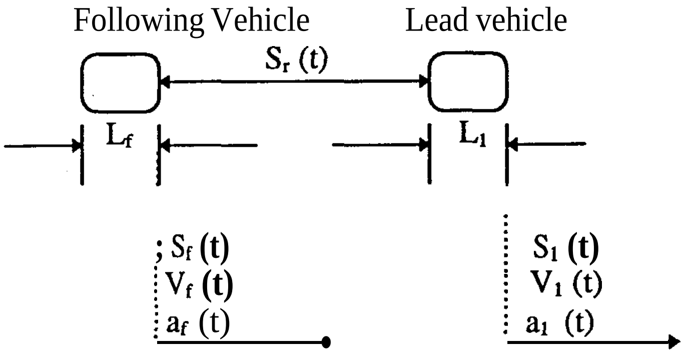

Figure 1: Vehicle Following

For a given braking scenario we would like to calculate the minimum value of the initial intervehicle spacing $S_r(0)$ for which there will be no collision. We refer to this value as the Minimum Safety Spacing, (*MSS*).

The spacing between the two vehicles measured from the front of the following vehicle to the rear of the lead vehicle is given by

$$S_r(t) = S_l(t) - L_l - S_f(t) \tag{1}$$

where

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau)d(\tau) \tag{2}$$

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau)d\tau \tag{3}$$

and

$$V_l(t) = V_l(0) + \int_0^t a_l(\tau)d\tau \tag{4}$$

$$V_f(t) = V_f(0) + \int_0^t a_f(\tau)d\tau \tag{5}$$

If the decelerations $a_l(t)$ and $a_f(t)$ and initial positions and velocities are specified, the MSS can be calculated as follows:

Assume that the two vehicles travel in the same direction but in two separate lanes. The position of the vehicles at time t = 0 is shown in figure 2.

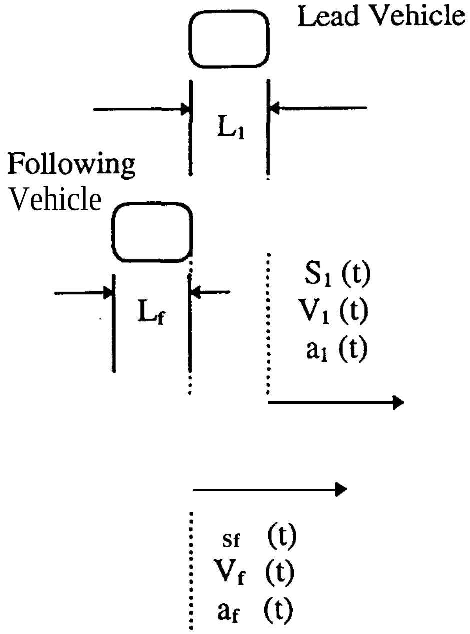

Figure 2: Hypothetical vehicle motion

Let t_s be the stopping time of the following vehicle. Then

$$V_f(0) + \int_0^{t_s} a_f(\tau) d(\tau) = 0 \tag{6}$$

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau) d(\tau), \ \forall t \le t_s \tag{7}$$

and

$$S_f(t) = S_f(t_s), \ \forall t > t_s \tag{8}$$

The position of the leading vehicle at each time t is given by

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau) d(\tau), \ \forall t \le t_s \tag{9}$$

The relative spacing at each time t is given by

$$S_r(t) = S_l(t) - L_l - S_f(t) \tag{10}$$

If both the leading and following vehicle are in the same lane, then $S_r(t) > 0$ for all $t \in (0,t_s]$ will imply no collision, whereas $S_r(t) < 0$ at some $t = t_c \in (0,t_s]$ will imply collision.

The MSS value denoted by S_{min} *is* given *as* $S_{min} = -\min[S_r(t),0]\ \forall\ t \in (0,t_s]$.

In other words S_{min} is equal to the maximum distance by which the following vehicle would overtake the leading vehicle at any time t in the interval $[0,t_s]$ in the scenario shown in figure 2.

Based on the above analysis, we adopt a numerical method to calculate S_{min}. Assume that the following vehicle brakes and it does so by following the given deceleration profile, and comes to a full stop at $t=t_s$. We divide the interval $[0,t_s]$ into small time steps and consider the time instants $t = 0, T_s, 2T_s, \ldots, kT_s$ where T_s is the length of the time step and k is an integer with the property $kT_s \le (k+1)T_s$. The method of calculation of S_{min} is shown in the flowchart of figure 3.

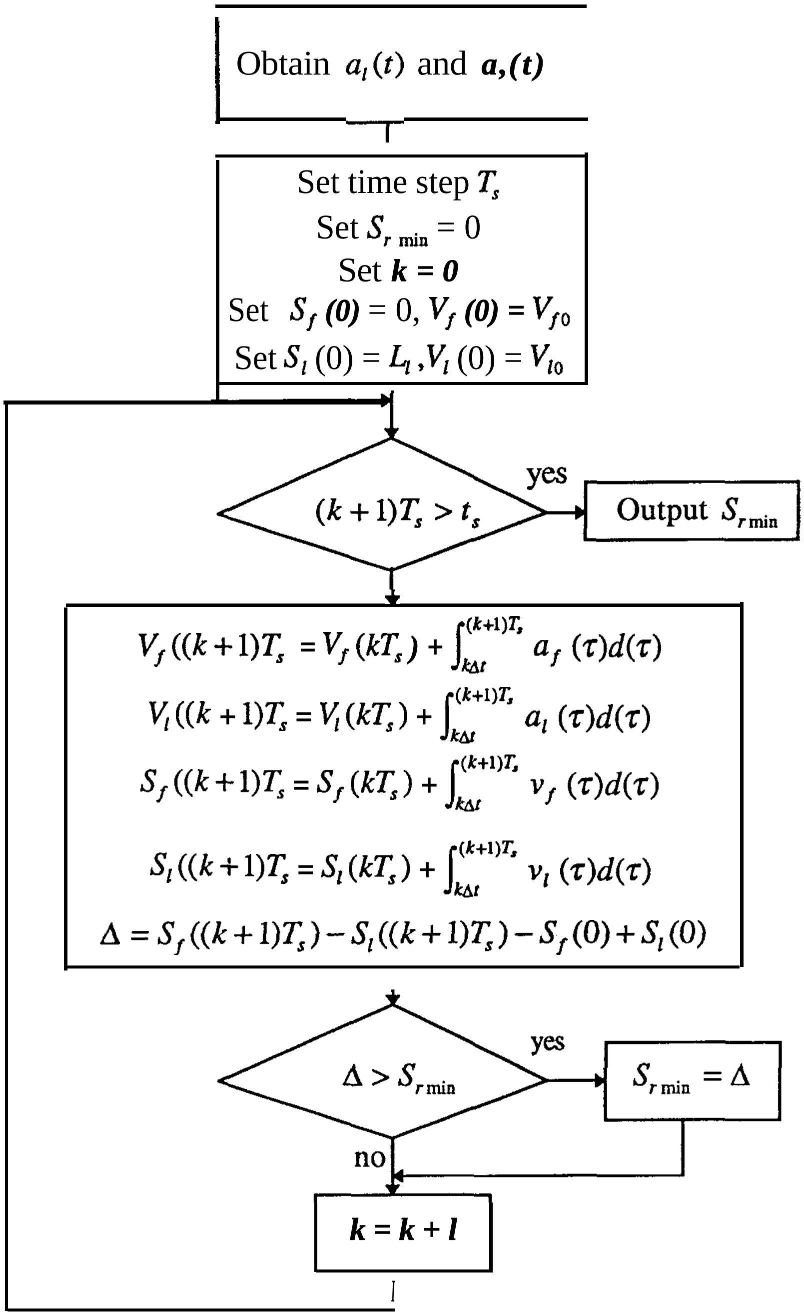

Figure 3. Flowchart for MSS calculation

2.2 Minimum spacing for low impact collisions

The relative velocity at impact is the most significant factor determining the severity of the collision and the extent of property damage and the possibility of passenger injury[4]. In vehicle following situations, the relative velocity between the leader and the follower is determined by differences in deceleration rate and by the time differential of the onset of braking. Assuming the leader and the follower had been traveling at approximately the same speed, the inter-vehicle spacing becomes the critical parameter. In principle, the possibility of having a rear-end collision can be reduced by increasing the inter-vehicle spacing. However, the spacing that theoretically guarantees collision-free vehicle following can be characterized only when the braking scenario is known and well defined and the parameters are not subject to variations. Furthermore, the amount of spacing required in order to provide a guarantee at a 100% confidence level that collisions will never happen, might be surprisingly large, much larger than the spacing we are used to seeing with manual driving. Hence, it might be very hard or impossible to guarantee a collision free environment. The dynamics and effects of inter-vehicle collisions should therefore be analyzed and understood.

Accepting the fact that inter-vehicle collisions may occasionally happen, requires that we carefully study the effects of such collisions to the vehicles involved. The conservation of momentum theorem states that after the collision of two objects the vector sum of the momentum before the collision will be equal to the vector sum of the momentum after the collision. If the two objects have mass ***ml*** and ***m2*** respectively and velocities ***ul*** and ***u2*** respectively before the collision, they will have velocities *vl* and *v2* respectively after the collision, such that:

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2 \qquad (11)$$

The collision coefficient cc has been defined to be the scalar:

$$\text{cc} = \frac{v_2 - v_1}{u_1 - u_2} = -\frac{\text{Av}}{\Delta u} \qquad (12)$$

The collision coefficient is the ratio of the relative velocity at which the two objects separate after a collision over the relative velocity that the two objects approached each other before the collision. When cc = *1* we have what we call “elastic” impact. When cc = 0 we have what we call “plastic” impact. In the former case the two objects bounce off each other at a relative velocity equal to their relative velocity before the impact. In the latter case the two objects essentially “stick” to each other and keep moving as one. Real world objects rarely behave like any of these extremes, so the collision coefficient will be assuming values between 0 and 1.

In this section we develop the basic equations that can be used to calculate the minimum spacing for vehicle following, given the deceleration response information for both the leading and the following vehicle parameterized in terms of the value of the collision coefficient.

2.3 Bounded Collision Energy Analysis

In recent literature Glimm and Fenton [3] expressed the accident severity index *(S^2)* for a platoon of (n+l) vehicles that collide as

$$S^2 = \sum_{i=1}^{n} \Delta V_{i+1,i}^2 (t_{ci})$$

where $\Delta V_{i+1,i}^2 (t_{ci})$ denotes the relative speed at impact between vehicle ***(i)*** and and (Z+Z), at time t_{ci}, the moment of the collision.

When only two vehicles are involved, the severity index is simply

$$S^2 = \Delta V^2 (t_c) = [V_f (t_c) - V_l (t_c)]^2$$

where t_c is the time of the collision.

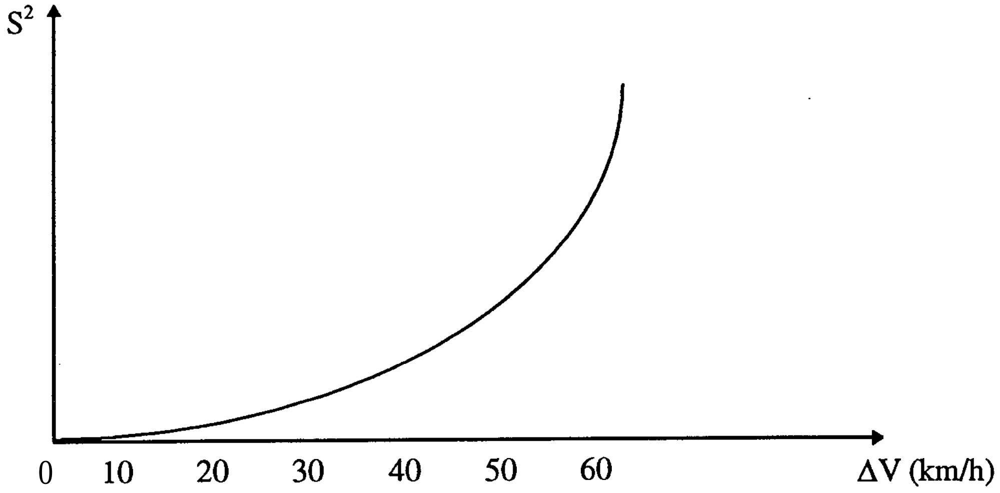

Figure 4: The Severity (impact energy) versus relative velocity at impact.

Consider two vehicles following each other, as shown in figure 1. Assume that at t = 0 the leading vehicle begins to brake according to the deceleration profile defined by al(t) and the following vehicle brakes according to the deceleration profile defined by a_f(t). Assume that L_l and L_f are the lengths of the leading and following vehicles respectively. At t=0 the leading vehicle has a velocity $V_l(0)=V_{l0}$ and a position $S_l(0)=S_{l0}$ and the following vehicle has a velocity $V_f(0)=V_{f0}$ and a position $S_f(0)=S_{f0}$. We want to determine the necessary spacing between the two vehicles at t=0, $S_r(0) = S_{l0} - S_{f0} - L_l$ such that if there is a collision during braking maneuvers, the impact will happen at a relative velocity bounded by a preset upper limit, AV, that gives a low accident severity index S^2.

