

UC Berkeley

Research Reports

Title

Intelligent Vehicle/highway System Safety: Multiple Collisions In Automated Highway Systems

Permalink

<https://escholarship.org/uc/item/6vm8z32v>

Author

Hitchcock, Anthony

Publication Date

1995

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

Intelligent Vehicle Highway System Safety: Multiple Collisions in Automated Highway Systems

Anthony Hitchcock

**California PATH Research Report
UCB-ITS-PRR-95-10**

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

Report for MOU 19

April 1995

ISSN 1055-1425

**Intelligent Vehicle/Highway System Safety:
Multiple collisions in Automated Highway Systems**

by

**A. Hitchcock, Ph.D.
PATH/ITS, University of California (Berkeley)**

ABSTRACT

A comparison is drawn between the casualty rates per failure on an automated highway system (AHS) according to the longitudinal control configuration used. It is suggested that the most important failure of this system is one in which brakes fail full on. The inverse failure - brakes will not apply—must be avoided by system designers. Incident for incident, it is clearly the more dangerous of the two, and the brakes-on failure is therefore the one selected in a "fail-safe" scheme. Further, unlike the "no-brakes" failure its consequences are sensitive to the control system configuration.

This possibility was the original reason put forward for selection of platooning as the operational mode for AHS. The comparison is drawn between close-spaced platooning, vehicle following of the types used in Autonomous Intelligent Cruise Control (AICC) and Cooperative Intelligent Cruise Control, and a point-following configuration (PFC). The model used permits evaluation of the consequences of a failure, allowing for the multiple collisions that usually ensue.

In terms of casualties per failure, short-spaced platooning is over ten times better than AICC at high capacities. Point Follower Control is better, in these terms, than platooning in ideal conditions (full, accurate knowledge by the system of the deceleration capabilities of all vehicles). However, if the information is not precise, casualties per failure increase many times. If it is desired that casualties due to this failure be much less than the present rate for all causes, the required reliability of the control system can be deduced. It is shown that the reliability of the control system against this form of failure for platooned systems needs to be around 0.1% failures/year/vehicle (mean time between failures = 100,000 hours operating time) if this target is to be achieved.

Some general observations are made about the impact of AICC in mixed traffic. It appears that the safety record of this device will at first be good, but will diminish if such systems are mounted, and used on the great majority of cars.

ACKNOWLEDGMENTS

CDS data reported here was provided by Ms Tonya Linsey of the National Center for Statistics and Analysis, National Highway Traffic Safety Administration. The author wishes to express his appreciation of the help provided here.

CONTENTS

ABSTRACT	iii
ACKNOWLEDGMENTS	v
TABLE OF CONTENTS	vii
LIST OF FIGURES	ix
LIST OF TABLES	xi
INTRODUCTION	1
SEVERITY OF INJURY	2
VEHICLE-RELATED PARAMETERS	6
MODEL	13
Initial condition: numbers of vehicles.....	15
Dependence on Flow	20
Effect of Speed	21
RESULTS	21
Platoons	22
Point Follow Control (PFC).....	24
AICC.....	28
Mixed-flow AICC	32
CICC.....	35
Absolute Magnitude of problem.....	37
Distribution of Casualties.....	40
CONCLUSIONS.....	40
PROGRAMS	42
REFERENCES	43

LIST OF FIGURES

FIGURE 1 Cumulative probabilities, P%, of f-values. Dry Conditions	9
FIGURE 2 Casualties, C (AIS \geq 2) per 100 incidents. Platoon in dry conditions. 1, 4, and 10 m spacings	23
FIGURE 3 Casualties, C, (AIS \geq 2) per 100 incidents. Platoons in wet conditions. 1, 4, and 10 m spacings	23
FIGURE 4 Casualties, C, (AIS \geq 2) per 100 incidents. Point follower control. Wet and dry conditions as indicated	27
FIGURE 5 Casualties, C, (AIS \geq 2) per 100 incidents. Dry conditions. AICC on reserved lane 31	31
FIGURE 6 Casualties, C, (AIS \geq 2) per 100 incidents. AICC on reserved lane. Wet conditions. 31	31
FIGURE 7 Casualties, C, (AIS \geq 2) per 100 incidents. AICC mixed with other traffic. Dry conditions	34
FIGURE 8 Casualties, C, (AIS \geq 2) per 100 incidents. AICC mixed with other traffic. Wet conditions	34
FIGURE 9 Casualties, C, (AIS \geq 2) per 100 incidents. CICC, dry conditions	36

LIST OF TABLES

TABLE 1 Capacity and casualty rates at capacity: platoons.....	22
TABLE 2 Capacity and casualty rates at capacity: PFC	26
TABLE 3 Capacity and casualty rates at capacity: AICC only	30
TABLE 4 Capacity and casualty rates in equipped vehicles at capacity: mixed-flow AICC ..	33
TABLE 5 Capacity and casualty rates: CICC	37

Intelligent Vehicle/Highway System Safety: Multiple collisions in Automated Highway Systems

by

A. Hitchcock, Ph.D.

PATH/ITS, University of California (Berkeley)

INTRODUCTION

An Automated Highway System (AHS) is designed to reduce congestion, partly by increasing the flow of vehicles on an automated lane (AL) by a factor of three or more. Spacings at which human drivers are too liable to run into the vehicle ahead can, it is suggested, be made safe by the use of automatic controls, not subject to human error. Thus congestion is relieved. Nevertheless, it is recognized that mechanical failures of both vehicles and control systems are possible, though hopefully rare. With a greatly increased lane flow, such failures can credibly lead on to accidents in which many people are hurt.

Shladover (1978) pointed out that if a vehicle is following another which decelerates abruptly the resulting collision occurs at low relative speed if the vehicles are either well-separated or very close together. Large separations between all pairs is inconsistent with the desired capacity. He was led on to propose motion in closely-spaced *platoons* containing 3-20 vehicles. The platoons are so far apart that the follower can stop without colliding if the leader suffers a mishap. Today, this concept lies at the basis of some AHS designs.

Others, notably *Autonomous Intelligent Cruise Control* (AICC), *Cooperative Intelligent Cruise Control* (CICC) and *Point Follower Control* (PFC) use other configurations. In AICC, autonomous controls are used by each vehicle to keep a desired distance behind its predecessor, which we take to be constant for all vehicles at any one speed. In CICC, the same result is achieved with communication between vehicles. AICC and CICC, unlike the other configurations, can operate in the presence of manually-controlled vehicles. We consider this *mixed-flow AICC* as well as *AICC-only*. Mixed-flow CICC is possible, but has no obvious

attractions. It will become apparent that it will not be very different from mixed-flow AICC. In PFC a vehicle stays in a *slot* defined by the infrastructure, which moves along the AL.

In all cases, if a failure does occur, multiple collisions are possible. The object of this paper is to extend Shladover's (1978) original ideas to cover multiple collisions with realistic distributions of values of the parameters involved and to indicate their effects on death and injury in a quantified way.

SEVERITY OF INJURY

In this paper the *Abbreviated Injury Scale* (AIS) (see AAAM, 1980) is used as the measure of human injury. AIS is a clinical measure of the severity of an injury at first presentation. It is but poorly correlated with longer-term disability (See Galasko *et al*, 1986). We shall speak mainly in terms of AIS 2, which the clinicians call "moderate injury". Roughly, an injury of AIS 2 is not life-threatening but requires several days' hospitalization. A compound fracture and an injury to the inner ear are both AIS 2. Most simple fractures are AIS 1.

In road safety practice, the terms "injury" and "serious injury" are not clinically defined. In California, at least, an injury is any visible damage or complaint of pain. Where the phrase "serious injury" is used it is usually defined in terms of hospitalization or not. Thus, almost all AIS 2 injuries are serious injuries, in this sense, and so are many AIS 1 ones. Complaint of pain, without detectable tissue damage, is often AIS 0. Thus, in spite of the clinicians' "moderate injury" term, the injuries (AIS ≥ 2) in terms of which this evaluation is made, are well into the area which road safety people classify as "serious". AIS 2 injuries represent 10% to 15% of "serious injuries" as defined in Police Accidents reports.

Except in the infrequent occurrences of occupant ejection or penetration of the passenger compartment injuries are generated by collisions between the occupant and his own car interior, and the relevant relative speed is the change in speed of the vehicle in collision. We call this *delta-V*. Delta-V depends on the relative masses of two colliding vehicles, as well as their relative speed.

The National Center for Statistics and Analysis, an office of the National Highway Traffic Safety Administration (NHTSA) provided the following data for all vehicles with front damage

only involved in accidents recorded in the National Center's Crashworthiness Data System (CDS) in the years 1990 and 1991.

- i. Numbers of all vehicles, and numbers of deaths, tabulated across values of delta-V.
- ii. Numbers of all vehicles, and numbers containing injuries of AIS values 0, 1, ...6, again across values of delta-V.
- iii. Vehicle masses.

It is well attested, e.g. in Ricci, (1980) and also in the CDS data (see Acknowledgements) that when the delta-V change corresponds to a blow from the rear, injuries are much less frequent or serious. Injuries arising in this way were ignored in this work.