For a given braking scenario we would like to calculate the minimum value of the initial intervehicle spacing S,(O) that will lead to collisions at relative velocities smaller than ΔV_s. We will refer to this value as the Minimum Impact Spacing, (*MIS*).

The spacing between the two vehicles measured from the front of the following vehicle to the rear of the lead vehicle is given by

$$S_r(t) = S_l(t) - L_l - S_f(t) \tag{13}$$

where

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau)d(\tau) \tag{14}$$

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau)d\tau \tag{15}$$

and

$$V_l(t) = V_l(0) + \int_0^t a_l(\tau)d\tau \tag{16}$$

$$V_f(t) = V_f(0) + \int_0^t a_f(\tau)d\tau \tag{17}$$

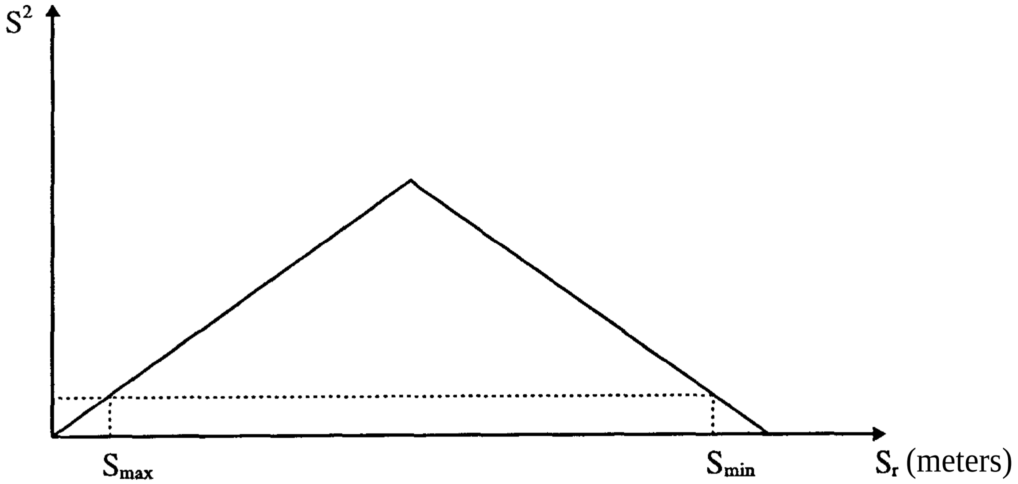

Figure 5: The Severity (impact energy) versus initial intervehicle spacing.

If the decelerations $a_l(t)$ and $a_f(t)$ and initial positions and velocities are specified, the MIS can be calculated in a way very similar to the method used earlier. Let's assume that we want to bound the energy of the collision by limiting the relative velocity just before the collision to less than *AK*

Let's also assume the existence of energy absorbing bumpers that can absorb and dissipate the energy of the collision, thus guaranteeing a perfectly plastic collision. (cc = 0). The diagram of figure 5 indicates that there are two ways to limit the relative velocity before the collision.

Assuming initial conditions where the leading and the following vehicle travel at approximately the same speed, we can guarantee that there is not enough time for a velocity differential to develop by limiting the relative spacing between vehicles to a very small distance. This leads to one possible vehicle following scenario, where in the event of an emergency the vehicles will always collide with each other and with the assumption of plastic collisions they will continue traveling as a single body until they come to a full stop.

The second likely braking scenario assumes that there is sufficient headway between vehicles but somewhat less than what would be required to guarantee no collisions in the event of emergency braking. We can apply the same methodology we used earlier to determine the minimum headway between vehicles that guarantees collisions with relative velocity less than a preselected *AV.* Assume that the two vehicles travel in the same direction but in two separate lanes. The position of the vehicles at time t = 0 is shown in figure 2.

Let t_{sl} be the time needed by the leading and the following vehicle to slow down from their initial velocities V_{lo} and V_{fo} to velocities V_{lsl} and V_{fsl} such that $V_{fsl} - V_{lsl} < \Delta V$. This condition may occur more than once, from the moment the leading vehicle applied deceleration until the moment the following vehicle comes to a full stop. Therefore we are interested in computing the headway for the two boundary cases. The case where the vehicles have first developed a sufficient *AV* and the case where the vehicles are at the end of the braking trajectory, the leader may have already stopped, but the follower is still moving and there is still a *AV* between them. The equations are practically the same as before. We have:

$$V_f(0) + \int_0^{t_s} a_f(\tau)d(\tau) = 0 \qquad (18)$$

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau)d(\tau), \ \forall t \le t_{sl} \qquad (19)$$

and

$$S_f(t) = S_f(t_s), \forall t > t_{sl} \qquad (20)$$

The position of the leading vehicle at each time t is given by

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau)d(\tau), \ \forall t \le t_{sl} \qquad (21)$$

The relative spacing at each time t is given by

$$S_r(t) = S_l(t) - L_l - S_f(t) \qquad (22)$$

and the relative speed at each time t is given by

$$-\Delta V(t) = V_l(0) + \int_0^t a_l(\tau)d\tau - V_f(0) + \int_0^t a_f(\tau)d\tau \qquad \textbf{(23)}$$

In this case we have to determine the time instances t_{c1} and t_{c2} where the relative velocity is equal to the desired threshold. Having determined t_{c1} and t_{c2} we can then determine the relative spacing between the two vehicles. Therefore the Minimum Impact Spacing, MIS has a minimum value and a maximum value. To limit the impact of the first collision at t_{c1}, we must allow for a maximum headway of $S_{max} = -\max S_r(t), \forall\, t \in (0,t_{c1}]$.

To limit the impact of the last collision at t_{c2}, we must allow for a minimum headway of $S_{min} = -\min\, [S_r(t),0],\ \forall\ t\ \in [t_{c1},t_{c2}]$.

From this description it becomes clear that the required headway must be either less than S_{max} or greater than $S_{min.}$ (see figure 5).

The two limits, S_{max} and S_{min}, are equal to the distance by which the following vehicle would have overtaken the leading vehicle at the time instances t_{c1} and t_{c2} respectively, which corresponds to the time instances when their relative velocity is equal to AV, assuming the initial conditions shown in figure 2. Based on the above analysis, we use numerical methods to calculate S_{max} and S_{min}.

3 VEHICLE FOLLOWING CONCEPTS

With advances in technology and in particular in vehicle electronics, systems that were previously considered impossible ***or*** too costly to implement are becoming feasible and available. One such system is a functional extension of the classic cruise control. It consists of a controller that uses a sensor to measure the relative distance and the relative speed to any vehicle ahead and controls a throttle and a brake actuator in order to follow at the same speed and maintain a desired relative distance. The relative distance may be characterized in terms of a constant length or it may be a function of the speed. If the majority of vehicles have such a controller on board, we can have an environment where vehicles follow each other automatically, in the same highway lane, without any other kind of interaction such as communication between them. The highway may provide a level of support to the vehicles by transmitting information about road conditions, congestion, routing suggestions and possibly recommended speeds. If the vehicles do not communicate and do not require any infrastructure support they are said to operate autonomously. A system like that, may provide a capacity increase by smoothing out traffic flow and eliminating the mistake that human drivers tend to do, that is to follow at short and unsafe distances and then overcorrecting by slowing down too much when a vehicle ahead starts to decelerate.

A further functionality enhancement comes by allowing the vehicles to communicate and notify each other about their braking intentions. Also the infrastructure may become involved in setting the desired velocity for each section of the highway, communicating to vehicles about the need for emergency braking and coordinating the flow of the traffic. Such systems may achieve significant improvements in flow rates and capacity increases of the existing highways. By adding more equipment and intelligence to the vehicle-infrastructure system we can come up with more advanced concepts that have the potential for bigger benefits. In this section we describe a number of operating AHS concepts for automatic vehicle following.

3.1 Autonomous Vehicles

A possible AHS concept is one where the vehicles operate independently i.e., autonomously, using their own sensors. Each vehicle senses its environment, including lane position, adjacent vehicles and obstacles. The infrastructure may provide basic traveler information services, i.e., road conditions and routing information. The infrastructure may also provide some means to assist the vehicle in sensing its lane position. Many different systems have been proposed to help the vehicle sense its position, such as implanted magnetic nails, magnetic stripes, radar reflective stripes, Radio Frequency cables, or GPS satellites [23].

In an autonomous environment, the vehicle does not rely on communications with other vehicles or the infrastructure in order to make vehicle following decisions. Each autonomous vehicle maintains a safe distance from the vehicle it is following or if a vehicle is not present within the sensing distance it travels at a constant speed in accordance with the posted speed limits and regional safety regulations and of course road conditions. In other words, if there is no vehicle ahead within the maximum safety distance, the vehicle travels at the speed limit or at a lower speed depending on the road conditions.

Since there is no communication between vehicles, each vehicle senses the relative spacing and speed to the vehicle ahead and selects a headway based on its own braking capabilities and by assuming that the vehicle in front may brake with the ‘worst’ possible deceleration. The technology that allows the vehicle to sense the relative position and speed to the vehicle ahead can also be adapted to allow the vehicle to estimate the size and indirectly the vehicle class and braking capabilities of the vehicle ahead. This knowledge will allow a less conservative assumption about the braking capabilities of the leading vehicle that will lead to a more accurate selection of intervehicle spacing. In the case where mixing of vehicles classes in the same lane is allowed, distinguishing whether the vehicle ahead is a truck, bus or a passenger vehicle will have a significant effect on the selection of spacing and therefore on capacity.

3.2 Free Agent Vehicles - Infrastructure Supported

A vehicle is considered a ‘Free Agent’ if it has the capability to operate autonomously but it is also able to receive communications from other vehicles and from the infrastructure. This implies that the infrastructure may get involved in a supporting role, by issuing warnings and recommendations for desired speed and headways but the infrastructure will not have the authority to issue direct control commands. Therefore this concept has been referred to as “Infrastructure Supported”. The fundamental difference between this concept and that described in subsection 3.1 is that there is vehicle to vehicle and vehicle to infrastructure communication. Each vehicle communicates to the vehicle behind its braking capabilities and its braking intentions. This allows the vehicle behind to choose its headway. For example a shorter headway can be selected by a passenger vehicle if the vehicle ahead is a heavy truck or a bus. A larger headway must be selected by a heavy vehicle if the vehicle ahead is a passenger vehicle. A free agent vehicle uses its own sensors to sense its position and environment, including lane position, adjacent vehicles and obstacles.

With this concept the MSS between vehicles is expected to be smaller than that on conventional highways because of the intelligent longitudinal control system and vehicle to vehicle and infrastructure to vehicle communications. Each vehicle senses the relative spacing and speed to the vehicle ahead and decides and selects a headway based on its own braking capability, the braking capability of the vehicle ahead and the road surface conditions which are either sensed by the vehicle or are broadcasted from the infrastructure. When a vehicle starts to brake, it notifies the vehicle behind about the magnitude of its braking force. Even if we assumed a relatively primitive form of communication between vehicles like a line of sight communication that transmits the applied braking force, we can achieve better separation control as we eliminate the delay in deciding if the vehicle ahead is performing emergency braking or routine braking.

3.3 Free Agent Vehicles - Infrastructure Managed

The concept of Free Agent vehicles with Infrastructure Management is based on the assumption that the traffic is composed of vehicles acting as free agents while the infrastructure assumes a more active and more complex role in the coordination of the traffic flow and control of vehicles. Each vehicle is able to operate autonomously and uses its own sensors to sense its position and environment, including lane position, adjacent vehicles and obstacles. The difference in this centrally managed architecture is that the infrastructure has the ability to send commands to individual vehicles.

This is envisioned to be a “request-response” type architecture, in which individual vehicles ask permission from the infrastructure to perform certain activities and the infrastructure responds by sending commands back to the requesting vehicle and to other vehicles in the neighborhood.

It is expected and assumed that the infrastructure is able to detect emergency situations and whenever it detects such emergency, the infrastructure will have the responsibility to send an emergency braking command to all vehicles affected. This concept minimizes the delay in performing emergency braking. This allows for some further reduction of the minimum headway, compared to the concepts presented so far. On the other side, the accurate timing of the emergency and stopping commands for each vehicle that must be issued by the infrastructure, requires accurate tracking of individual vehicles as well as extensive and frequent communications between individual vehicles and the infrastructure.

3.4 Platoouing without coordinated braking

This concept represents the possibility that the safest and possibly most cost-effective way of achieving maximum capacity is by making platoons of vehicles the basic controlling unit. This will boost road capacity by expanding on the concept of infrastructure managed control [17,18,19].

Platoons are clusters of vehicles with short spacing between individual vehicles in each group and longer spacing between platoons. The characterizing differentiation is that the platoon is to be treated by the infrastructure as an "entity" thereby minimizing some of the need for communicating with and coordinating individual vehicles. The infrastructure does not attempt to control any individual vehicle under normal circumstances, keeping the cost and necessary bandwidth low. The infrastructure is expected to be an intelligent agent which monitors and coordinates the operation of the platoons.

Tight coordination is required within the platoon in order to maintain a close spacing and this requires that the vehicles must be communicating with each other, constantly. The significantly longer inter-platoon spacing is required to guarantee no inter-platoon collisions.

Each vehicle is expected to be equipped with the sensors and intelligence to maintain its lane position, sense its immediate surroundings, and perform the functions of merging into and splitting off a platoon. It is not expected to accomplish lane changes, or merging and splitting without the infrastructure's or the platoon entity's help.

The main mode of operation of the infrastructure would be of a request-response type. Each platoon's and/or vehicle's request is processed and appropriate commands are sent to the appropriate vehicles/platoons to respond to that request. The infrastructure takes a more pro-active role in monitoring traffic flow, broadcasting traffic flow messages, advising lane changes to individual vehicles and platoons in addition to the usual information provider functions.

Once a vehicle has merged into a platoon, the headway maintenance controller must take into account the braking capabilities of the vehicle ahead in the platoon in order to set an appropriate separation distance that minimizes the possibility of collision. The platoon leader may also provide corrections to the individual intra-platoon headways in order to reduce the possibility of a rear-end collision between two vehicles propagating to the other members of the platoon.

Mixing of vehicle classes, although an implicit feature of the present highway system, creates a major complication because of the dissimilar braking characteristics of each vehicle class. Therefore it makes sense to form platoons of vehicles belonging to the same class, exclusively. In this concept we assume that no coordination of the braking sequence takes place within a platoon in order to distinguish it from the next one where coordinated braking is employed.

3.5 Platooning with coordinated braking

The platooning concept with coordinated braking is based on the concept of maximizing capacity by carefully coordinating the timing and degree of braking among the vehicles participating in a platoon entity. This allows the minimization of the spacing between vehicles without compromising safety. For example, during a braking maneuver the platoon leader may dictate a braking sequence to be followed by each vehicle so that the maneuver is performed without any intra-platoon collision. Such a sequence may require the last vehicle to brake first followed by the second last vehicle etc. The distinguishing feature of this concept is the minimization of intra-platoon spacing and the promise of higher capacity.

3.6 Infrastructure Managed Slotting

Under the Infrastructure Managed Slotting concept, an infrastructure based control system creates and maintains vehicle “slots” in space and time. Slots can be thought of as moving roadway segments, each of which holds at most one vehicle at any time. The vehicles are identified and managed only by association with these slots. For simplicity in management i.e., to achieve slots of uniform length, vehicles that need more space may be assigned multiple slots. Heavy loaded light trucks may be assigned two slots, unloaded semis may be assigned three slots, loaded heavy trucks may be assigned four slots etc.

In the basic slotting concept the slots should be of fixed length. The virtual leading edge of each slot can be thought of as a moving point that the vehicle assigned to the slot has to follow. Thus the controller on the vehicle is assigned to follow this virtual moving point, not another vehicle. In essence this relieves the requirement of *using* headway sensors on the vehicle and of sensing the relative distance and speed to any other vehicle. Under no circumstances is a vehicle allowed to violate the edges of its assigned slot.

The distinguishing feature of this concept is that the sensing requirements are theoretically simplified. At least, the vehicle does not need to sense the relative position and speed of other vehicles. Yet the vehicle must be able to sense its position relative to the edge of the slot and the virtual point it tries to follow. A global and accurate longitudinal position sensing system is required.

In terms of separation policy, the slotting method is bounded by the limitations of the inherently “synchronous” architecture. This means that the size of each slot must be sufficient such that the spacing between individual vehicles occupying a single slot is sufficient to avoid collisions under the worst case scenario. Thus the weakest link in the chain is the vehicle with the worst braking performance that the system tries to accommodate in a single slot. Once the spacing is set to accommodate such a vehicle, every other vehicle which has better braking performance will not be able to utilize this capability to shorten the spacing to the vehicle in front. There will be “dead space” in between them. Similarly, a vehicle that does not meet the minimum braking requirement to occupy a single slot will be assigned two (or more) consecutive slots, with the resulting inefficiency of wasting even more space than is really needed.

By comparison, an architecture where each vehicle optimizes the headway between itself and the vehicle in front based only on the braking capabilities of the two vehicles involved is inherently an "asynchronous" architecture, which results in true minimization of the unused space between vehicles.

The relative merits of a "synchronous" versus "asynchronous" architecture have been intriguing the designers of computers and communications systems ever since digital systems became a reality. The typical tradeoff is complexity versus performance. It has been well established through extensive research in other fields that asynchronous architectures provide the potential for maximizing performance at the cost of increased complexity[24]. It is almost obvious that the same is true on the subject of the AHS separation policy architecture.

4 SPACING AND CAPACITY EVALUATIONS

In this section we present briefly the fundamental factors that affect traction during vehicle acceleration and braking. Traction is what ultimately defines the braking capabilities of any kind of vehicle, under any kind of whether and road conditions. Then we develop likely emergency stopping scenarios for each AHS concept under consideration which we then use to calculate inter-vehicle spacing and capacity.

4.1 Adhesion and Friction

The friction force between two surfaces is defined as the force opposing the relative displacement of the two surfaces when a force is applied as shown in figure 6. In the context of vehicle traction this force is referred to as adhesion. Adhesion (attraction between two surfaces) and friction (resistance to relative motion of adjacent surfaces) are very complex physical phenomena. But for practical purposes it is common to use the approximation that the magnitude of the friction force F depends on two factors only: The normal force G between the two surfaces and a dimension-less coefficient of friction m, such that:

$$F = \mu G \tag{24}$$

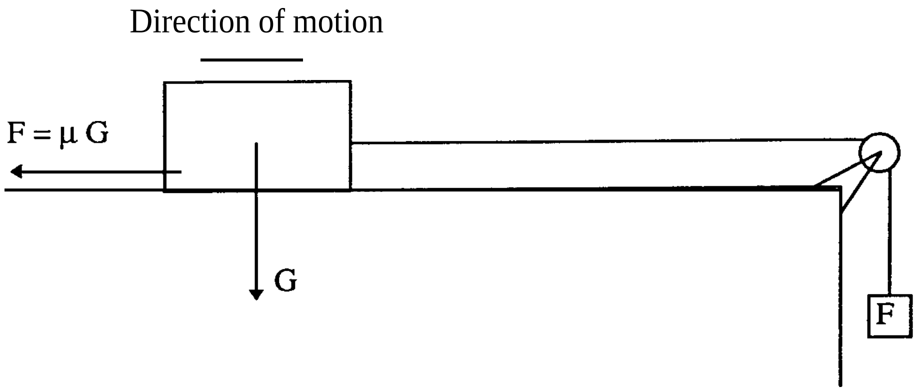

Figure 6: Physical representation of friction force F.

The value of the coefficient of friction μ depends on the characteristics of the two surfaces, primarily their smoothness and their hardness, and on the relative speed V_r between them. For most surfaces, as V_r increases, μ decreases. When the two surfaces do not move μ assumes a considerably higher value, referred to as the static friction coefficient.

Applying the general concept to the problem of vehicle traction, it is clear that the maximum Tractive or Braking Effort (TE_{max}) which can be utilized is limited by the tire to road surface adhesion.

$$TE_{max} = \mu G_a \tag{25}$$

where G_a is the weight on the wheels which apply the force. For propulsion G_a is the weight on the powered axle while for braking G_a represents the total vehicle weight G since the brakes act on all wheels. The actual weight distribution between front and rear axles depends on vehicle design and furthermore varies as a function of the actual deceleration due to the mass transfer phenomenon.

The change of μ with speed is very important in traction and friction. It makes braking at high speeds more difficult than at low speeds because it increases the possibility of skidding. Any spinning or skidding of the wheels results in a rapid increase of the relative speed V_r between the wheels and the road surface and therefore a sudden reduction of μ. As a result, traction is lost. To restore the friction coefficient spinning or skidding must be terminated by reducing the tractive or braking effort. This is the principle of operation of the so called Antilock Braking Systems (ABS).

The value of μ for vehicles depends on the type and condition of the road surface, the vehicle speed and the condition of the tires. A range of values of μ for most types of vehicles is shown in figure 7 [8].

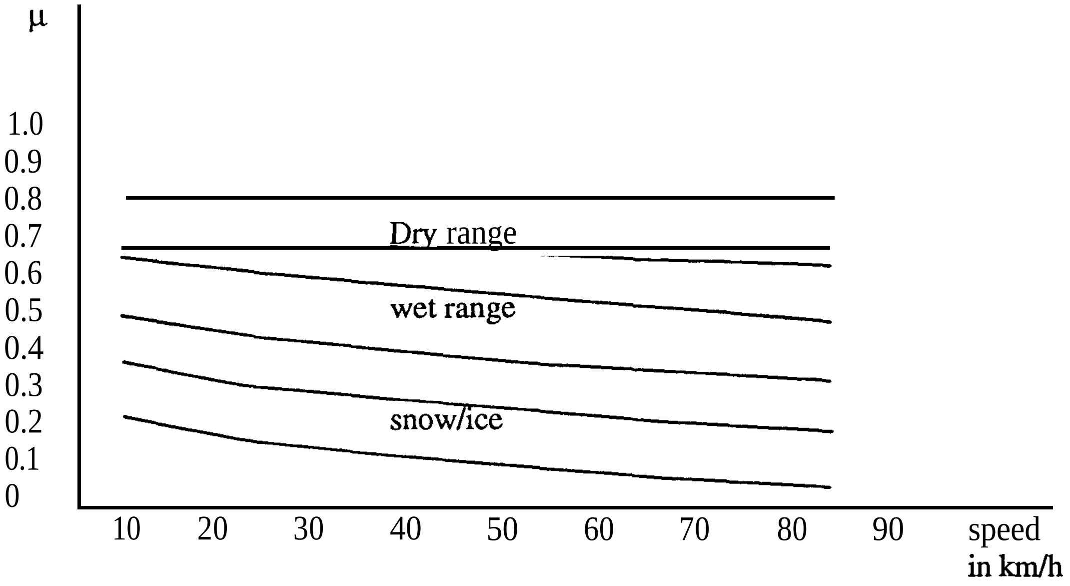

Figure 7: Friction coefficient of vehicles with rubber tires.

The braking ability of all vehicles is best on dry pavement. It degrades substantially on wet pavement and braking ability is virtually lost on snow.

In our analysis, we use data from vehicle tests performed by established authorities. For passenger vehicles, we use information from the "Consumer Reports" publication [9] and the consumer oriented "Road and Track" magazine [10]. For heavy vehicles like buses and trucks, we obtained information from actual tests [11]. Based on these data, we have estimated the braking capabilities of a range of passenger and heavy vehicles on dry, wet and snowed road pavement. In a more or less expected fashion, we found that sports cars can achieve the best braking distances (highest deceleration), followed by middle and upper class medium size vehicles (such as in the "sports sedan" category), followed by small or economy class vehicles. The last finding is a little counter intuitive, based on the fact that small vehicles are light weight thus require less energy dissipation to achieve braking and are less demanding of good tire performance. Yet there is an obvious trend for auto manufacturers to try to match the braking capabilities with the acceleration capabilities of a given vehicle. We found that the trend is to offer approximately double the deceleration (in g's) to the available acceleration (also in g's) in low gear. This is a ball park figure, of course, and deviations do exist.

The braking capability of any vehicle degrades on wet pavement by a factor determined by the texture of the pavement and the type of tires used. We represent that as a change in the friction coefficient μ. The data collected give a quantitative estimate of the friction coefficient on dry, wet and snowed pavement. The numbers of course vary depending on the vehicle, its tires and the presence of ABS. A typical vehicle that can achieve 0.8g deceleration on dry pavement can go down to 0.55g in wet conditions and to as low as 0.15g in snow conditions. The collected braking test results are presented in Appendix A.

In our study, we simplified somewhat our assumptions regarding the friction coefficient μ. Instead of assuming a maximum deceleration of 1 g and scaling it by the typical value of μ, i.e., 0.8 for passenger vehicles, we used the value 0.8 g for maximum deceleration and assumed that μ is 1.0. This does not affect the results for braking on dry road pavement. Then for wet road conditions we assumed a worst case scenario where the friction coefficient becomes half, i.e., μ becomes 0.5 while the maximum deceleration remains at 0.8 g for passenger vehicles. Similarly, instead of assuming different values of μ for buses and for heavy trucks, we used the same value for all of them, but we used a different value of maximum deceleration for each class. We used 0.4 g maximum deceleration for buses and 0.3 g maximum deceleration for heavy trucks. These numbers are based on measurements on actual vehicles, and the data can be found in Appendix A.

The maximum deceleration that each vehicle can achieve depends on many factors and therefore it cannot be predicted exactly. It depends mostly on the tires of course, like the quality and type of tread, hardness, temperature, inflation pressure and the age of the tire. It also depends on the size and type of friction materials in the brakes, the mass distribution of the vehicle, the presence of ABS and many other factors. In our analysis we simplify these complex dependencies by using the abstraction of uniform value of μ and assuming appropriate values for maximum deceleration for different classes of vehicles, without affecting the accuracy of the results.