There were consistent values of zero for the higher AIS values ($AIS \geq 3$) at lower speeds. It is apparent that there is a threshold. We took the threshold to be at 3.3 m/s (7.5 mph). We then experimented, using graph paper and a straight edge, with various analytical forms for the relationships. None of these have any theoretical justification, and the use of statistical methods such as maximum likelihood to determine the constants is therefore inappropriate. Further the data themselves are sparse at speeds below 5 m/s and uncertainties here are large. The following formulas fit the data below delta-V values of 20 m/s (≈ 45 mph) to within 10% or so.

$$\begin{aligned}
 \text{Prob(fatality)} &= 3.2 \cdot 10^{-5} \cdot (V - 3.3)^{3.2} && \} \\
 \text{Prob(AIS} \geq 3) &= 6.2 \cdot 10^{-3} \cdot (V - 3.3)^{1.5} && \} \quad \dots(1) \\
 \text{Prob(AIS} \geq 2) &= 6.1 \cdot 10^{-3} \cdot V^{1.7} && \} \\
 \text{Prob(AIS} \geq 1) &= 1.0 - \exp(-(0.143 \cdot V + 0.000806 \cdot V^3))
 \end{aligned}$$

where V is in m/s: 3.3 m/s = 7.5 mph.

At higher delta-V values the formulas are clearly inaccurate —the values can exceed unity, and the values for $AIS \geq 3$ exceed those for fatality. (In fact, in the range 15 - 25 m/s the probability of fatality is underestimated, but that for $AIS > 3$ is underestimated even more.) However, collisions between vehicles moving in the same direction at speeds of less than 30 m/s, which is what we consider here, do not lead to values of delta-V exceeding 20 m/s, so that the defects in these formulas are of no significance in the context of this work. (See the work of Joksch (1993), who used no threshold and obtained a different relation.)

Strictly, these values are valid only for single collisions—in the present state of the art one cannot deduce delta-V from examination of accident debris if there are multiple collisions. In this work we quote the probability of injury arising from the first forward collision suffered by each vehicle. This clearly leads to an underestimate of the extent of injury. It is may be biased between the alternative control schemes, for at closer spacings more multiple collisions are likely. It should also be remembered that the data, especially for the more serious injuries, are very sparse at speeds below 5 - 8 m/s, and the uncertainties are correspondingly large. Any errors here are unbiased between control schemes.

VEHICLE-RELATED PARAMETERS

In this work we examine the consequences if a vehicle in an automated mode suffers a longitudinal control failure. Longitudinal controls, like other electro-mechanical systems, will be subject to failure, but a designer may be able to influence the relative probability of alternative modes of failure—this is often called "fail-safe" design. A braking system may fail in one of four ways:

1. The brakes lock off—i.e. they cannot be applied. Less serious variants here include excessive delay in braking, or less torque applied than is ??? In a safety study like this, it is necessary to consider the extreme case.
2. The brakes lock in their current position. Since brakes are normally off this will usually be the same as 1.
3. Brakes lock on. That is to say, full braking starts and will continue until the vehicle comes to rest.
4. Brakes are applied, on and off, randomly. This is less serious than 3, but may approach it.

Failures 1 and 2 are likely to result in a serious accident every time a vehicle has space ahead of it, and traffic ahead reduces speed. This will routinely occur as a vehicle exits from the system. Designers are therefore likely to select failure 3 as the "fail-safe" mode. (Failure 4 is likely to be difficult to design for—in its more serious forms it is very like failure 3.)

It is the consequences of failure 3 that we examine here. In doing so we imply that the possibility that braking vehicles will strike some fixed part of the infrastructure, or enter an adjacent lane and hit vehicles there has been eliminated. This can perhaps be ensured by either by the presence of an appropriate "fence" or "divider" between lanes (see Hitchcock, 1991) or by appropriate performance of the steering and lateral control systems after collision.

It is intuitively clear (and it has been verified in this work) that one of the factors affecting the severity of the more severe collisions is the variability between vehicles. In any of the schemes, if vehicles were able to respond instantly to a change in speed of their predecessors and all had identical limitations on their accelerations, there would be no collisions. But this is not so. The maximum deceleration that a vehicle can achieve depends on the condition of its brakes, and, in wet weather, on the condition of its tires. In well maintained vehicles these do vary, but not very much. However, some vehicles are not well-maintained. We have been able to find no data about the range of variation in practice. We think that worn tires are much more common than worn brakes, and observations in local car parks suggest that one-third of vehicles have worn tires. For a more detailed discussion of the possible effects here, see Hitchcock 1994.

Deceleration forces achieved during braking depend on both the friction between brake and drum in the vehicle, and between tire and road. The topic has been widely studied: what follows here reflects common knowledge. usually the maximum rate of deceleration achievable is limited by friction at the road. If no large lateral forces intrude (i.e. if the vehicle is not also attempting to turn sharply) and if the wheel does not lock and if there is no standing water on the road, the deceleration is tolerably independent of speed, and can be described by a simple constant coefficient of friction. Traffic on an AHS is not called on to turn sharply. If the wheel locks, but the other conditions apply, the frictional forces are reduced, but the effective coefficient of friction is still constant. Non-linearities become significant only if lateral accelerations come into play, or if there is standing water. Automated highway systems will run on heavily-trafficked roads which will be maintained well enough to avoid standing water in most cases. In exceptionally inclement weather, speeds will on doubt be limited—we do not consider this case here.

If a vehicle has poor brakes, the deceleration may be limited by friction at the brake drums. Here, the maximum force available can decline with time as the brake becomes heated. But heating during a single stop, even from high speed, is not a very large effect.

In this paper therefore the maximum deceleration that a vehicle can maintain is assumed to be independent of speed and equal to fg m/s/s where $g(\approx 10 \text{ m/s/s})$ is the acceleration of gravity. f is thus analogous to a constant coefficient of friction. We assume here, that for both brakes and tires, there are two populations. The majority have f -values evenly distributed between 0.675 and 0.75 in dry weather, and between 0.405 and 0.45 in wet weather. (Higher values are not realistic unless one envisages road surfaces made of something other than concrete or asphalt.) The minority population has f -values in a triangular distribution (see figure 1), ranging from 0.3 to 0.675 in dry weather, and 0.25 to 0.405 in the wet. In the wet, one-third of the population is in the minority. In dry weather we take the fraction to be one-thirtieth. The triangular distribution means that the percentage of very low values, between 0.25 and 0.265 in the wet, is 0.33%; while the fraction between 0.3 and 0.337 in the dry is 0.033%.

The standard "wet" and "dry" conditions thus differ both in the magnitude of the f -values and in the fraction of ill-maintained vehicles. As will be seen, predicted casualty rates are usually greater in wet conditions. It seems that in most cases it is the increased variability, rather than the reduced friction that accounts for most of the difference.

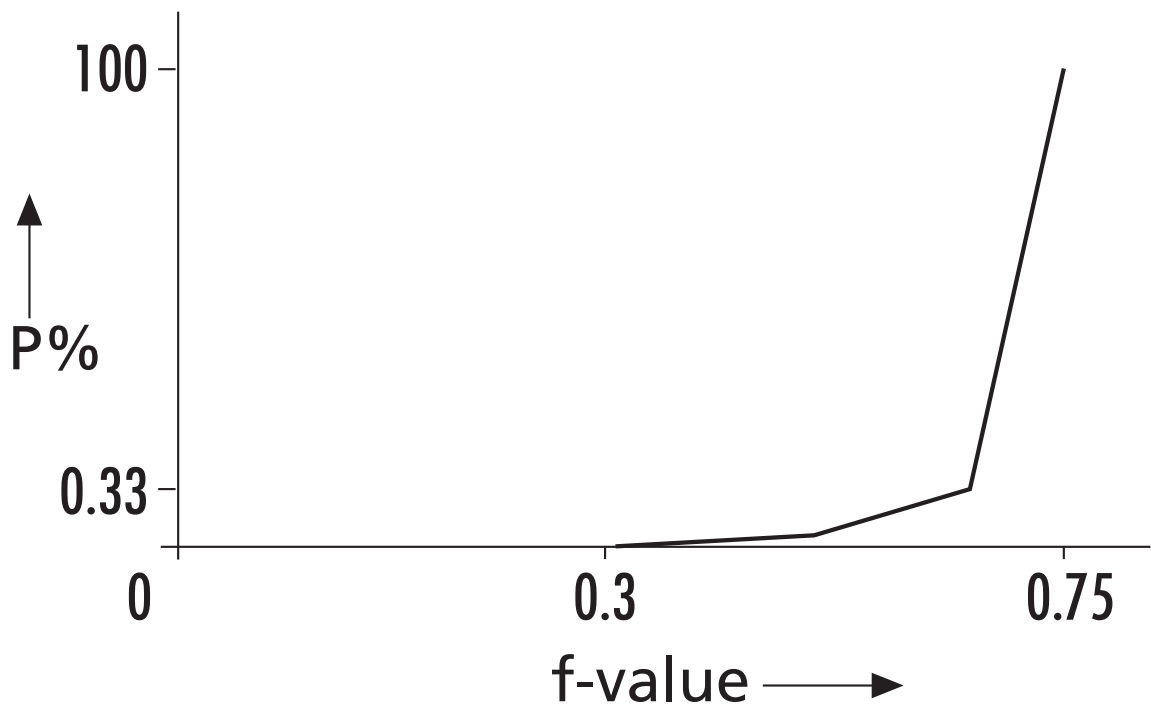


Fig 1 Cumulative probabilities, P%, of f-values. Dry Conditions

It will be noted that aerodynamic effects have been ignored. Their effect is certainly not negligible, especially for platooned cases, where Browand (1995) has shown that there is a shielding at close spacings, so that the aerodynamic effects depend on position in a platoon and on the size of any gaps that may develop. Present data goes up to platoons of length 4 only, and only one or two vehicle shapes have been investigated. Thus, to include these effects in work like that reported here would involve a good deal of extrapolation. However, when the work reported was started, there was no information about these effects, and they were, of necessity, ignored. Even when calculations were complete and the work was being written up, there were no final results.

These effects may well act here as a source of bias between the platooned cases and others. Common sense suggests that because these forces are not dominant they will not cause changes in the results by orders of magnitude, and in many cases the differences which appear are so large that it is unlikely that the qualitative conclusions will be affected.

It would be desirable, now that more is known, to verify the presumptions above by further modelling. To do so will complicate the model considerably and add to the computation time. So that only a few cases should be studied.

We assume that in all cases there is a mechanical delay of 0.09 s before braking can start, but that it then instantaneously attains its maximum value. This is representative of the behavior of antilock braking systems somewhat better than those available today.

1. In the *platooned* condition, a vehicle is warned to brake by a message, 0.01 s long, passed back from vehicle to vehicle in the platoon. Each vehicle in a platoon will start to brake at its maximum rate. With very close spacing, this is a reasonable response to the danger of a forward collision.
2. With *AICC*, each vehicle can only detect the vehicle ahead of it. When it perceives that the vehicle ahead is braking, the safest response for the occupant is to apply the brakes fully, 0.09 s after the preceding one has done so. In an *AICC-only* configuration, there is no limit on the length of a line of vehicles, and if the only controller is the automatic one, full braking will be propagated back down the line. If the line is taken to be infinite, the numbers of casualties is also infinite. This is not realistic. It is not realistic, not only

because lines may be long, but are not infinite but because it fails to take into account emergency action by the drivers. Also one might choose to brake more temperately in order to avoid approaching this theoretical infinity, as is done for PFC—see below. This will be discussed further later. In a *mixed-flow AICC* situation, on the other hand, lines are short, and there is no reason to believe that the automatic controllers will not be the primary actuators.

3. *PFC* systems are controlled from the infrastructure, and the infrastructure can advise all vehicles simultaneously of the incident, and in contradistinction to the AICC case, not only of its occurrence, but of its location. This makes it possible and reasonable to tailor the response to the stimulus. The PFC vehicle in the i th slot behind a failed vehicle is assumed to decelerate at either the rate which will bring it to rest i vehicle lengths behind the failure, or at the maximum value of which it is capable, whichever is the smaller. This starts after 0.01 sec. This reaction requires that it is "aware" of its own capability—of delays in message-passing and braking—and of the frictional properties of the road at the time. We do investigate the effect if the implied values in the relevant control algorithm are wrong.

This procedure reduces the total number of casualties at the cost of increasing the risks to the first two or three vehicles immediately following the failed one.

The distribution of vehicle masses and of f -values is taken to be random. The calculation is a "Monte Carlo" one—that is, values of the random parameters are given fixed values determined by an unbiased process for each run, and the runs are repeated many times, till the probabilities or expected rates of death and injury in a given situation can be determined statistically. In the cases studied here, the means of 25000 cases are taken. Even so, however, we are dealing with quantities which increase very rapidly with delta-V, and which are significant only at the extreme values of delta-V. As a result of this the distributions with which we are concerned are strongly skewed.

The skewness has two consequences:

1. Large numbers of runs are needed. Even the 25000 runs which have been carried out here often do not suffice to determine accurate values of the probabilities of death or the more serious (AIS ≥ 3) injuries.
2. The relation between any confidence interval of a mean value and the observed variance of a sample differs from that for a near-normal distribution. In general, we are unable to give precise confidence limits for the numbers we quote—if they seem likely to exceed 2% - 5%, this is drawn expressly to the reader's attention.

Finally, we assume an average vehicle length of 5 m.

MODEL USED

The basic configuration which is modelled is a line of vehicles, one behind the next, and separated by defined gaps, which may vary with position in the line. Vehicles remain in line whatever happens. At time zero all vehicles have the same speed, and a leading one starts to decelerate at its maximum rate. Simultaneously or successively, the following vehicles all begin to decelerate at constant rates. The rate of deceleration is either the maximum of which the vehicle is capable, as determined by its f -value, or a lesser value determined as described in the preceding section. The time at which deceleration starts is determined by the mechanical delay before braking, and by the method by which vehicles are advised of the need to brake. This is discussed in the preceding section also.

The model is an event-based analytic model. The motion of each vehicle or v -mass can be described by a quadratic function of time between events. A v -mass is either a free vehicle or several vehicles which have collided, and remain in contact. Events are of three kinds:

- i. a vehicle starts to brake.
- ii. a vehicle or v -mass comes to rest.
- iii. a vehicle or v -mass strikes its predecessor.

After an event, the equation of motion of the relevant v-masses changes. In the model, at any time, the time of the next event of each kind for each v-mass is calculated. The first of these events will occur. After an event, the equations of motion of the affected v-masses are recalculated, and so are the times of subsequent events. The process continues until all v-masses are at rest.

When a collision occurs, the vehicle at the front of the colliding v-mass suffers its first instantaneous reduction in speed. This delta-V value is recorded, and later translated into a probability of injury, using the relations in equation (1) above. Any other vehicles in the v-mass also suffer this reduction in speed, but since we only take account of the first forward collision, this is ignored.

All collisions are inelastic, so that v-masses, once formed, move as a single rigid body. The numbers used are such that in all the cases discussed here, vehicles will have started to brake before their first collision. After a collision, a vehicle applies the same braking force to the v-mass of which it is part, as it did before the collision.

Initial Conditions: number of vehicles

Four kinds of situation are considered in which an automated vehicle suffers a fault and brakes suddenly, and in consequence may induce collisions between other automated vehicles behind it.

In the *platooned* cases, the vehicle is the leader or another member of a platoon separated by small spacings. The calculation includes all members of the platoon behind the failed vehicle. When relating casualty rates to flow, we make use of the result that, under some very general conditions, the distribution of platoon lengths at any point of an AHS is a Poisson distribution with a constant number of platoons per unit length. (The mathematics, due to the author, will not be reproduced here: see note on “Programs” **on page 42.**) Variations in flow thus result in changes in the mean size of a platoon. Here we consider gaps of 1 m, 4 m, and 10 m and correspondingly 8, 4, and 2 platoons per km. These combinations result in similar capacities.

In the *PFC* cases, the space available for a vehicle, the *slot*, is of fixed length. Here we consider slots of length 10 m, 12 m and 15 m. The collision dynamics is now dependent on

vehicle length, which varies randomly, and we should have included this as a stochastic variable. However, we did not find where a distribution of vehicle lengths could be found. We therefore use a standard vehicle length of 5 m. It turns out that the results are not very sensitive to the choice made here. Depending on flow, each slot has a certain probability of being occupied. We assume that this probability is independent of the occupancy of adjacent slots. We have described above the law which determines the deceleration rate of each vehicle. Clearly we do not have to consider vehicles that can certainly stop without collision (i.e. for which the required f -value exceeds the minimum of the distribution). This limits the number of slots which have to be considered. The probability that a slot is occupied is determined by the flow. The occupancy of a particular slot is determined at random, as part of the Monte Carlo process.

In the *mixed-flow AICC* cases, we consider a stream of traffic in which some traffic is manually driven, and some use AICC. The flow thus consists of a series of platoons, each headed by a manually-driven vehicle. The distribution of manual spacings is assumed to be that which would result in a lane capacity of 1800 veh/hr, while the AICC ones are each a constant spacing behind their predecessors. Spacings of 5 to 50 m are considered. The ratio of AICC to manual vehicles is a parameter of the calculation. Once again, the distribution of numbers of AICC vehicles associated with a single manual vehicle can be shown to be Poisson, if all the AICC vehicles operate independently. In this case we consider only faults in the AICC vehicles, and collisions of other AICC vehicles with them. Failures in the manual vehicles will also generate casualties, but it is arguable that the use of AICC should not be debated with them. It is thus unnecessary to make any assumptions about the distribution of headways between groups which are selected by the manual drivers. The results are independent of flow. The number of casualties per incident is a function of the mean of the Poisson distribution, that is, of the mean number of AICC vehicles following a manual one. This, clearly, is a function only of the relative number of the two kinds of vehicle, and is independent of flow.

For small values of the fraction of all vehicles which are AICC-controlled, there will be very few all-IVHS collisions (the only ones we consider) since the number of consecutive pairs of AICC vehicles will be very small.

In the *AICC-only* and *CICC* cases, we consider a stream of traffic containing AICC cars alone. One possibility here is that very long lines are formed. If full automated braking is the only control action that would be taken, following a failure, the effect is the same as if each vehicle induced a failure in the one behind it. This leads to numbers of casualties limited only by the length of the line. However, this is unrealistic. Drivers will certainly see and hear successive crashes ahead of them, and will be able to resume manual control. The geometry may permit them to steer out of the automated lane: if they can, the procedure will not be free of danger. They will certainly be able to commence gentle braking, given sufficient warning. We have no data about how much time would pass before drivers took action, or what action they would or could take. It is possible that these times would be longer than when AICC or CICC was not in use: certainly they could not be much shorter so we have to consider action that would be effective in a time between 0.7 and 2 or 3 s. In this time the message that something was wrong would have reached 8 to 20 or 30 vehicles. Here, therefore, to cover this case we quote numbers of casualties for lines of 10 and 20 vehicles following a failure in the leading one.

Another possibility is that some drivers will choose, rather than join a very long line, to retain manual control and become the leader of a line of AICC-controlled vehicles. We assume that they are successful in choosing gaps which do in fact protect them from running into the vehicle ahead if the latter brakes. If they do not, there will be increased casualties, but we do not wish to AICC casualties due to faults of manual drivers. The figures here are intended to represent excess casualty due to AICC. We consider the cases in which such drivers form 10%, 5% and 3.3% of the population, resulting in means of Poisson-distributed line lengths of 10, 20 and 30 respectively.