During the emergency braking phase the jerk is not intentionally limited and the maximum deceleration is allowed to be as large as the vehicle can achieve. The jerk clearly depends on the mass of the vehicle first and on the hydraulic brake system second. It clearly depends on the rate of change of the force that the driver applies on the brake pedal in the case of manually driven vehicles. For automated vehicles it will depend on the dynamics of the brake actuator. It would simply be inversely proportional to the mass of the vehicle if all the vehicles had exactly the same actuators and hydraulic systems, but this is certainly not going to be the case.

Based on our experience with an actual brake system which is in use in a prototype automated passenger class vehicle, we made an educated guess for other classes of vehicles. We assumed that the maximum jerk is limited to 50 $meters/sec^3$ for passenger vehicles, 40 $meters/sec^3$ for buses and 30 $meters/sec^3$ for heavy loaded trucks.

4.2 Uniform versus non-uniform braking.

For a realistic estimation of the theoretical capacity, we have assumed a “typical” maximum deceleration level for each class of vehicles, based on actual test data. Since discrepancies of 10% or more can be clearly seen in the braking capabilities among vehicles of the same class, we have made the assumption of a 10% discrepancy in maximum deceleration between the leader and the follower in the sense that the follower has inferior maximum deceleration capability, an assumption which inevitably generates the need for more spacing.

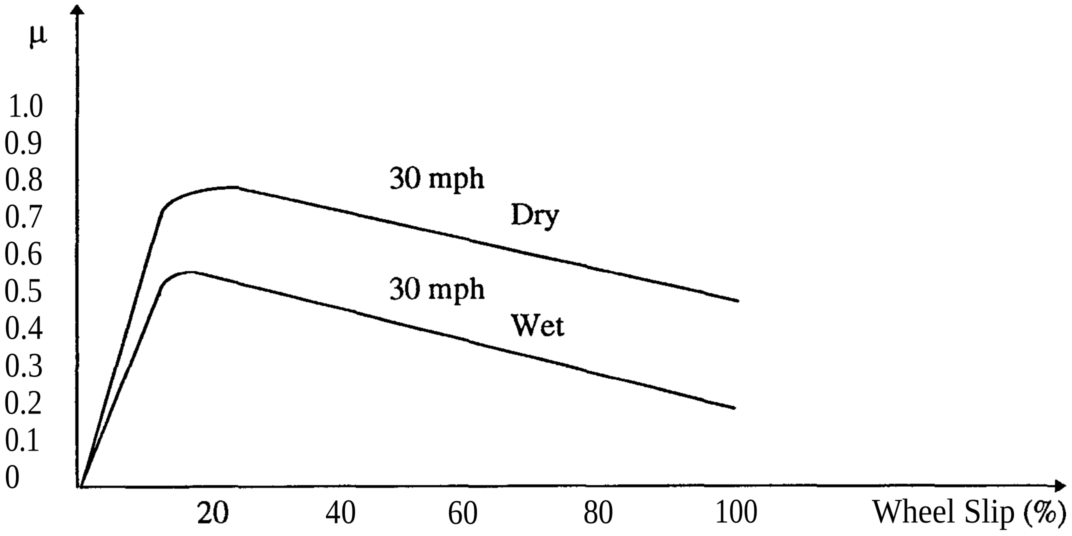

Figure 8: Braking coefficient versus slip.

To be realistic, this discrepancy exists mostly at the limit of the braking capability of the vehicles, when braking occurs in the unstable region where the slope of μ versus wheel slip is negative as seen in figure 8[7]. At that point, demanding slightly higher deceleration results in skidding of the tires and in a sharp reduction in the μ and in overall deceleration. In our effort to represent a realistic worst case scenario, we assumed 10% deviation from the maximum braking capability for the following vehicle in all cases of unrestricted braking, i.e., when the traction of the tires is pushed to the limits. On the other hand, braking by applying less than the maximum deceleration is easier because we can stay away from the unstable region of the μ curve. This can be used to our benefit if we impose a limit in deceleration for all vehicles. This limit is a common denominator that all vehicles should be able to meet by a proper design of their control system. This is the definition of the concept we will henceforth call “uniform braking”. By staying away from the unstable braking region we can almost guarantee a better control of the magnitude of the deceleration. This justifies using only 5% deviation from the nominal braking capability for the follower in the case of uniform braking. Uniform braking is more crucial in platooning where, in the interest of efficiency, vehicles within each platoon have to have similar performance. For completeness and for the sake of comparison, we analyzed the effects of uniform braking both in platooning and non-platooning environments.

The concept that all vehicles should be restricted to a closely matched (i.e. uniform) degree of deceleration is clearly an architectural decision. We assumed that the braking deceleration on a dry road can be restricted to 0.5g for all passenger vehicles, 0.3g for all buses and 0.2g for all heavy trucks. The idea here is to use a number that every vehicle in its respective class can comfortably achieve. This helps guarantee that the deviation from one vehicle to another will be less than 5% in the worst case. So we used a 5% discrepancy in the deceleration of the leading and following vehicle to represent the worst case mismatch in the case of uniform braking.

4.3 Mixing of vehicle classes

The mixing of different classes of vehicles on the same AHS will affect capacity due to the different braking capabilities of the different classes of vehicles. In out analysis we consider three different vehicle classes, possessing fundamentally different characteristics: Passenger vehicles (P), buses (B) and heavy trucks (T).

This leads to the following possible combinations:

(a) PP: A Passenger vehicle leading a Passenger vehicle

(b) PB: A Passenger vehicle leading a Bus

(c) PT: A Passenger vehicle leading a Truck

(d) BP: A Bus leading a Passenger vehicle

(e) BB: A Bus leading a Bus

(f) BT: A Bus leading a Truck

(g) TP: A Truck leading a Passenger vehicle

(h) TB: A Truck leading a Bus

(i) TT: A Truck leading a Truck

We made the following distinctions in mixing possibilities:

a) No mixing.

Traffic consists of passenger vehicles only, i.e. we have 0% mixing. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between all vehicles.

b) Allowed mixing of vehicle classes.

All cases of mixing assume uniform mixing, i.e., the minority vehicles are uniformly distributed among the population of passenger cars. This is a realistic assumption as long as the percentage of mixing is fairly low.

Case 1:

Traffic consisting of passenger vehicles with 5% mixing of buses. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to bus (PB) minimum headway between 5% of the vehicles and bus to passenger vehicle (BP) between 5% of the vehicles.

Case 2:

Traffic consisting of passenger vehicles with 5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to truck (PT) minimum headway between 5% of the vehicles and truck to passenger vehicle (TP) between 5% of the vehicles.

Case 3:

Traffic consisting of passenger vehicles with 2.5% mixing of buses and 2.5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to bus (PB) minimum headway between 2.5% of the vehicles passenger vehicle to truck (PT.) minimum headway between 2.5% of the vehicles bus to passenger vehicle (BP) between 2.5% of the vehicles. and truck to passenger vehicle (TP) between 2.5% of the vehicles.

Case 4:

Traffic consisting of passenger vehicles with 5% mixing of buses. and 5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 80% of the vehicles, passenger vehicle to bus (PB) minimum headway between 5% of the vehicles passenger vehicle to truck (PT) minimum headway between 5% of the vehicles bus to passenger vehicle (BP) between 5% of the vehicles. and truck to passenger vehicle (TP) between 5% of the vehicles.

4.4 Autonomous Vehicles

In the case of autonomous vehicles, each vehicle relies on its own sensors to determine the motion intentions of the leading vehicle. Since there is no vehicle to vehicle communication, each vehicle has to use relative speed and spacing measurements to determine the intentions of the vehicle ahead. Therefore, in calculating a safe intervehicle spacing we consider the following worst case stopping scenario.

The acceleration (actually deceleration) profile of the leading and following vehicles involved in a braking maneuver is assumed to follow the trajectories shown in figure 9.

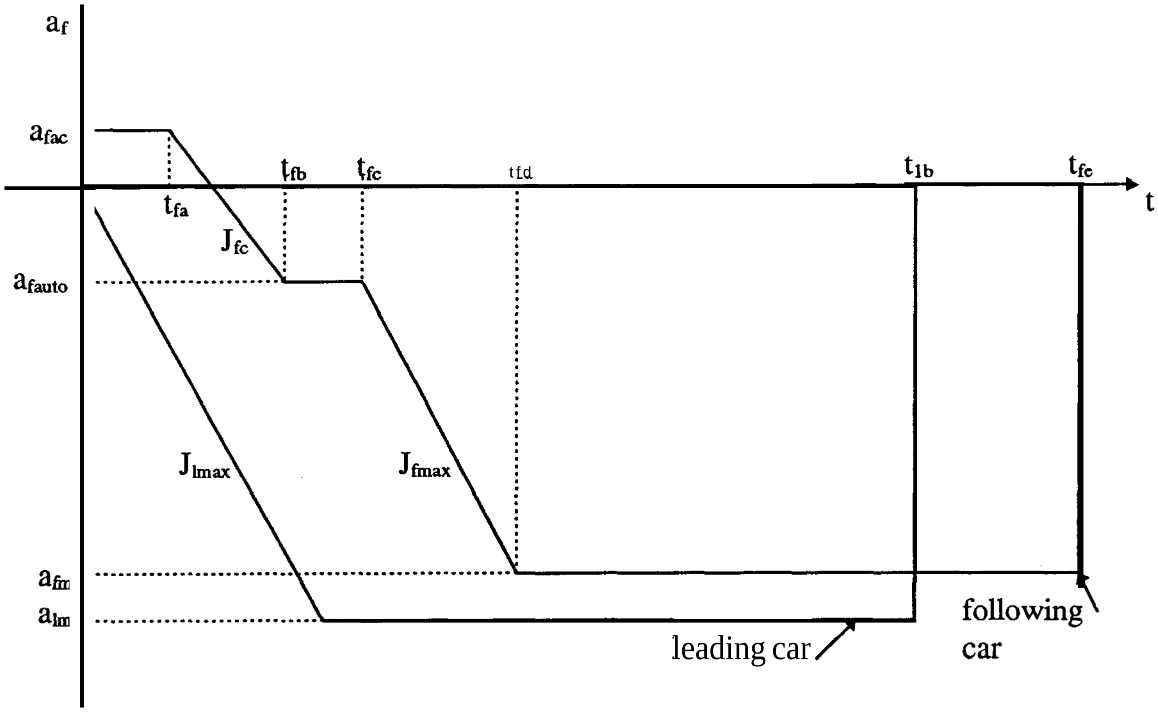

Figure 9: Autonomous vehicles.

The leading vehicle performs emergency braking at time t = 0, at a maximum rate of change (jerk) equal to J_{lmax} until it reaches a maximum deceleration of a_{lm}. The follower, which might have been accelerating initially, at a_{fac} starts decelerating after a detection and brake actuation delay equal to t_{fa} in an effort to maintain the desired spacing. Since initially the follower is not aware that the leader is performing emergency braking, it limits its jerk and deceleration to J_{fc} and a_{fauto} respectively, in an effort to meet the vehicle control objective and at the same time maintain passenger comfort. The follower detects and initiates emergency braking at $t = t_{fc}$. At this time passenger comfort is no longer a crucial issue and braking is done with maximum jerk J_{fmax} and maximum deceleration a_{fm}.

In this section we use the above stopping scenario to calculate the minimum time headway for collision free vehicle following by substituting appropriate numerical values for all the above parameters.

In evaluating the above scenario we adopted a set of likely initial conditions at the onset of braking. The assumptions regarding the initial conditions are the following: The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity 5% higher, i.e. 63 miles per hour and an instantaneous acceleration $a_{fac} = 0.15g$. These conditions represent the realistic scenario that the follower had been performing a position adjustment as in trying to catch up with the leader. Therefore the vehicle is accelerating just before it has to start braking. When the vehicle detects that the leader is braking (which involves a 0.1 sec delay for detection and a 0.1 sec delay in the actuator) it starts braking until it reaches the maximum allowable deceleration a_{fauto} = -O.lg for passenger comfort.

The vehicle initially applies a limited amount of braking because at the onset of braking it is not known if the leader is simply slowing down or performing emergency braking. If the follower applies emergency braking every time it detects the leader slowing down it would be detrimental to the stability of the traffic flow. Therefore the follower applies limited braking at first, with the objective of not upsetting the quality of the ride of the passengers or the position and velocity error of any vehicles behind. For this reason, the Jerk is limited to 5 $meters/sec^3$ during this phase.

Eventually, the follower will detect that the headway is diminishing rapidly and therefore the leader is performing an emergency braking maneuver. We assumed that the detection of emergency braking involves 0.3 seconds of delay.

Using these parameter values, we computed the necessary headways for different road conditions and levels of mixing of classes of vehicles using the algorithm presented in section 2.1. The spacing results are presented in Table 1 for the case of dry road surface. The spacing results for the case of wet road surface are presented in Table 2.