We have also tried to find a braking rule, analogous to the one chosen for PFC vehicles, which will contain the infinity, as so reduce the total number of casualties per incident. First, we considered what happens if the rule is that the vehicle will try to come to rest immediately behind the one ahead, on the basis that the latter has the same f -value as the vehicle itself. (We are advised that it may be possible to derive a sensor that will measure f , based on responses to steering wheel, brakes, and throttle.) This did not contain the infinity or reduce the casualty numbers under any conditions. The results are not reported here.

Another possibility is that each vehicle can determine the deceleration of the preceding vehicle by observation in the 0.09 s available, and selects that deceleration which will bring it to rest just behind its predecessor, on the assumption that the predecessor comes to rest without collision. We shall see that for CICC this reduces total casualties. For AICC it does so at low capacities, though not at high ones. In all cases, however, it increases casualties in the vehicles immediately behind the failure.

However this search for a socially desirable braking strategy for AICC and CICC may be merely academic. The rules which are desirable for society as a whole increase the risk for each driver. If the driver ahead of you starts to brake suddenly your best action for the occupants of your own vehicle (if not to protect your vehicle from damage) is to brake flat out. You thus minimize the chances of a death/injury-causing forward collision. You may increase the chance of a rear collision, but such collisions will provoke injury mainly in the following vehicle. If the vehicle ahead is, for unselfish reasons, braking more gently than is possible, so much the better for you. Even, therefore, if a social-optimum rule exists, it might be impossible to ensure its use in an AICC context, where the emphasis is on driver choice and driver responsibility. There are moral and legal issues here, on which we do not feel qualified to comment.

Dependence on flow

We express our results as casualties on automated vehicles, AIS ≥ 2 , per failure of an automated vehicle. They are described as functions of flow on the automated lane.

In PFC systems, our calculation relates the expected number of casualties per accident directly to flow. For platooned systems, mixed flow AICC and AICC only, the result is a function of the average platoon size \tilde{n} , which in turn depends on flow and the number of platoons/km. Every vehicle in a platoon has an equal chance of being the failed one. The expected number of casualties is therefore:

$$C(\tilde{n}) = \sum_{n=1, \infty} P(n, \tilde{n}) \{[\sum_{m=1, n} c(m)]/n\} \quad \dots(2)$$

where $c(m)$ is the expected number of casualties if the failure is suffered by the leader of a platoon with m members (so $c(1) = 0$), and $P(n, \tilde{n})$ is the Poisson probability:

$$P(n, \tilde{n}) = \exp(-\tilde{n}) * \tilde{n}^n / n!$$

In the case of both CICC and AICC, including mixed AICC, the casualty rates are functions of the variables which affect capacity, but the configuration is such that casualty rates per incident are unaffected by changes in flow. The graphs (figures 5-9) here show casualty rates as a function of capacity, though the close-spaced-platoon curve shown for comparison refers to flow.

Tables 1 - 5 show the capacities of many of the configurations considered and the probable number of casualties (AIS ≥ 2) per incident at capacity.

Effect of speed

As would be expected, the numbers of casualties are sensitive to the speed of traffic on the automated lanes. In this paper we quote results for two speeds, 30 m/s (67 mph) and 25 m/s (56 mph). In the platooned case, the gap between platoons must increase with speed so that platoons cannot collide, and this affects the capacity. Within capacity limits, however, an increase in speed at constant flow is reflected in a reduced density, and so, in the platooned case, in a reduction in platoon size. It is this which accounts for the different sensitivity of our results to speed changes in the different control schemes and the apparent paradox that casualties (AIS ≥ 2) per failure decreases as speed increases for platooned vehicles.

RESULTS

In all cases the results displayed are for casualties with AIS ≥ 2 . We do discuss the prevalence of more serious casualties. For short we shall refer to cases where all collisions are at ΔV values less than the threshold for injury, AIS ≥ 3 or death, as "green"; "yellow" will refer to cases where the ratio, deaths/injury (AIS ≥ 2) is less than 1%, and other cases are "red". These terms are relative: the collisions considered here do not involve head-on cases or collisions with massive stationary objects, so that they are much less severe than the average.

On Californian urban freeways at present the ratio of deaths to injuries, AIS ≥ 2 , is approximately 15%.

Platoons

Figures 2 and 3 show the main results with the "dry" and "wet" parameters respectively. Some results are also tabulated in table 1, where other parameters are also detailed. We consider three systems with 1-, 4- and 10-meter intraplatoon spacings.

Table 1

Capacity and casualty rates at capacity: platoons

Intraplatoon Spacing (m)	Plats/km	Speed (m/s)	Capacity (Vehicles/h)	Casualties (AIS ≥ 2) per 100 incidents	
				dry	wet
1.0	8	30	6480	0.27	1.37
4.0	4	30	8180	1.18	3.34
10.0	2	30	6040	1.55	6.72
1.0	8	25	8330	0.62	0.80
4.0	4	25	7780	0.90	3.51
10.0	2	25	5330	1.42	6.44

The 1-meter spacing case is green, the others are yellow.

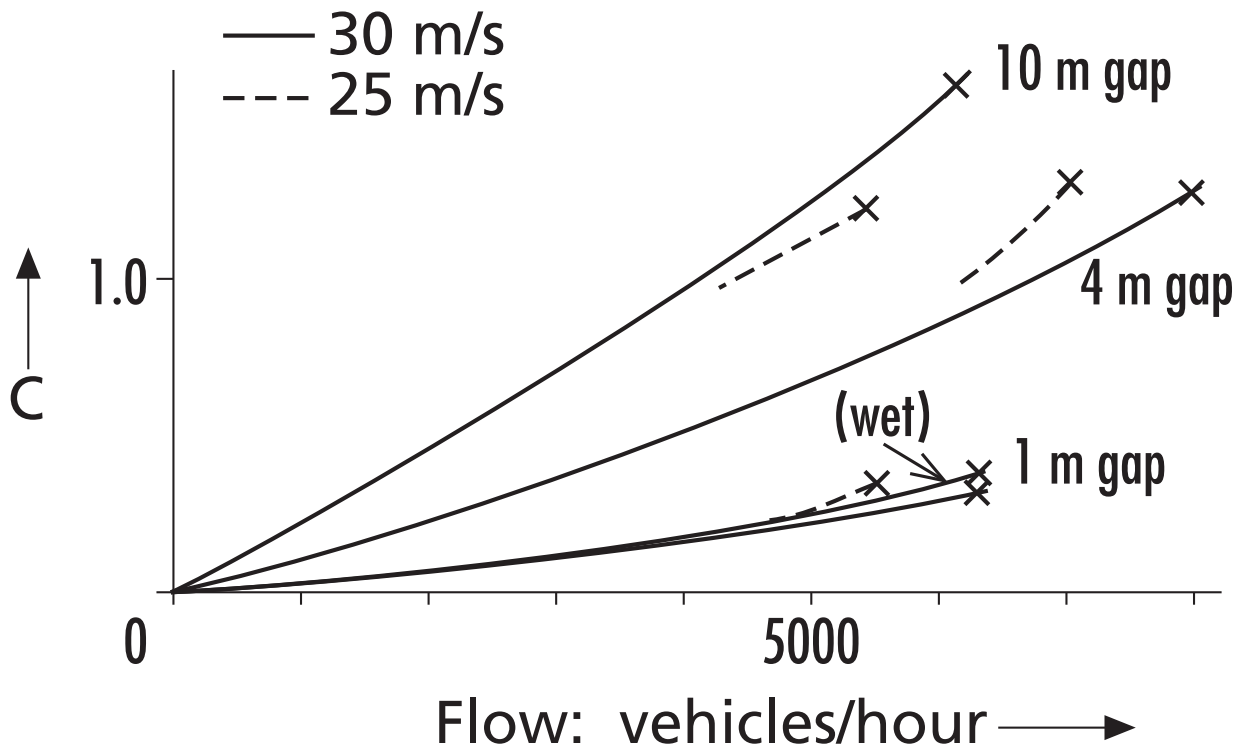


Fig 2 Casualties, C (AIS 2) per 100 incidents. Platoon in dry conditions. 1, 4, and 10 m spacing