The spacing calculations in tables 1 and 2 are based on the assumption that vehicles can brake with maximum possible deceleration depending on their capabilities. Another possible scenario is to use the concept of uniform braking that limits the maximum deceleration and maximum jerk to values that could be met and used by all vehicles of the same class. These limits will make the braking performance of the vehicles very similar. Using this scenario we calculated spacings based on the vehicle values shown in Table 3. In this case due to uniformity we assume 5% deviation between decelerations of vehicles of the same class. This 5% deviation accounts for inaccuracies in measuring acceleration/deceleration and maintaining the desired one using the on board vehicle controller.

Based on the above spacings the maximum possible throughput referred to as the capacity C measured as the number of vehicles per hour per lane is given by the formula

$$C = (360000V)[(100-2W_T-2W_B)(L_P+h_{PP}V) + W_T(L_P+h_{PT}V+h_{TP}V+L_T)$$

$$+ W_B(L_P+h_{PB}V+h_{BP}V+L_B)]^{-1} \qquad (26)$$

where V is the speed of flow measured in meters/sec, L_p is the length of passenger cars, L_B is the length of buses and L_T is the length of trucks with trailers, in meters. The parameter h_{PP} is the minimum time headway between passenger cars, h_{PT} is the minimum time headway between a passenger car and a truck that follows it, h_{TP} is the minimum time headway between a truck and a passenger car that follows it, h_{PB} is the minimum time headway between a passenger car and a bus that follows it and h_{BP} is the minimum time headway between a bus and a passenger car that follows it, in seconds. W_B is the percentage of buses and W_T is the percentage of trucks in the mix. We use eq. (26) and the numerical results of tables 1, 2 and 3 to calculate the capacity values which are presented in Table 4a.

In eq.26 we assumed that a bus or a truck is always between two passenger vehicles and the passenger vehicle recognizes when its leader is a truck or a bus. This is a reasonable assumption because the radar sensors used for ranging measurements can be designed to be able to distinguish different classes of vehicles. Without this assumption each vehicle has to assume the worst possible situation which is the one where each vehicle treats its leader as a passenger vehicle i.e., a vehicle with the highest possible braking capability. In this case eq. 26 is modified to

$$C = (360000V)[(100-2W_T-2W_B)(L_P+h_{PP}V) + W_T(L_P+h_{PT}V+h_{PP}V+L_T) + W_B(L_P+h_{PB}V+h_{PP}V+L_B)]^{-1} \tag{27}$$

The capacity results for this case are listed in Table 4b.

4.5 Free Agent Vehicles - Infrastructure Supported

In the case of Free Agent Vehicles we assumed the braking scenario shown in figure 10. The use of vehicle to vehicle communication simplifies the task of determining when the leading vehicle is performing emergency braking. The leader at t = 0 starts performing emergency braking. At t = 0 it communicates its intention to the following vehicle. The following vehicle receives the information from the leader and verifies using its own sensors that it has to perform an emergency braking as well.

The assumptions regarding the initial conditions are the same as in the previous case: We assume the leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 63 miles per hour and an instantaneous acceleration of 0.15g, as if the follower had been trying to catch up with the leader.

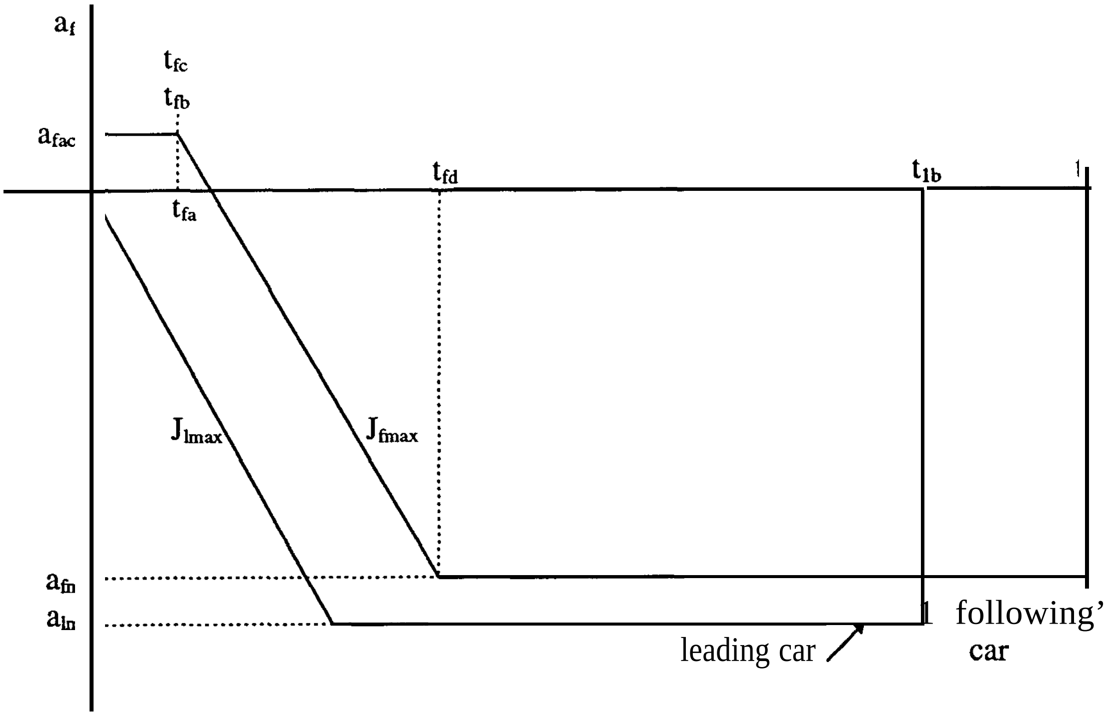

Figure 10: Infrastructure Supported Free Agent vehicles.

When the vehicle detects the leader is braking and at the same time receives the information that this is emergency braking, it bypasses the limited jerk / limited braking stage shown in figure 9 in the previous section. In figure 10, we have clustered the detection and the actuation delay into a single 0.1 seconds delay before the follower applies emergency braking. In effect, the actuation delay is compensated for by the fact that the vehicle knows in advance it will have to apply the brakes, and the brake actuator may be pre-loaded. Therefore in figure 10 we assume $t_{fa} = t_{fc} = 0.1$ sec. The minimum headway results together with the numerical values of the variables shown in figure 10 are presented in tables 5, 6 and 7. Equation (27) is used to calculate capacity for different levels of mixing of different classes of vehicles. The results are shown in Table 8.

4.6 Free Agent Vehicles - Infrastructure Managed

In the case of Free Agent Vehicles with infrastructure management we have assumed that the infrastructure has the primary responsibility of detecting the presence of emergencies and synchronizing the onset of emergency braking of all vehicles involved. This results in the most favorable timing for braking delays.

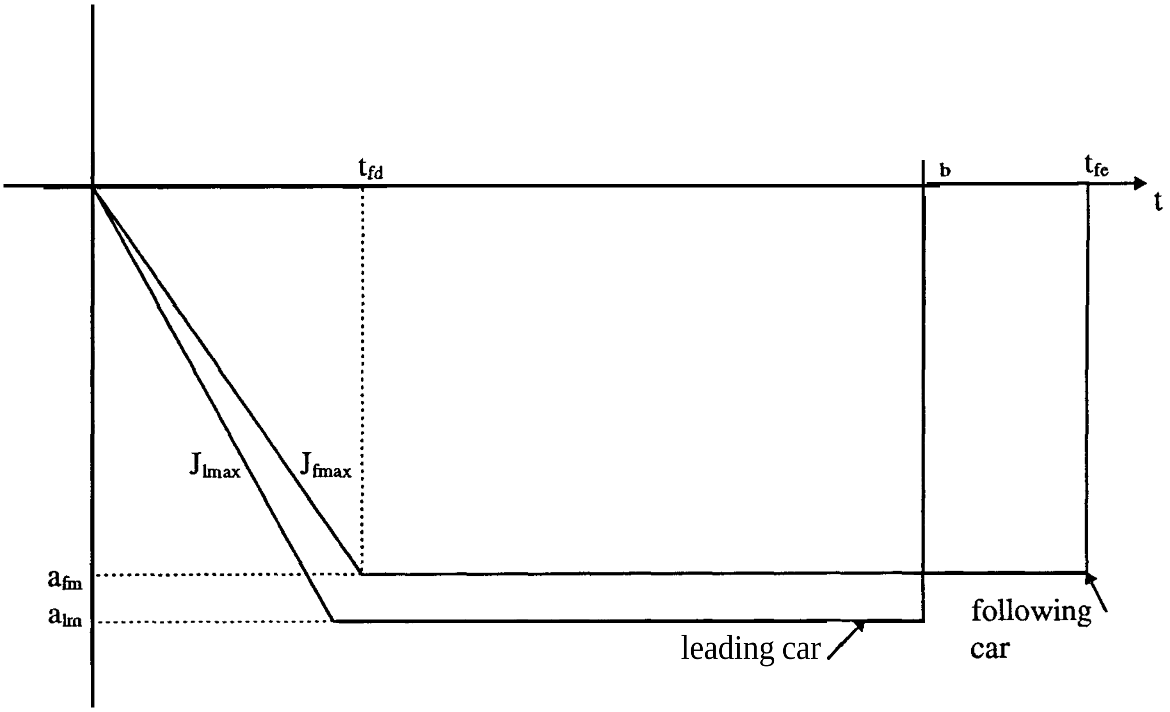

Figure 11: Infrastructure Managed Free Agent vehicles.

The infrastructure may simply issue the command "Begin emergency braking now" and all vehicles receiving this will have to apply maximum braking without further delay. This, not only simplifies the task of determining when the leading vehicle is performing emergency braking but also minimizes the relative delay in propagating the onset of emergency braking from each vehicle to the vehicle behind, effectively down to zero.

We have listed the actuation delay as a single 0.1 seconds delay before each vehicle applies emergency braking, but since all the vehicles receive the command at the same time the relative delay is zero and this is reflected in the value of the parameter t_{fc}. The time t_{fc} represents the total delay between the onset of emergency braking between the leader and the follower and in this case $t_{fc} = 0$.

The assumptions regarding the initial conditions are the same as before: The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 63 miles per hour and an instantaneous acceleration of 0.15g, as if the follower had been trying to catch up with the leader. The minimum headway results together with the numerical values of the variables shown in figure 11 are presented in tables 9, 10 and 11. Equation (27) is used to calculate capacity for different levels of mixing of different classes of vehicles. The results are shown in Table 12.

4.7 Vehicles Platoons without coordinated braking

In the platooning without coordinated braking case, we have assumed that each vehicle notifies the vehicle behind about its braking capabilities and the magnitude and timing of the braking force used.

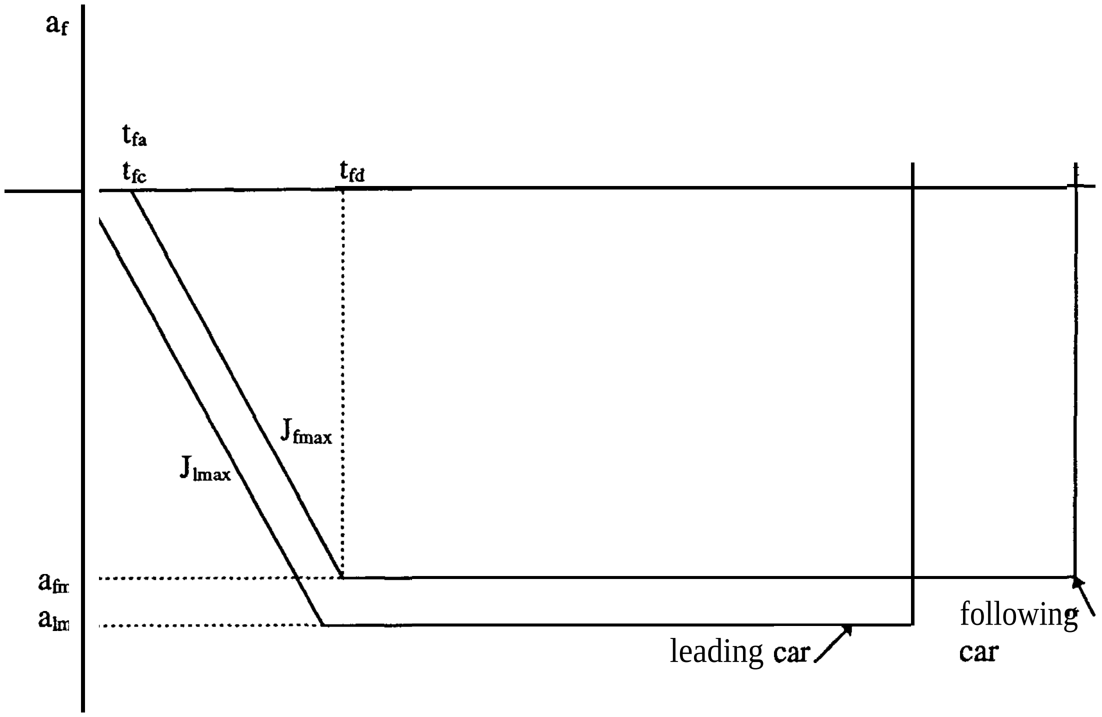

Figure 12: Platoons without coordinated braking.

When the platoon leader detects an emergency, it immediately notifies the vehicle that follows. There will be a delay while the message propagates from each vehicle to the vehicle behind, as well as an actuation delay. But the actuation delay is not affecting the scenario as long as it is approximately the same for each vehicle. We have assumed that the total delay is 0.1 seconds for every vehicle and it is represented by the parameter t_{fa}. Therefore we have accounted for only a 0.1 seconds total delay in propagating the message from each vehicle to the vehicle behind and this becomes the value of the parameter t_{fc}, which represents the delay of the onset of emergency braking.

The assumptions regarding initial conditions are as follows: The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 61.5 miles per hour. Since the platoon protocol involves a much tighter control of individual vehicle velocity than in the case of free agents, only a 2.5% difference is assumed in the initial vehicle velocities. The instantaneous acceleration was also taken to be Og as it would be impossible for a vehicle in a platoon to be accelerating while the vehicle ahead is maintaining constant speed. Both the velocities and the accelerations of vehicles in platoons are expected to be closely coordinated. In addition, for reasons explained earlier we assumed no mixing of vehicle classes.

The inter-platoon spacing depends on the concept used for platoon following. We compared three different concepts.

a) Autonomous platoons, where platoons do not communicate with each other and each platoon relies on its own sensors to detect the motion of a leading platoon. In this case, the inter-platoon spacing is calculated as in the case of autonomous vehicles. Therefore, each vehicle assumes $t_{fc} = 0.1$ seconds and each platoon entity assumes the parameters of autonomous vehicles: $t_{fc} = 0.3$ seconds for 10 car platoons and again $t_{fc} = 0.3$ seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure support. Each vehicle in the platoon assumes $t_{fc} = 0.1$ seconds. Each platoon entity assumes the parameters of free agent infrastructure supported vehicles: $t_{fc} = 0.1$ seconds for 10 car platoons and $t_{fc} = 0.1$ seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure management. Each vehicle in the platoon assumes $t_{fc} = 0.1$ seconds. Each platoon entity assumes the parameters of free agent infrastructure managed vehicles: $t_{fc} = 0$ seconds for 10 car platoons and $t_{fc} = 0$ seconds for 20 car platoons.

The capacity is calculated in each case using the equation:

$$C = (3600\ V\ N) / ((h,\ V + L_p)\ (N-1) + H_{pp}\ V + L_p) \qquad (28)$$

where L_p is the length of each vehicle in the platoon (we have assumed vehicles of same length), h_{pp} is the intra-platoon time headway, H_{pp} is the inter-platoon time headway and N is the number of vehicles in the platoon. The resulting intra-platoon spacing for platoons without coordinated braking can be found in Table 13. Allowing intervehicle collisions at up to 5 miles per hour yields the results of Table 13a. The capacity results with and without intervehicle collisions are presented in Table 14.

4.8 Vehicle Platoons with coordinated braking and no delay

In platooning with coordinated braking we assume that the vehicle in the platoon leader position assumes the primary responsibility of detecting emergencies and notifying each and every vehicle in the platoon. This notification takes place through a network style vehicle to vehicle communications system that minimizes the communication delays. The platoon leader notifies all the vehicle in the platoon about the magnitude of the braking force that is to be applied and also the exact time this is to be applied. This architecture, not only eliminates the need for each vehicle to detect the magnitude of braking and if the braking should be limited or emergency braking, but also can adjust the onset of emergency braking for an effective 0 seconds relative delay, or even to an artificial negative relative delay.

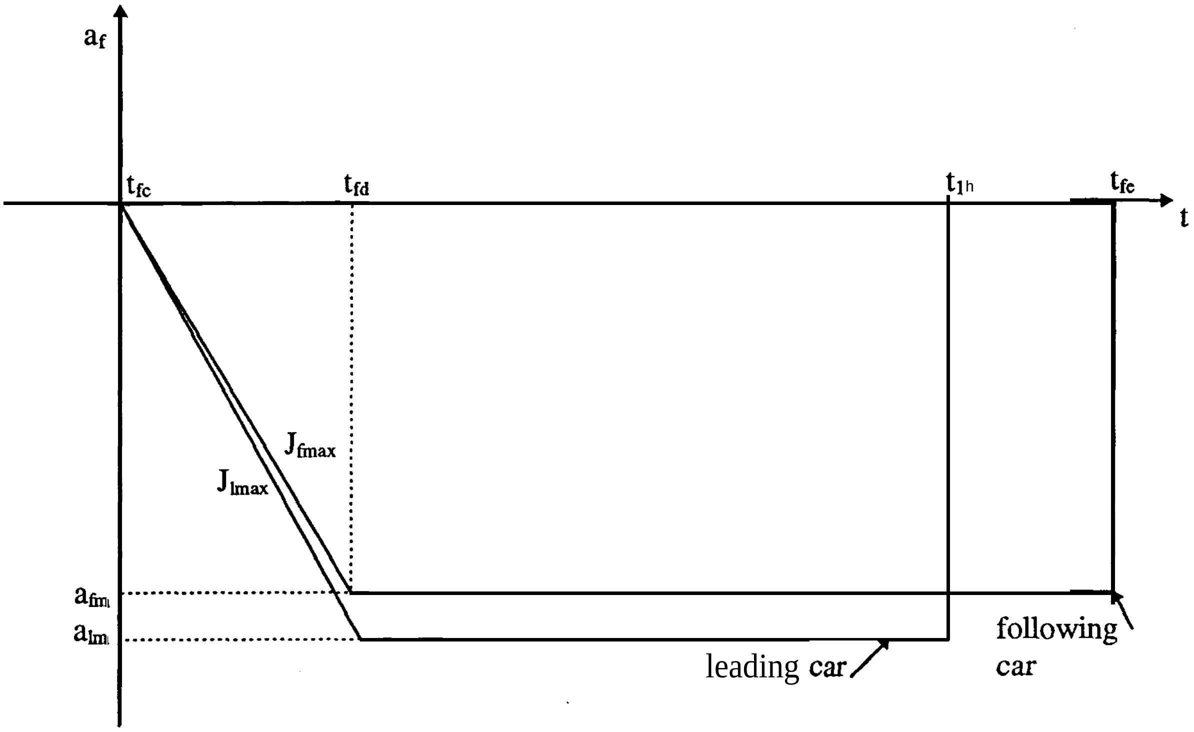

Figure 13: Platoons with coordinated braking and no delay.

The brake actuation delay can be completely compensated for and it is not affecting the scenario as long as it is approximately the same for each vehicle. We have assumed it is 0.1 seconds on every vehicle. Therefore we have made the assumption of exactly 0 seconds total delay for the onset of braking for each vehicle in the platoon and this is the value of the parameter t_{fc} which represents this delay.

The other assumptions regarding the initial conditions are the same as in all architectures involving platoons. The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 61.5 miles per hour. The instantaneous acceleration was also take to be Og as it would be impossible for a vehicle in a platoon to be accelerating while the vehicle ahead is maintaining constant speed. Both the velocities and the accelerations of vehicles in platoons are expected to be closely coordinated.

For the inter-platoon spacing we used and compared three different concepts.

a) Autonomous platoons where the inter-platoon spacing is calculated as in the case of autonomous vehicles. Therefore, each vehicle assumes t_{fc} = 0 seconds and each platoon entity assumes the parameters of autonomous vehicles: t_{fc} = 0.3 seconds for 10 car platoons and again t_{fc} = 0.3 seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure support. Each vehicle in the platoon assumes t_{fc} = 0 seconds. Each platoon entity assumes the parameters of free agent infrastructure supported vehicles: t_{fc} = 0.1 seconds for 10 car platoons and t_{fc} = 0.1 seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure management. Each vehicle in the platoon assumes t_{fc} = 0 seconds. Each platoon entity assumes the parameters of free agent infrastructure managed vehicles: t_{fc} = 0 seconds for 10 car platoons and t_{fc} = 0 seconds for 20 car platoons.

The inter-platoon spacing results for platoons with coordinated braking are calculated using equation (28), based on the intra-platoon spacings presented in Table 15. Allowing intervehicle collisions at up to 5 miles per hour yields the results of Table 15a. The capacity results with and without intervehicle collisions are presented in Table 16.

4.9 Vehicle Platoons with coordinated braking and staggered timing

This case is identical to the previous one except for the purposeful timing of the onset of emergency braking. In the platooning with coordinated braking case we have assumed the vehicle in the platoon leader position assumes the prirnary responsibility of detecting emergencies and notifying each and every vehicle in the platoon. This notification takes place through a network style vehicle to vehicle communications system that minimizes the communication delays. The platoon leader notifies all the vehicles in the platoon about the magnitude of the braking force that is to be applied and also the exact time this is to be applied. This architecture, not only eliminates the need for each vehicle to detect the magnitude of braking and if the braking should be limited or emergency braking, but also can adjust the onset of emergency braking to an artificial negative relative delay.

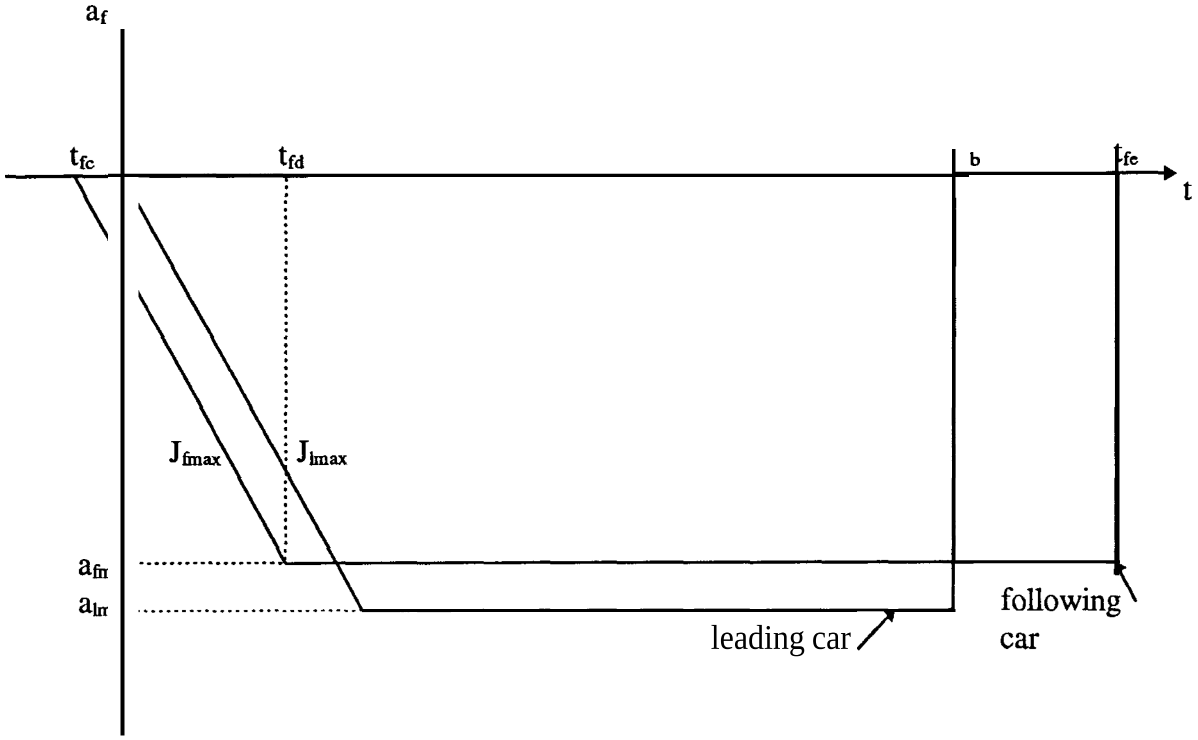

Figure 14: Platoons with coordinated braking with staggered delay.

Therefore we have made the choice of using a 0.1 seconds total delay for the onset of braking for each vehicle in the platoon going from the tail to the head, in the sense that the tail of the platoon is requested to brake first, then the vehicle ahead after a delay of 0.1 seconds, until the command to begin braking becomes effective for the platoon leader. Therefore we used a negative value, -0.1 seconds, as the value of the parameter t_{fc} which represents the relative delay for two consecutive vehicles within the platoon..

We cannot omit mentioning the fact that the platoon leader which detects the presence of emergency is subsequently restrained from braking until every other vehicle in the platoon has begun braking. Therefore, while this architecture allows us to minimize the necessary spacing between vehicles in the platoon, it increases the inter-platoon spacing requirement.

The other assumptions regarding the initial conditions are the same for all architectures involving platoons. For the inter-platoon spacing we used and compared several different concepts.

a) Autonomous platoons where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of autonomous vehicles and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds. Each platoon entity assumes t_{fc} = 1.3 seconds for 10 car platoons and t_{fc} = 2.3 seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of free agent vehicles with infrastructure support and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds. Each platoon entity assumes t_{fc} = 1.1 seconds for 10 car platoons and t_{fc} = 2.1 seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of free agent vehicles with infrastructure management and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds.