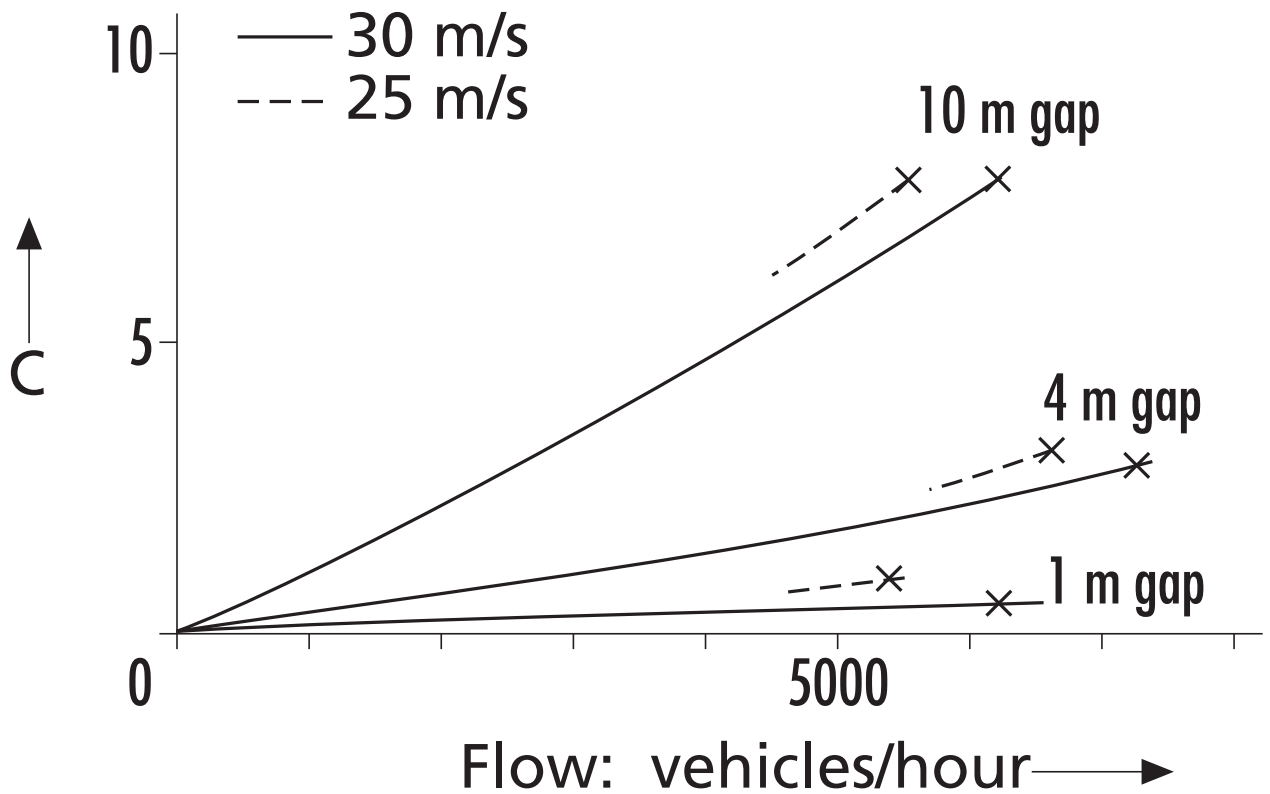


Fig 3 Casualties, C (AIS 2) per 100 incidents. Platoon in wet conditions. 1, 4, and 10 m spacing

In all cases, the casualty rate per 100 incidents increases, roughly linearly, with flow. All the cases are insensitive to the distinction between dry and wet conditions and also to speed in the range of interest. It seems that, at these speeds, the effect of increased speed in increasing delta-Vs and in reducing platoon length cancel out. As Shladover's (1978) work suggested, both the numbers and the severity of casualties are least at the least intraplatoon spacing. Of course, if the spacing is large enough casualty rates reduce again. In dry condition the reduction stands at about 20 m spacing, while in wet conditions, it stands at 25-40 m. At spacing large enough for casualty rates similar to those at 1 m spacing, capacity is very low and the system is not economic. The curve for platoons at 1 meter spacing is reproduced on all the figures to help give a common sense of scale.

Point Follower Control

Figure 4 shows the results for PFC configurations. Some results are also shown in table 2, which gives parameters describing the different configurations. It will be remembered that in this case we assume that the system imposes "unselfish" braking behavior. Each vehicle, on hearing that there has been heavy braking i vehicles ahead, itself brakes (if it can) with the deceleration it calculates will bring it to rest i vehicle lengths behind the failure. If this were not done, but all braking were as severe as possible, then the effect would be the same as if every vehicle failed simultaneously, and the collisions and associated casualties would stretch back to the beginning of the automated lanes. The rule we suggest avoids this theoretical infinity at the cost of increasing the casualty rate in the vehicles which indulge in this "graded" braking. There are legal and moral issues here, which will not be discussed in this paper.

This rule implies that the control system uses assumed f -values for the failed vehicle to compute its own deceleration. It is not clear how each vehicle will be informed of the correct value, or if its information will always be accurate. Figure 4 is drawn on a logarithmic scale because of the very large differences that errors here can make.

Again, the casualty rates per 100 failures increase roughly linearly with flow. We first consider the case where the conditions are "dry", and the vehicles, in calculating their braking rates correctly identify the range of f -values of vehicles on the road (0.3 to 0.75 in "dry" conditions). This produces casualty rates (AIS ≥ 2) less than the 1-meter platooned case. Their severity is a little greater, however, for this is a yellow case. In "wet" conditions the accident

rate is increased four-fold, again on the basis that the control systems correctly identify the range of f -values present.

If the conditions are wet, but the control system incorrectly uses the "dry" values to compute desired decelerations, the casualty rate is more than doubled over the well-organized "wet" conditions—a ten-fold increase over the "dry" values. In the reverse condition, where conditions are in fact dry, but the control system calculates on the basis of a "wet" range, the increase in casualty rates is over 250-fold.

In practice, it may be difficult for the central system (and PFC is controlled from the infrastructure) to "know" just what the appropriate conditions are at every point in the network. The large effect of errors here is therefore not academic. There may be solutions

Table 2.

Capacity and casualty rates at capacity: PFC

Slot length (m)	Speed (m/s)	Capacity(1) (vehicles/h)	Casualties (AIS ≥ 2) per 100 incidents	
			dry	wet
15 30	5760		0.27	1.37
12 30	7200		0.37	1.78
10 30	8640		0.51	2.20
15 25	4800		0.14	0.64
12 25	6000		0.18	1.01
10 25	7200		0.28	1.27
# 15 30	5760	930	..	(2)
# 15 30	5760	..	30.4	(3)
# 15 30	5760	94.4	84.4	(4)

indicates that fraction of casualties (AIS ≥ 2) which are fatalities exceeds 1%. ("**red**"). others are "**yellow**".

Notes:

- (1) 20% allowance in capacity for flexibility in joining.
- (2) Deceleration formula uses "wet" values in "dry" conditions.
- (3) Deceleration formula uses "dry" values in "wet" conditions.
- (4) Deceleration formula uses "own" value.

based on vehicle-based observations of local conditions. We tested here the one in which each vehicle can measure its own f -value, and assumes that the failed vehicle has the same value. This does not work: in dry conditions it produces a 50-fold increase in casualty rate. There may be better solutions: we have not been able to find them.

In the present state of knowledge, it would be unwise to use the very favorable curve at the bottom of fig 4 as a realistic basis for evaluation of PFC, even in dry conditions. It

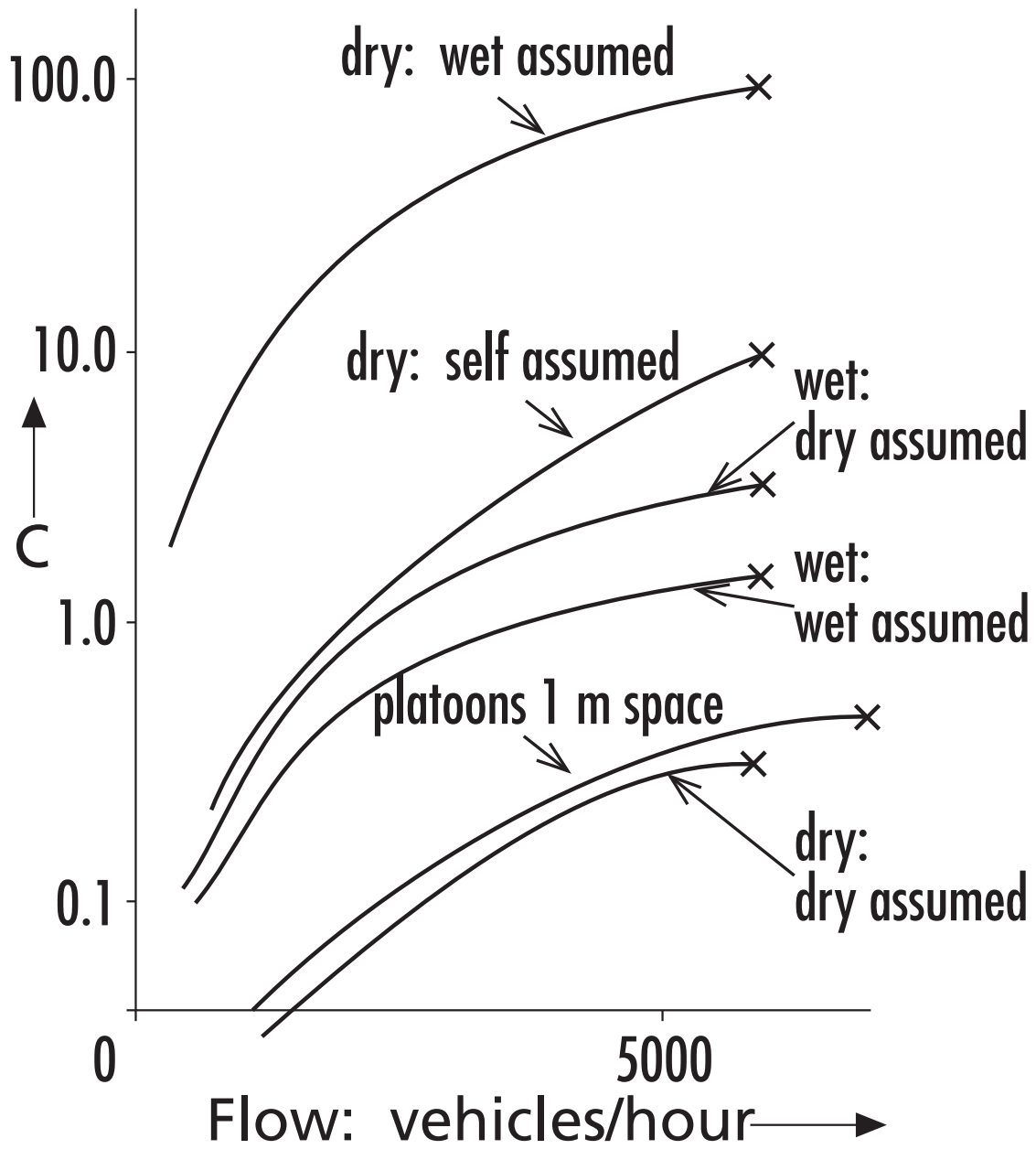


Fig 4 Casualties, C (2) per 100 incidents. Point follower control.
Wet and dry conditions as indicated

seems that in this configuration, casualty rates are very sensitive to predicated f -values, and perhaps to other control parameters also.