Each platoon entity assumes t_{fc} = 1.0 seconds for 10 car platoons and t_{fc} = 2.0 seconds for 20 car platoons.

The capacity is calculated using the following formula:

$$C = (3600\ V\ N) / [(h_{pp}\ V + L_p)\ (N-1) + L_p + (H_{pp} + N\ t_b)\ V]$$

where L_p is the length of each vehicle in the platoon (we have assumed vehicles of same length), h_{pp} is the intra-platoon time headway, H_{pp} is the inter-platoon time headway, N is the number of vehicles in the platoon and t_b is the coordinated braking delay. The spacing is calculated using equation (29) based on the intra-platoon spacings given in Table 17. Allowing intervehicle collisions at up to 5 miles per hour yields the results of Table 17a. The capacity results with and without intervehicle collisions are presented in Table 18.

4.10 Infrastructure Managed Slotting

The infrastructure managed slotting concept involves a different set of assumptions and parameters. We have not presented it in detail in the tables, except one table which shows capacity estimates under this architecture concept. We used the spacing data for passenger cars by assuming a doubling of all communication delays with an additional 3 meters to account for position inaccuracy, due to the inability to utilize space effectively by using the exact slot size for each vehicle. We also assumed that the follower has no initial acceleration. The capacities computed under these assumptions can be found in Table 19.

5 DISCUSSION AND CONCLUSIONS.

The capacity estimates for each concept considered are summarized in Table 20. These results indicate that the capacity is reduced by 30% to 40% by going from dry road to wet road conditions under each concept. The capacity is also reduced by about 10% if all vehicles are required to use lower but similar braking force during emergency stopping. Mixing of different classes of vehicles reduces capacity by about 11% in the case of mixing 2.5% buses and 2.5% trucks with passenger vehicles and by about 23% for 5% buses and 5% trucks. Platooning with coordinated braking gives the highest capacity. Infrastructure managed slotting gives the lowest. The use of vehicle to vehicle communication for notifying vehicles about the onset of braking used in the Free Agent and Platooning based concepts helps increase capacity considerably.

The results developed are based on several assumptions regarding braking capabilities, worst case stopping scenarios etc. We tried to make these assumptions as realistic as possible, by using braking data from actual experiments and by considering a wide class of concepts that cover a wide range of AHS configurations. Despite this effort there are still a lot of uncertainties in the choice of inter-vehicle spacing that need to be addressed. The level of conservatism is one of them and is related to the trade off between safety and capacity. The frequency of failures on AHS operations that lead to the need for emergency braking is another uncertainty that depends on how AHS will be designed and operated. The results of this chapter are therefore qualitative in nature and can be used to compare the requirements and benefits of different AHS concepts.

ACKNOWLEDGMENT

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

The authors would like to thank Steve Shladover, Jacob Tsao, Datta Godbole, and Jim Misener of PATH for many useful discussions on the subject of inter-vehicle spacing.

REFERENCES

[1] C. C. Chien Intelligent Vehicle Highway System (IVHS): "Advanced vehicle Control Systems." ***Doctoral Dissertation,*** University of Southern California, 1994.

[2] Y. Sun and P. Ioannou "A Handbook for Inter-Vehicle Spacing in Vehicle Following." ***California PATH Research Report*** UCB-ITS-PRR-95- 1, University of Southern California, 1995.

[3] J. Glimm and R. Fenton "Dynamic Behavior of Strings of Automated Transit Vehicles." ***SAE Paper Series, No. 770288,*** 1977.

[4] W. L. Calson "Crash Injury Loss: The Effect of Speed, Weight and Crash Configuration. Accident Analysis and Prevention." 1977.

[5] M. Lenard, "Safety Consideration for a High Density Automated Vehicle System." General Electric Company, Erie, Pennsylvania, 1969.

[6] A. Rahimi ***et al.*** "Safety Analysis for Automated Transportation Systems." ***Transportation Science, Page-l -17,*** 197 1.

[7] T. D. Gillespie. "Fundamentals of Vehicle Dynamics", Published by the SAE, 1992

[8] V. R. Vuchic. "Urban Public Transportation, Systems and Technology", Prentice-Hall, 1981

[9] ***Consumer Reports magazine,*** March to September 1995

[10] ***Road and Track magazine,*** April 1989 and October 1995

[11] NHTSA. "Heavy duty vehicle brake research program report no. 1. Stopping capability of air braked vehicles volume 1." Technical Report no. DOT HS 806 738, April 1985

[12] C.C. Chien and P. Ioannou. "Automatic vehicle following." ***Proc. American Control Conference,*** 1992

[13] J.K. Hedric, D. McMahon, V. Narendran, D. Swaroop. "Longitudinal vehicle controller design for IVHS systems." ***Proc. American Control Conference,*** pages 3107-3112, 1991

[14] P. Ioannou, F. Ahmed-Zaid, D. Wuh. "A time headway autonomous intelligent cruise controller: Design and simulation." Technical Report, USC-SCT 92-l 1-O 1, 1992

[15] P. Ioannou and C.C. Chien. "Autonomous intelligent cruise control." ***IEEE Transactions on Vehicular Technology,*** 42:657-672, ***Nov. 1993***

[16] U. Karaslan, P. Varaiya, J. Walrand. "Two proposals to improve freeway traffic flow." Preprint, 1990

[17] B.S.Y. Rao, P. Varaiya, F. Eskafi. "Investigations into achievable capacities and stream stability with coordinated intelligent vehicles." PATH Technical Report, 1992

[18] S. Sheikholeslam, C.A. Desoer "A system level study of the longitudinal control of a platoon of vehicles." ***ASME Journal of Dynamic System, Measurement and Control,*** 1991

[19] S.E. Shladover. "Longitudinal control of automotive vehicles in close-formation platoons." ***ASME Journal of Dynamic Systems, Measurement and Control,*** 113:231-241, 1991

[20] A. Stotsky, C.C. Chien, P. Ioannou. "Robust platoon-stable controller design for autonomous intelligent vehicles." ***Proceedings of the 33rd Conference on Decision and Control,*** Florida, December 1994

[21] S. Swaroop, C.C. Chien, P. Ioannou, J.K. Hedrick. "A comparison of spacing and headway control laws for automatically controlled vehicles." ***Journal of Vehicle System Dynamics,*** 1993

[22] A. Sage, editor, "System Design for Human Interaction." IEEE Press, 1987

[23] S.E. Shladover, C.A. Desoer, J.K Hedrick, M. Tomizuka, J. Wah-and, W.B. Zhang, D.McMahon, S. Sheikholeslam, "Automatic vehicle control developments in the PATH program." ***IEEE Transactions on Vehicular Technology, 40:*** 114-130, 1991

[24] B.W. Stuck, E. Arthurs "A Computer Communications Network Performance Analysis Primer", Prentice Hall, 1985

Appendix A: Vehicular data references

Table A. 1

Braking performance comparisons of popular passenger vehicles on dry and wet roads.
(from Consumer Reports, March 1995) (Family sedans)

	DRY			WET		
	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
Chrysler Cirrus Lxi	60 mph	145 ft	0.83 g	60 mph	167 ft	0.72 g
Mercury Mystique LS	60 mph	140 ft	0.86 g	60 mph	165 ft	0.73 g
Ford Contour GL	60 mph	148 ft	0.81 g	60 mph	158 ft	0.76 g
Honda Accord LX	60 mph	143 ft	0.84 g	60 mph	175 ft	0.69 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, May 1995) (Upscale sedans)

	DRY			WET		
	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
Toyota Avalon XLS	60 mph	129 ft	0.93 g	60 mph	146 ft	0.82 g
Mazda Millenia S	60 mph	136 ft	0.88 g	60 mph	157 ft	0.77 g
Lexus ES300	60 mph	133 ft	0.90 g	60 mph	167 ft	0.72 g
Oldsmobile Aurora	60 mph	136 ft	0.88 g	60 mph	155 ft	0.78 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, June 1995) (Low-Priced Sedans)

	DRY			WET		
	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
Mazda Protege ES	60 mph	135 ft	0.89 g	60 mph	167 ft	0.72 g
Chevrolet Cavalier LS	60 mph	133 ft	0.90 g	60 mph	165 ft	0.73 g
Nissan Sentra GXE	60 mph	142 ft	0.85 g	60 mph	158 ft	0.76 g
Saturn SL2	60 mph	138 ft	0.87 g	60 mph	157 ft	0.77 g

Table A.2

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, July 1995) (Mid-Sized Coupes)

	DRY			WET		
	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**
Dodge Avenger ES	60 mph	129 ft	0.93 g	60 mph	157 ft	0.77 g
Ford Thunderbird LX	60 mph	131 ft	0.92 g	60 mph	153 ft	0.79 g
Chevrolet Monte Carlo 234	60 mph	139 ft	0.87 g	60 mph	165 ft	0.73 g
Buick Riviera	60 mph	133 ft	0.90 g	60 mph	147 ft	0.82 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, August 1995) (Sport-utility vehicles)

	DRY			WET		
	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**
Ford Explorer	60 mph	148 ft	0.81 g	60 mph	181 ft	0.66 g
Jeep Grand Cherokee	60 mph	144 ft	0.84 g	60 mph	159 ft	0.76 g
Chevrolet Blazer	60 mph	156 ft	0.77 g	60 mph	172 ft	0.70 g
Land Rover Discovery	60 mph	143 ft	0.84 g	60 mph	202 ft	0.60 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, S tember 1995) (Small, Cheap Cars)

	DRY			WET		
	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**	Initial Velocity	Stopping Distance	**Deceler/n (avg. g)**
Hyundai Accent 4-door	60 mph	137 ft	0.88 g	60 mph	172 ft	0.70 g
Hyundai Accent 2-door L	60 mph	145 ft	0.83 g	60 mph	204 ft	0.59 g
Toyota Tercel 4-door DX	60 mph	156 ft	0.77 g	60 mph	195 ft	0.62 g
Toyota Tercel 2-door base	60 mph	153 ft	0.79 g	60 mph	193 ft	0.62 g
Geo Metro 4-door LSi	60 mph	151 ft	0.80 g	60 mph	172 ft	0.70 g
Geo Metro 2-door LSi	60 mph	152 ft	0.79 g	60 mph	199 ft	0.60 g

Table A.3

Braking performance comparisons of seven 4-wheel drive vehicles on dry roads and on snow.
(from Road and Track, April 1989)

	DRY			SNOW		
	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
BMW 325iX	60 mph	142 ft	0.85 g	20 mph	75 ft	0.18 g
Audi 90 Quatro	60 mph	143 ft	0.84 g	20 mph	99 ft	0.14 g
VW Quantum GL5	60 mph	145 ft	0.83 g	20 mph	59 ft	0.23 g
Toyota Celica All-Trac	60 mph	146 ft	0.82 g	20 mph	80 ft	0.17 g
Subaru Justy 4WD GL	60 mph	151 ft	0.80 g	20 mph	63 ft	0.21 g
Subaru XT6 4WD	60 mph	153 ft	0.79 g	20 mph	49 ft	0.27 g
Pontiac 6000 STE 4WD	60 mph	N/A	N/A	20 mph	56 ft	0.24 g

Braking performance comparisons on dry roads of passenger vehicles representing extremes
(from Road and Track, October 1995)

	DRY			DRY		
	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
BMW 325i	60 mph	126 ft	0.95 g	80 mph	212 ft	1.01 g
Chevrolet Corvette LT1	60 mph	123 ft	0.98 g	80 mph	225 ft	0.95 g
Ford Mustang Cobra	60 mph	123 ft	0.98 g	80 mph	214 ft	1.00 g
Toyota Supra Turbo	60 mph	122 ft	0.99 g	80 mph	208 ft	1.03 g
Porsche 911 Turbo	60 mph	116ft	1.04 g	80 mph	199 ft	1.07 g
BMW 740i	60 mph	144 ft	0.84 g	80 mph	255 ft	0.84 g
Chevrolet Camaro V6	60 mph	162 ft	0.74 g	80 mph	282 ft	0.76 g
Mercury Villager	60 mph	178 ft	0.68 g	80 mph	293 ft	0.73 g
Toyota Corolla DX	60 mph	186 ft	0.65 g	80 mph	319 ft	0.67 g
VW Golf III GL	60 mph	175 ft	0.69 g	80 mph	301 ft	0.71 g

Braking performance comparisons on dry roads of air braked heavy duty vehicles
(From NHTSA test data)