AICC

We first consider the case where only AICC vehicles are present. Figures 5 and 6, and table 3, present results and some details of the configurations considered here. In this case, the casualty rates are largely independent of flow, but are affected by parameters which also affect capacity. In the figures, casualty rates are plotted against capacity. In the curve for 1-meter spaced platoons casualty rates are plotted against flow, and a little care may be needed in interpretation.

In reserved-lane AICC, as in the PFC case, long lines can be formed, though drivers may not choose to do this. If the only reaction to braking ahead is full braking, a theoretical infinity arises. As we have indicated already this is not realistic, for in AICC drivers have choices. We show the effects of three possible resolutions of the situation.

1. When an incident occurs, drivers some distance behind will see or hear trouble ahead and have time to take avoiding action. If all those more than ten vehicles behind, (who have 0.9 seconds warning) successfully avoid collision the casualty rates are those shown in the figures and tables as "line of 10". If avoidance needs 1.8 seconds, (drivers may come to rely on the automatic braking), the "line of 20" curves are appropriate. The ascending parts of these curves, at the lower capacities, are **red**. The rest of the curves is **yellow**.
2. Some, drivers, recognizing these problems, may choose voluntarily to leave gaps in the lines of vehicles which are large enough for them to brake gently to rest in the event of a failure ahead. Thus no problems arise behind them and difficulties are restricted to the platoon-like group in which the failure occurs. We consider, in table 3, the cases where such non-conforming drivers are 3.3%, 5% and 10% of the total. The curves are similar in shape to the line-of-10 and line-of-20 curves shown in the figures discussed above, and again, the part corresponding to spacings exceeding 20-30 meters is **red**, while the rest is **yellow**.

3. We also consider the possibility of automated "graded" braking, in which each vehicle in the 0.09 seconds before braking is supposed to detect the deceleration of the vehicle ahead of it, and chooses a deceleration which will cause it to come to rest just behind its predecessor, on the basis that its speed does not change suddenly. As the figures show, this is an improvement over the other strategies at low capacity, but it does not contain the theoretical infinity at higher capacities.

There may be other automated strategies which are superior to this. As indicated above, our search for one was not successful. Certainly it has not been proved that there are none. However many alternatives were considered and no better one was found, as has been said above.

Table 3 Capacity and casualty rates at capacity: AICC only

(These values apply at all flows)

Vehicle spacing (m)	Speed (m/s)	Capacity(1) (veh. /h)	Casualties (AIS ≥ 2) per 100 incidents					graded braking
			line of vehs		voluntary gaps			
			20	10	10%	5%	3.3%	
Dry Conditions.								
50	30	1570	0.38	0.19	0.09	0.20	0.28	..
45	30	1730	..	..	..	..	..	0.04
40	30	1920	0.90	0.41	0.21	0.44	0.69	..
35	30	2160	..	..	..	..	..	0.16
30	30	2470	1.80	0.76	0.40	0.88	1.35	..
25	30	2880	..	..	..	..	..	0.40
20	30	3460	2.42	1.18	0.58	1.24	1.86	..
15	30	4320	..	..	..	..	..	2.22
10	30	6480	2.41	1.16	0.58	1.23	1.86	*
5	30	8640	4.73	2.16	1.06	3.22	3.60	*
50	25	1300	0.02	0.01	..	..	..	..
45	25	1440	..	..	..	..	..	0.002
40	25	1600	0.14	0.08	0.03	0.07	0.10	..
35	25	1800	..	..	..	..	..	0.01
30	25	2060	0.53	0.24	0.12	0.26	0.40	..
25	25	2400	..	..	..	..	..	0.09
20	25	2880	1.41	0.68	0.34	0.70	1.07	..
15	25	3600	..	..	..	..	..	0.56
10	25	5400	1.88	0.89	0.44	0.93	1.44	*
5	25	7200	2.77	1.30	0.62	1.36	2.13	*
Wet Conditions								
50	30	1570	1.84	0.87	0.43	0.92	1.41	..
45	30	1730	..	..	..	..	..	0.17
40	30	1920	5.05	2.37	1.20	2.51	3.85	..
35	30	2160	..	..	..	..	..	0.64
30	30	2470	9.31	4.36	2.18	4.63	7.08	..
25	30	2880	..	..	..	..	..	1.55
20	30	3460	12.11	5.71	2.87	6.02	9.22	..
15	30	4320	..	..	..	..	..	8.00
10	30	6480	12.55	5.77	2.80	6.14	9.52	22.8
5	30	8640	11.15	4.96	2.26	5.25	8.39	*
50	25	1300	0.02	0.01	..	..	..	..
45	25	1440	..	..	..	..	..	0.01
40	25	1600	0.53	0.25	0.12	0.26	0.38	..
35	25	1800	..	..	..	..	..	0.07
30	25	2060	2.96	1.41	0.70	1.48	2.26	..
25	25	2400	..	..	..	..	..	0.44
20	25	2880	7.33	3.46	1.73	3.36	5.60	..
15	25	3600	..	..	..	..	..	2.26
10	25	5400	9.54	4.44	2.20	4.74	7.26	..
5	25	7200	9.30	4.21	2.00	4.50	7.03	52

(*Theoretical Infinity) (.. Not calculated) ((1) no allowance for provision of gaps to allow easy entry and exit)

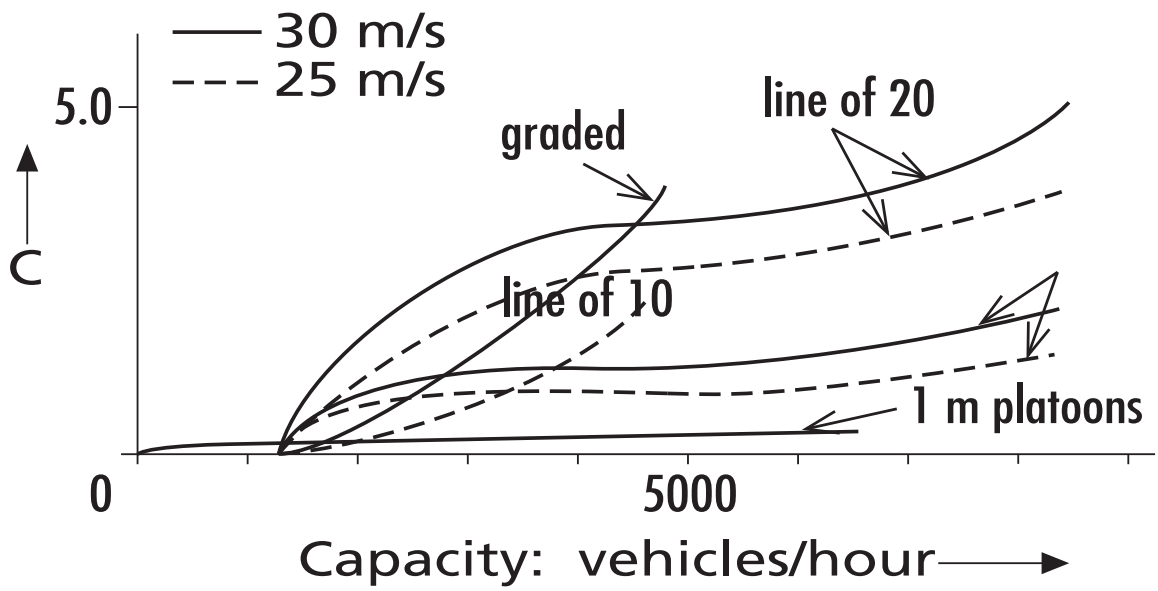


Fig 5 Casualties, C, (AIS 2) per 100 incidents. Dry conditions. AICC on reserved lane.

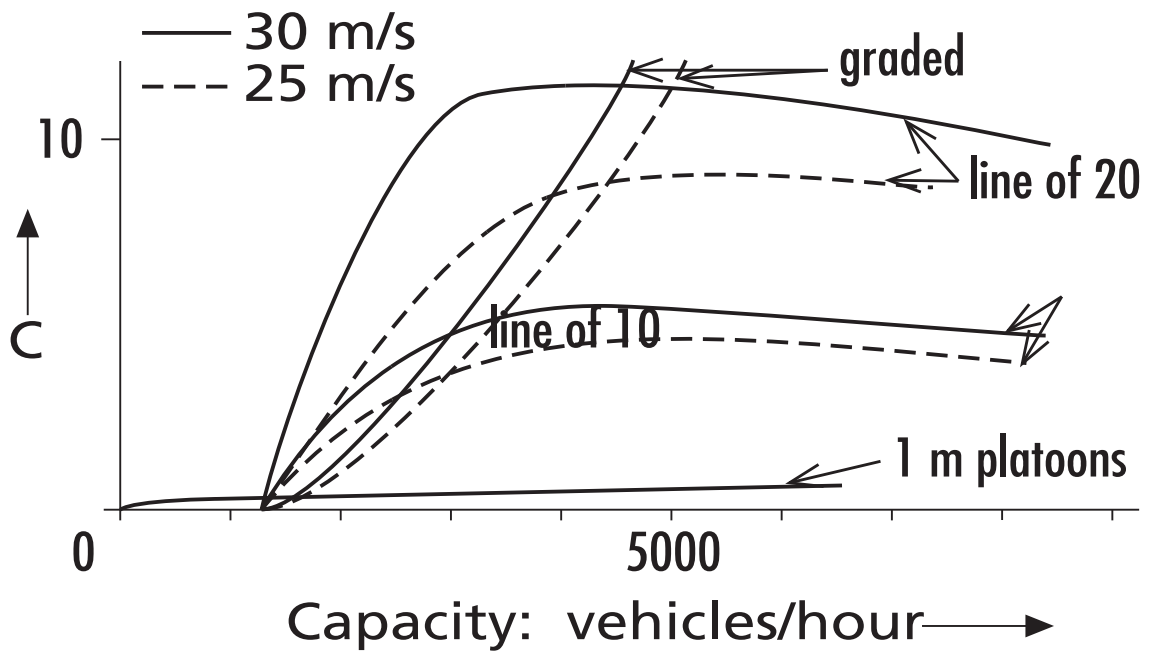


Fig 6 Casualties, C, (AIS 2) per 100 incidents. Wet conditions. AICC on reserved lane.

In all cases, but especially in "wet" conditions, casualty rates in an AICC-only configuration are many times more numerous, and more severe, than is the case for 1 meter spaced platoons. The effect is particularly large if spacings are reduced so as to approach the capacities characteristic of platooned systems.

Mixed-flow AICC.

In the study here of mixed-flow AICC we consider only accidents resulting from a brakes-on failure of an automated vehicle which results in collision with another automated vehicle. There will, no doubt, be other accidents following aberrant behavior of manual drivers or their vehicles: they are not counted here.

Table 4
Capacity and casualty rates in equipped vehicles at capacity: mixed-flow AICC
 (These values apply at all flows)

Vehicle Spacing (m)	Capacity (vehicles per hour)	Speed 30 m/s		Capacity (Vehicles per hour)	Speed 25 m/s	
		Casualties (AIS \geq 2) per 100 incidents			Casualties (AIS \geq 2) per 100 incidents	
		dry	wet		dry	wet
Fraction of equipped vehicles = 0.83						
5	5900	0.45	0.87	5400	0.27	0.80
10	4800	0.24	1.17	4320	0.20	0.94
20	3500	0.26	1.24	3090	0.15	0.76
30	2770	0.18	0.97	2400	0.05	0.31
40	2280	0.10	0.54	1960	0.02	0.14
50	1930	0.01	0.19	1660	0.01	0.02
Fraction of equipped vehicles = 0.67						
5	4050	0.121	0.219	3860	0.072	0.200
10	3600	0.084	0.302	3750	0.056	0.211
20	2940	0.072	0.344	2700	0.045	0.090
30	2490	0.050	0.276	2250	0.014	0.016
40	2160	0.036	0.153	1930	0.006	0.008
50	1900	0.012	0.052	1800	..	..
Fraction of equipped vehicles = 0.50						
5	3090	0.038	0.062	3000	0.023	0.060
10	2880	0.030	0.093	2770	0.018	0.078
20	2540	0.023	0.109	2440	0.017	0.068
30	2280	0.016	0.089	2120	0.015	0.029
40	2060	0.014	0.050	1900	0.004	0.008
50	1880	0.004	0.017	1800	..	..

Thus the casualties enumerated here can only arise when one AICC vehicle is following one or more others. Such occurrences will not be frequent unless the fraction of AICC vehicle in the whole is large. Figures 7 and 8, and table 4 indeed confirm that

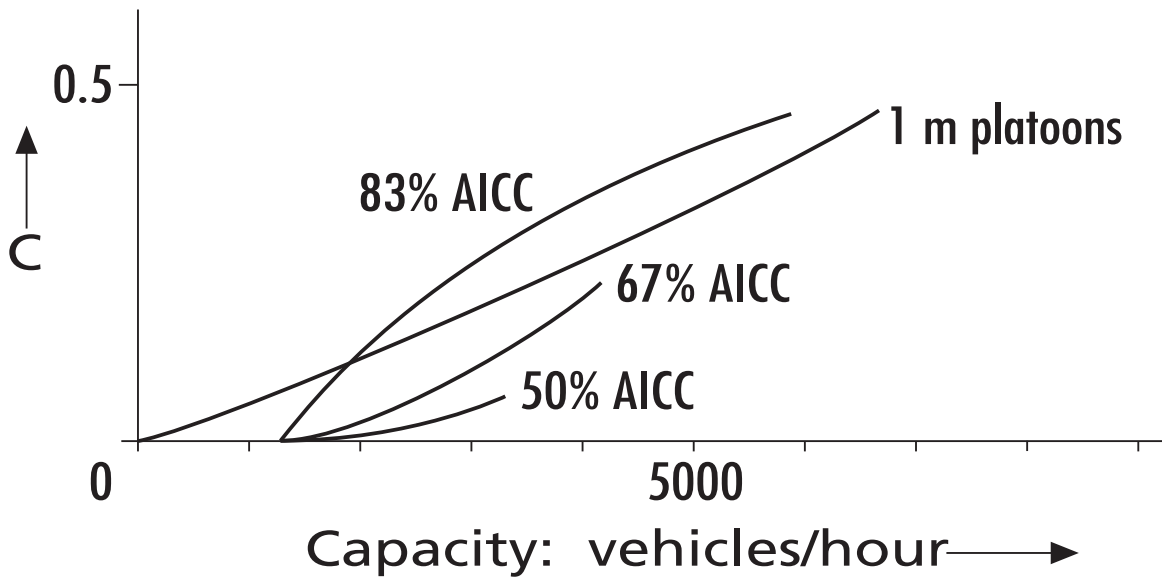


Fig 7 Casualties, C, (AIS 2) per 100 incidents. AICC mixed with other traffic. Dry Conditions.

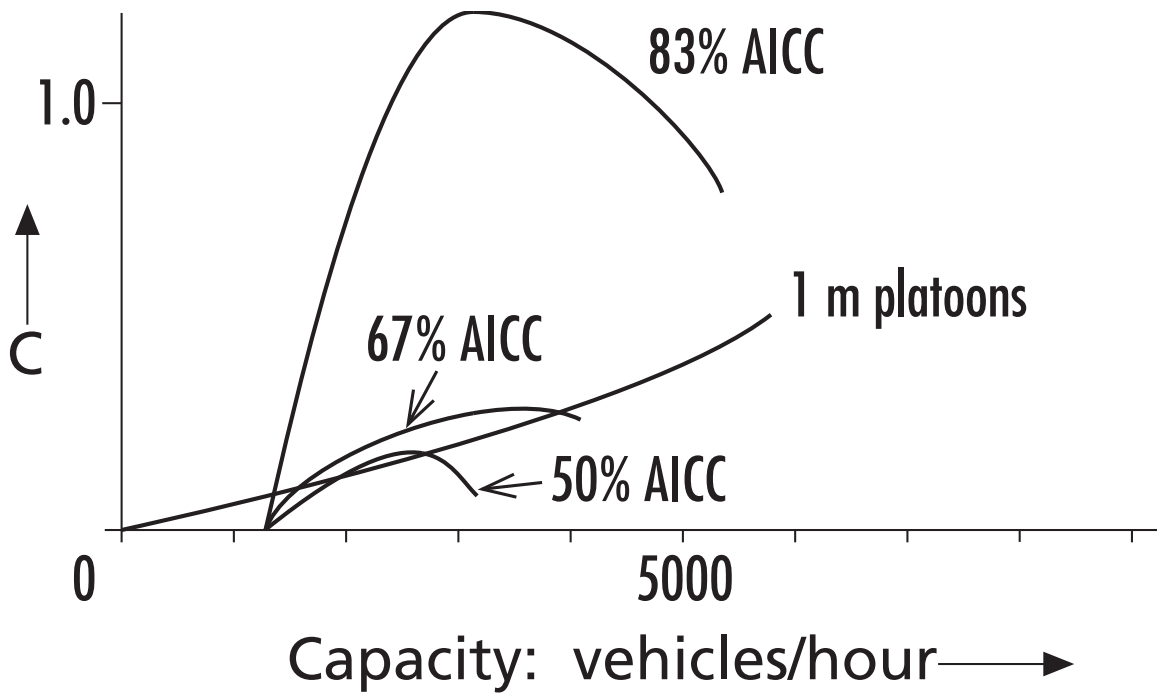


Fig 8 Casualties, C, (AIS 2) per 100 incidents. AICC mixed with other traffic. Wet Conditions.

casualties per failure are low at values of the fraction of equipped vehicles much less than one, but rise rapidly, especially in wet conditions, as the fraction grows.

AICC is sometimes spoken of as an "early winner" for IVHS applications. For this type of control failure, nothing that is said here affects this, provided control systems of sufficient reliability for any AVCS application can be produced. However, if AICC should become too popular, a safety problem can arise when the market penetration reaches 60-80%. This will be especially true if there is any tendency to use AICC for close following. This may increase capacity—it will also increase casualties.

CICC

CICC operation is similar to platooned operation in the form of communication, but with larger spaces between vehicles. It is similar to AICC in the tendency to form long lines, and the dependence with long lines of casualty rates on capacity, rather than flow.

One use of CICC which is put forward from time to time is as an introductory stage to platooning: groups of CICC vehicles, separated by within-group spaces of 10 - 40 m and larger inter-group spaces will run on partially automated lanes (no lateral control?). For this reason we give below results for such configurations with mean group numbers of 10, 15 and 20 vehicles. We also give results for lines of 10 and 20 vehicles behind the failure, and for graded braking.