	Initial Velocity	Stopping Distance	Deceler/n (avg. g)	Initial Velocity	Stopping Distance	Deceler/n (avg. g)
IH School Bus	20 mph	28 ft	0.48 g	60 mph	310 ft	0.34 g
Ford/IH Short School Bus	20 mph	36 ft	0.37 g	60 mph	375 ft	0.32 g
Thomas Transit Bus	20 mph	36 ft	0.37 g	60 mph	292 ft	0.41 g
Ford 4 by 2 Truck	20 mph	36 ft	0.37 g	60 mph	331 ft	0.36 g
GMC 6 by 4 Truck	20 mph	54 ft	0.25 g	60 mph	528 ft	0.23 g
Mack 6 by 4 Truck	20 mph	44 ft	0.30 g	60 mph	363 ft	0.33 g
Peterbilt 4 by 2 Tractor	20 mph	39 ft	0.34 g	60 mph	407 ft	0.30 g
Ford 4 by 2 Tractor	20 mph	30 ft	0.45 g	60 mph	289 ft	0.42 g
White 4 by 2 Tractor	20 mph	42 ft	0.32 g	60 mph	366 ft	0.33 g
IH 6 by 4 Tractor	20 mph	51 ft	0.26 g	60 mph	475 ft	0.25 g
Western Star 6 by 4 tractor	20 mph	46 ft	0.29 g	60 mph	431 ft	0.28 g
Stuart Conv. auto hauler	20 mph	43 ft	0.31 g	60 mph	434 ft	0.28 g
Stuart Stringer auto hauler	20 mph	39 ft	0.34 g	60 mph	354 ft	0.34 g

Appendix B: Tables of results

Table B.1 Symbols and Notation

PP: Passenger car leader, Passenger car follower
PB: Passenger car leader, Bus follower
PT: Passenger car leader, Truck follower

BP: Bus leader, Passenger car follower
BB: Bus leader, Bus follower
BT: Bus leader, Truck follower

TP: Truck leader, Passenger car follower
TB: Truck leader, Bus follower
TT: Truck leader, Truck follower

L_P: Length of a passenger vehicle, in meters
L_B: Length of a bus, in meters
L_T: Length of a truck with trailer, in meters

h_{PP}: Minimum time headway between Passenger car leader Passenger car follower, in sec.
h_{PB}: Minimum time headway between Passenger car leader, Bus follower, in seconds
h_{PT}: Minimum time headway between Passenger car leader, Truck follower, in seconds
h_{BP}: Minimum time headway between Bus leader, Passenger car follower, in seconds
h_{BB}: Minimum time headway between Bus leader, Bus follower, in seconds
h_{BT}: Minimum time headway between Bus leader, Truck follower, in seconds
h_{TP}: Minimum time headway between Truck leader, Passenger car follower, in seconds
h_{TB}: Minimum time headway between Truck leader, Bus follower, in seconds
h_{TT}: Minimum time headway between Truck leader, Truck follower, in seconds

V_{lo}: Leading Vehicle initial Velocity, in miles per hour.
V_{fo}: Following Vehicle initial Velocity, in miles per hour.
A_{lm}: The maximum achievable deceleration of the leading vehicle in g
A_{fm}: The maximum achievable deceleration of the leading vehicle in g
J_{lmax}: The maximum achievable jerk of the leading vehicle in meters/sec^3
J_{fmax}: The maximum achievable jerk of the following vehicle in meters/sec^3
μ_{lmax}: The maximum road-tire friction coefficient (dimensionless)
μ_{fmax}: The maximum road-tire friction coefficient (dimensionless)
A_{fauto}: The acceleration value under automatic brake control during soft braking, in g
A_{fac}: The initial acceleration value during vehicle following, in g
J_{fc}: The jerk value under automatic brake control during soft braking, in meters/sec^3
t_{fa} : Detection and brake actuation delay applicable to the following vehicle, in seconds.
t_{fc}: The time at which the following vehicle starts the emergency braking maneuver, in seconds

Table 1: Autonomous Vehicles, Dry road surface

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{fc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	0.66	2.63	3.97	0.063	1.04	2.37	0.045	0.171	1.28
min headway	m	18.71	74.2	111.7	1.79	29.15	66.63	1.29	4.81	36.07

Table 2: Autonomous Vehicles, Wet road surface

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
μ_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{fc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	1.03	4.99	7.65	0.065	1.77	4.43	0.049	0.211	2.26
min headway	m	29.01	140.7	215.6	1.847	49.77	124.7	1.379	5.937	63.57

Table 3: Autonomous Vehicles - Uniform braking - Dry road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{fc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	0.72	2.73	5.25	0.075	1.00	3.52	0.045	0.100	1.36
min headway	m	20.33	76.83	147.7	2.112	28.27	99.15	1.290	2.833	38.19

Table 4: Autonomous **Vehicles.** Capacity Estimates under different road conditions, with and without detection ability.

a) With Identification of different vehicle classes	Dry road surface	Wet road surface	Uniform braking
0% mixing	4116	2860	3850
5% buses	3746	2516	3525
5% trucks	3458	2278	3096
2.5% buses + 2.5% trucks	3596	2391	3297
5% buses + 5% trucks	3193	2054	2882
b) No identification of different vehicle classes	**Dry road surface**	**Wet road surface**	**Uniform braking**
0% mixing	4116	2860	3850
5% buses	3631	2432	3416
5% trucks	3356	2207	3007
2.5% buses + 2.5% trucks	3488	2314	3198
5% buses + 5% trucks	3026	1943	2735

Table 5: Free Agent Vehicles - Infrastructure Supported - Dry road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{fa}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	0.463	2.432	3.762	0.027	0.832	2.162	0.021	0.088	1.077
min headway	m	13.03	68.50	106.0	0.784	23.45	60.91	0.600	2.466	30.35

Table 6: Free Agent Vehicles - Infrastructure Supported - Wet road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
μ_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{fa}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	0.828	4.792	7.451	0.037	1.564	4.224	0.028	0.140	2.054
min headway	m	23.34	135.0	210.0	1.039	44.07	119.0	0.800	3.951	57.85

Table 7: Free Agent Vehicles - Infrastructure Supported - Uniform braking - Dry road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{fa}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	0.519	2.525	5.041	0.036	0.800	3.317	0.023	0.058	1.151
min headway	m	14.64	71.11	142.0	1.030	22.55	93.44	0.668	1.638	32.43

Table 8: Free Agent Vehicles - Infrastructure Supported. Capacity Estimates

	Dry road surface	Wet road surface	Uniform braking
0% mixing	5400	3425	4942
5% buses	4730	2923	4377
5% trucks	4276	2605	3730
2.5% buses + 2.5% trucks	4492	2755	4025
5% buses + 5% trucks	3845	2304	3400

Table 9: Free Agent Vehicles - Infrastructure Managed - Dry road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{fa}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	0.36	2.327	3.655	0.014	0.73	2.056	0.012	0.054	0.971
min headway	m	10.15	65.55	103.0	0.409	20.5	57.91	0.326	1.538	27.35

Table 10: Free Agent Vehicles - Infrastructure Managed - Wet road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
μ_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{fa}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	0.726	4.687	7.344	0.025	1.460	4.117	0.019	0.109	1.947
min headway	m	20.46	132.0	206.9	0.697	41.12	116.0	0.546	3.066	54.85

Table 11: Free Agent Vehicles - Infrastructure Managed - Uniform braking - Dry road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
μ_{lmax}		1	1	1	1	1	1	1	1	1
μ_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{fa}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	0.416	2.43	4.93	0.021	0.695	3.21	0.014	0.040	1.042
min headway	m	11.72	68.13	138.9	0.602	19.56	90.36	0.404	1.123	29.36

Table 12: Free Agent Vehicles - Infrastructure Managed. Capacity Estimates

	Dry road surface	Wet road surface	Uniform braking
0% mixing	6437	3823	5810
5% buses	5472	3197	5018
5% trucks	4873	2820	4184
2.5% buses + 2.5% trucks	5155	2997	4563
5% buses + 5% trucks	4299	2464	3756

Table 13: Platoons without coordinated braking

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1
min headway	sec	0.37	0.65	0.38
min headway	m	10.26	17.93	10.48

Table 13a: Platoons without coordinated braking allowing Smph collisions

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1
min headway	sec	0.36	0.63	0.36
min headway	m	9.90	17.22	9.94
max headway	sec	0.076	0.186	0.277
max headway	m	2.09	5.14	7.61

Table 14: Platoons of passenger vehicles without coordinated braking **(tfc=** 0.1 **sec).** Capacity Estimates with/without Smph collisions.

A. Autonomous Platoons	Dry road surface	Wet road surface	Uniform braking
10 car platoons	621716090	**4171/4059**	613915955
20 car platoons	639916257	**4280/4156**	**6349/6142**
B. Free Agent Infrastructure Supported Platoons			
10 **car** platoons	645316317	427614158	636916172
20 car platoons	**6522/6374**	433514207	647016255
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	658016438	**4331/4211**	649516289
20 car platoons	658616435	436314234	653416314

Table **15: Platoons** with coordinated braking - no delay

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	0	0	0
min headway	sec	0.27	0.55	0.28
min headwav	m	7.51	15.18	7.73

Table **15a:** Platoons with coordinated braking - no delay - allowing **5mph** collisions

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	0	0	0
min headway	sec	0.26	0.52	0.26
min headway	m	7.16	14.47	7.20
max headway	sec	0.109	0.214	0.26
max headway	m	3.00	5.89	7.20

Table 16: Platoons of passenger vehicles with coordinated braking (tfc= 0 **sec).**
Capacity Estimates with/without **5mph** collisions

A. Autonomous Platoons	Dry road surface	Wet road surface	Uniform braking
10 car platoons	739117217	**4671/4531**	728017028
20 car **platoons**	**7733/7532**	**4841/4683**	**7660/7365**
B. Free Agent Infrastructure Supported Platoons			
10 car platoons	772717537	**4802/4654**	76071733 1
20 car **platoons**	**7913/7703**	491 **1/4748**	**7836/7529**
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	**7909/7710**	**4872/4720**	778617498
20 car platoons	800717792	**4947/4782**	793017615

Table 17: Platoons with coordinated braking. (Delay of 0.1 **sec** from tail to head)

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	-0.1	-0.1	-0.1
min headway	sec	0.173	0.452	0.18
min headway	m	4.76	12.43 1	4.98

Table 17a: Platoons with coordinated braking. (Delay of 0.1 **sec** from tail to head) - allowing 5mph collisions

		DRY	WET	UNIFORM
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
μ_{lmax}		1	0.5	1
μ_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	-0.1	-0.1	-0.1
min headway	sec	0.160	0.426	0.164
min headway	m	4.41	11.72	4.50
max headway	sec	0.116	0.229	0.164
max headway	m	3.19	6.30	4.50

Table 18: Platoons of passenger vehicles with coordinated braking **(tfc=** -0.1 **sec).**
Capacity Estimates with/without **5mph** collisions

A. Autonomous Platoons	Dry road surface	Wet road surface	Uniform braking
10 car platoons	722617060	460414468	7108/6889
20 car platoons	763717442	4802/4646	7551/7291
B. Free Agent Infrastructure Supported Platoons			
10 car platoons	754017359	472914586	7408/7171
20 car platoons	7808/7604	4870/4709	7716/7445
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	771417525	4797/4649	757917330
20 car platoons	790117692	4905/4743	7808/7530

Table 19: Infrastructure Managed Slotting. Capacity Estimates

	Dry road surface	Wet road surface	Uniform braking
0% mixing	4047	2826	3773

Table 20: Capacity comparisons

Capacity without platooning	0% mixing of ehicle			5% mixing of buses			5% mixing of truck		
	Dry	Wet	Uni-form	Dry	Wet	Uni-form	Dry	Wet	Uni-form
Autonomous Vehicles with class identification	4116	2860	3850	3746	2516	3525	3458	2278	3096
Autonomous Vehicles without class identification	4116	2860	3850	3631	2432	3416	3356	2207	3007
Free Agents - Infrastructure Supported with class identification	5400	3425	4942	4730	2923	4377	4276	2605	3730
Free Agents - Infrastructure Managed with class identification	6437	3823	5810	5472	3197	5018	4873	2820	4184
Infrastructure Managed Slotting	4047	2826	3773						
				2.5% buses+ 2.5% tru ks			5% buses+ 5% trucks		
				Dry	Wet	Uni-form	Dry	Wet	Uni-form
Autonomous Vehicles with class identification				3596	2391	3297	3193	2054	2882
Autonomous Vehicles without class iden tification				3488	2314	3198	3026	1943	2735
Free Agents - Infrastructure Supported'with class identification				4492	2755	4025	3845	2304	3400
Free Agents - Infrastructure Managed with class identification				5155	2997	4563	4299	2464	3756
Capacity with piatooning	1 r platoons			20 car platoons					
	Dry	Wet	Uni-form	Dry	Wet	Uni-form			
Autonomous platoons without coordinated braking	6090	5652	5955	5257	5977	6142			
Infrastructure supported platoons without coordinated braking	6312	5843	6166	5372	6081	6252			
Infrastructure managed platoons without coordinated braking	5434	5947	6283	5433	6137	6311			
Autonomous platoons with coordinated braking	7217	4531	7028	7532	4683	7365			
Infrastructure supported platoons with coordinated braking	7531	4652	7323	7700	4747	7524			
Infrastructure managed platoons with coordinated braking	7704	4718	7489	7789	4780	7611			
Autonomous platoons with delayed braking	7060	4468	6889	7442	4646	7291			
Infrastructure supported platoons with delayed braking	7359	4586	7171	1604	4709	7445			
Infrastructure managed platoons with delayed braking	7525	4649	7330	1692	4743	7530			