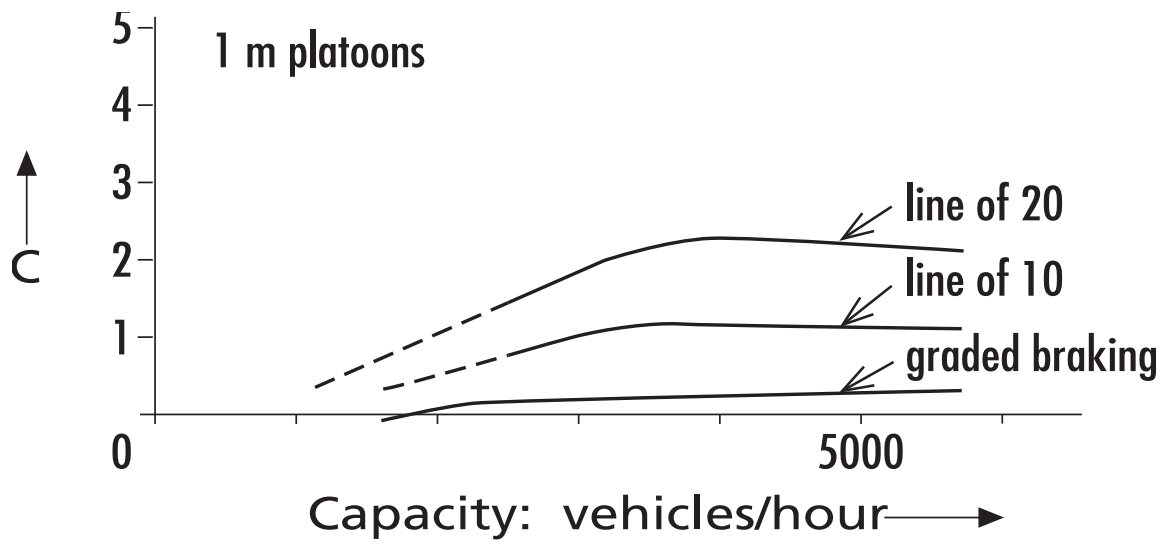


Fig 9 Casualties, C, (AIS 2) per 100 incidents. CICC, Dry Conditions.

The results are given in table 5 and figure 9. Casualty rates are lower than with AICC, but show similar trends. In particular the range which is of interest in an introductory AHS is, regrettably, the range of maximum casualty rates. Unlike the AICC case, however, graded braking is effective here in the cases shown, which use dry values of coefficients of friction in the formula which uses the predicted slowing of the first vehicle to compute its own deceleration rate. If an error is made in predicting this, the results are similar to that shown in table 2.

Table 5

Capacity and casualty rates: CICC

Vehicle spacing (m)	Speed (m/s) braking	Capacity (1) (veh/h)	Casualties (AIS ≥ 2) per 100 incidents					graded
			line of vehs		groups (2)			
			20	10	10	15	20	
10	30	5760	2.14	1.02	0.50	0.76	1.06	0.38
15	30	4320	2.18	1.09	0.53	0.83	1.13	0.26
20	30	3460	2.19	1.09	0.51	0.75	0.97	0.17
#30	30	2470	1.40	0.69	0.37	0.57	0.79	0.10
#40	30	1920	0.71	0.34	0.18	0.28	0.37	0.06

Notes:

(1) Capacity reduced to 80% for flexibility for entry: values for vehicle groups somewhat less, depending on inter-group spacing.

(2) Group size is constant.

In cases marked # the fatality rate exceeds 1% of the number given (red). In other cases it is less than this but non-zero (yellow).

Absolute magnitude of problem

The results reported here are all in terms of casualties per failure. To go further, the failure rates must be known, as well as a good deal of data about the way automated vehicles would be used. Alternatively, one can use these numbers to specify required reliabilities, if one can define an "acceptable" casualty rate.

Suppose that the brakes-on failure which induces these accidents occurs, on the average, x times per 1000 years on the average vehicle. The vehicle may be new, or anything up to 15 or 20 years old. In California, approximately 60% of all vehicle-miles travelled (VMT) occurs on urban freeways, and the average car does 10,000 miles/ year. Some vehicles travel very little on urban freeways, and we would not expect their owners to go to the expense of buying automation equipment. We assume therefore that vehicles which use automated freeways average 7500 miles/year on them. x failures per 1000 years is equivalent to $13.3 \cdot x$ failures/100 MVMT, or a mean operating time between failures of about $125000/x$ hours.

On Californian urban freeways the police-reported injury rate per MVMT in 1992 was 0.28 (Caltrans 1993). This refers to all cases where there is visible injury or complaint of pain. This may include more cases than a clinical AIS 1. The CDS data (see acknowledgment) indicate that, overall there are around 7 injuries AIS 1 for every one of AIS ≥ 2 . We deduce that the present injury rate (AIS ≥ 2) on urban freeways is about 4 per 100 MVMT. The death rate (Caltrans, 1993) is 0.6 per 100 MVMT.

If therefore the casualty rate per 100 failures is y , and the injury rate for this cause alone is not to exceed the present injury rate from all causes, we must have

$$13.3 \cdot x \cdot y / 100 < 4$$

or

$$x \cdot y < 30$$

In practice, it is probably desirable to aim for a smaller fraction of the present rate, since there may well be other sources of injury on an AHS.

When it comes to a choice between different configurations, one might suggest that before one can say that a higher value of y , i.e. of casualties per failure, is not important, the number of injuries due to the less safe configuration needs to be less than 3% of the present rate. This implies:

$$x \cdot y < 1$$

For example, if for AICC controls, (for which values of y are in the range 2 - 3) the reliability were such that x were less than 0.5, it would be permissible to argue that the safety benefit of other configurations was not important—zero times anything is zero. A value of 0.5 for x corresponds to a mean time between failures of some 10^6 hours. At somewhat lesser values of the reliability, the number of casualties could be still less than at present, but would be large enough to have to be balanced against other benefits.

Distribution of Casualties

Detailed examination of the results shows that the order of events in the collisions is not always, or indeed usually that (1) vehicle no. 1 starts to brake; (2) it is struck by no. 2; (3) the resulting v-mass is struck by no. 3, and so on. Collisions can, and often do, occur in almost any order. Often one or more vehicles will not strike the ones ahead of them, even though there are multiple collisions behind them. Much too depends on the way the masses of vehicles happen to vary.

There is some tendency for casualties to peak in the second and third vehicle behind the failure. These vehicles will tend to have a smaller relative speed at the moment of impact than the first. However they strike a more massive object, made up of two or three cars, and the value of delta-V therefore tends to be greater.

CONCLUSIONS

At high capacities the performance of closely spaced platoons is superior to that of competing configurations in terms of casualty rate per failure. If ways of improving the provision of data about the performance of other vehicles in a PFC system can be found this could change—but the precision needed is such that this seems unlikely. Close-spaced platoons are certainly superior to high-density AICC-only configurations by at least an order of magnitude. One very desirable feature of platoons is the fact that all collisions occur below the threshold at which deaths can occur, and another is the lack of sensitivity to road surface conditions and system speed.

Whether or not all this is important depends on the frequency of the brakes-on failure. If the reliability of the longitudinal control system leads to the brakes-on failure at a rate of 1%/year, then the injury rate for the non-platooned systems due to this cause alone exceeds that due to all causes at present, while that for platooned systems is around 10% of the present rate. If the failure rate is reduced to 0.1%/year, the platooned system will still have a worth-while advantage, in reducing injuries to about 10% of the present rate. If the failure rate is reduced to 0.01%/year—a mean time between failures of about 10^6 hours operating time—the advantage becomes insignificant.

The position of AICC, mixed with ordinary manual traffic, is interesting. At low fractions of the total traffic, it gives rise to no great safety problems, but as the possibility rises that one AICC vehicle will follow another, the risk of casualties rises sharply, and by the time that there are 5 AICC vehicles for every manual one, it may come to be thought necessary to prescribe stringent conditions on the mean time between failures of the automatic braking system.

In the form expressed above, the conclusions seem to be tolerably robust. However, all these conclusions depend to some degree on the validity of the assumptions made about the fraction of vehicles with poor brakes or tires in the fleet, and on an assumption that it will be possible to keep reasonably high f -values for well maintained vehicles, despite the unusual conditions under which the road surface will operate. (Wear will be concentrated in narrow tracks.) Further, these conclusions relate only to failures in longitudinal control. Work in progress suggests that the consequences of failures in lateral control can also be affected by the configuration choices discussed here.

PROGRAMS

The programs used to obtain the results reported in this paper are written in Turbo C™. They will run on PCs, but not on UNIX systems. They are fully commented and, hopefully, user-friendly. Source code, programs and a text describing them can be obtained on disk from the Technical Editor's office at PATH. Please send a disk with the request.

References

AAAM (American Association for Automotive Medicine; Committee on Injury Scaling) "The Abbreviated Injury Scale: 1980 revision". Morton Grove, IL 1980.

California Department of Transportation (Caltrans). "Route Segment Report for 1992", Sacramento, CA, 1993.

Galasko, C. S. B., P. Murray, M. Hodson, R. J. Tunbridge & J. T. Everest, "Long-term Disability following Road Traffic Accidents". TRRL Report 59, Crowthorne, England, 1986.

Hitchcock, A., "IVHS System Safety: Problems of Requirement Specification and Hazard Analysis". TRB Research Record 1318 pp 98-103, Washington, D.C., 1991.

Hitchcock, A., "Coefficients of Friction and Automated Freeways", PATH Working Paper to be published Berkeley, CA, 1994.

Joksch, H.C., "Velocity Change and Fatality Risk in a Crash - a Rule of Thumb" Accident Analysis & Prevention, Vol 25, No 1., pp 103-4, 1993.

Ricci, L. L., "NCSS Statistics: Passenger Cars" DOT HS-805 531, Springfield, VA, 1980

Shladover, S. E., "Dynamic Entrainment of Automated Guideway Transit Vehicles". High Speed Ground Transportation Journal, Vol 12, No. 3 pp 87-113, 1978.