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Layout, Design and Operation of a Safe Automated Highway System

by

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LAYOUT, DESIGN AND OPERATION OF A SAFE AUTOMATED HIGHWAY SYSTEM

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Abstract

The paper is concerned with the consequences of control system failures and external intrusions to a fully Automated Highway System (AHS). A model has been developed which enables the casualty rates in lines of automated vehicles to be calculated, following an initial event. It is applied to several situations here for a variety of possible physical layouts and operational modes of an AHS. It is believed that these configurations encompass all those proposed which are economically attractive, and that the accident types encompass the most important ones. For all accident types, there is one system which has casualties per incident no greater than 10% of its nearest rivals. This “preferred” system is described, and the predicted casualty rate results are quoted and discussed. If reliability of the control systems is sufficient, the advantages of the preferred system become unimportant. Values of reliability required are discussed.

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INTRODUCTION

In some earlier papers (Hitchcock 1993a, b, 1994) a model has been described which makes quantitative estimates of the casualty rates in particular kinds of accidents on an automated highway system (AHS). The casualty rates depend on the way motion is organized within the AHS. As a result of this work it becomes possible to integrate the total picture, and determine the total impact of safety constraints on acceptable physical layout and operational scheme of an AHS. In some cases, an alternative to acceptance of the constraining features described here is to ensure high reliability of vehicle control systems: in others the initial element of the danger to be guarded against is external to the system, and cannot be affected by system design.

We shall conclude that there is one preferred scheme among those which are economically viable in that they offer the prospect of those significant increases in capacity which are the *raison d'être* of an AHS. In the event of control system failures, the preferred scheme results in far fewer casualties per failure (by factors of at least 10 or so) than any other scheme of which the author is aware. Thus, if continued high reliability of vehicle-borne control systems can be achieved cheaply, the scheme meets safety criteria significantly more severe than its competitors.

The schemes discussed here assumes a system that has automated cars and light trucks only. Any possible preferred scheme involving heavier vehicles will not be discussed here. Further, the discussion in this paper refers mainly to systems in which the lanes with automated vehicles (*automated lanes* or *ALs*) share a structure with lanes of manual vehicles (*manual lanes*) and are accessed from them. The conclusion, however, also applies to automated systems which are accessed directly from surface streets, in which vehicles become automated on the on-ramps, and resume manual control on the off-ramps. The arguments are basically very similar, and brief explanations of the differences will be made throughout the paper. It is apparent to the author that if there is a network of ALs, so that some are accessed from other ALs, the conclusions also continue to apply. However this does not seem to be transparently valid to others, and the detailed argument, which would be lengthy, has not yet been formulated. This extension must therefore remain speculative.

In this paper we shall first describe the preferred scheme. The reader will then be able to see where our argument is going. We shall then draw attention to the features it possesses which, we shall argue, are essential to a viable AHS. The model which has been described in the earlier papers, and the particular values chosen for some of the parameters, will be reviewed. We shall then turn to the particular accident types which, we shall argue, are critical. We discuss the results of modeling these accidents in a variety of configurations. These configurations encompass all configurations known to the author to have been put forward. The conclusion that only the preferred configuration meets all the criteria will become evident.

There are conceivable accidents, such as the collision of a moving platoon with a stationary one, that are more severe than anything considered. However, it has been shown by Hitchcock (1992) that by the choice of appropriate degraded modes of operation, the use of appropriate design techniques and fault tree analysis, it can be assured that such catastrophes only occur if three or more independent faults occur simultaneously. This will be very infrequent and can be ignored for the present purpose.

DESCRIPTION OF PREFERRED CONFIGURATION

Figures 1 a, b & c show the preferred layout and mode operation. As explained above, this shows an AHS which shares space with manual lanes on a freeway, and is accessed from those manual lanes. If the AHS were on its own structure, and accessed by ramps, figure 1a does not apply, and figure 1b requires a little modification. Figure 1c is unaltered.

Figures 1a, b & c. Layout of preferred AHS. Thick lines indicate a high barrier, dotted lines a low one. Thin lines are road markings. The “dormitory” in figure b receives vehicles rejected at entry, and vehicles which have not resumed manual control after exit.

Figure 1 a

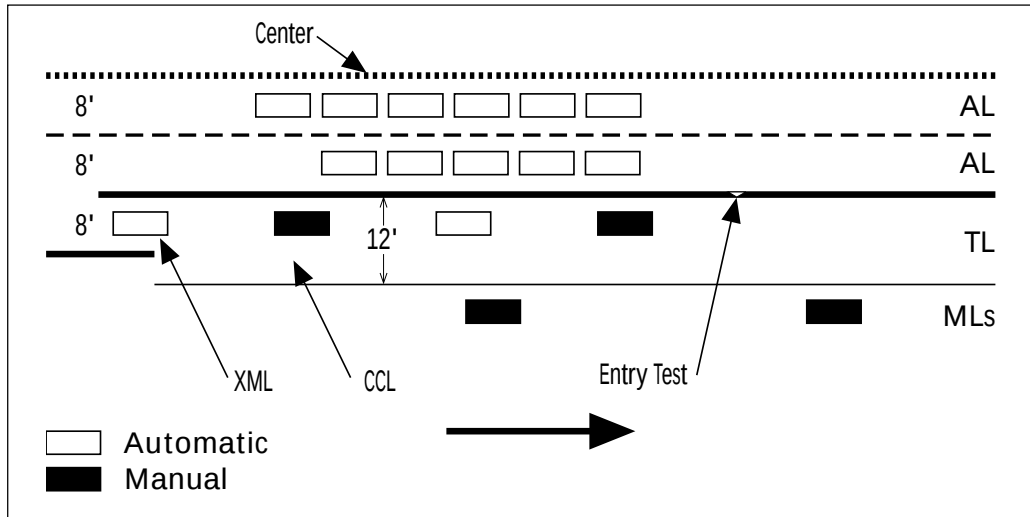


Figure 1 b

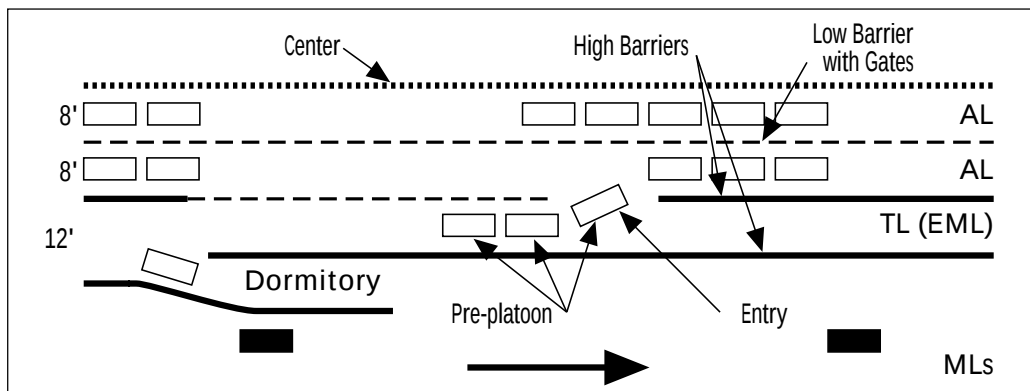
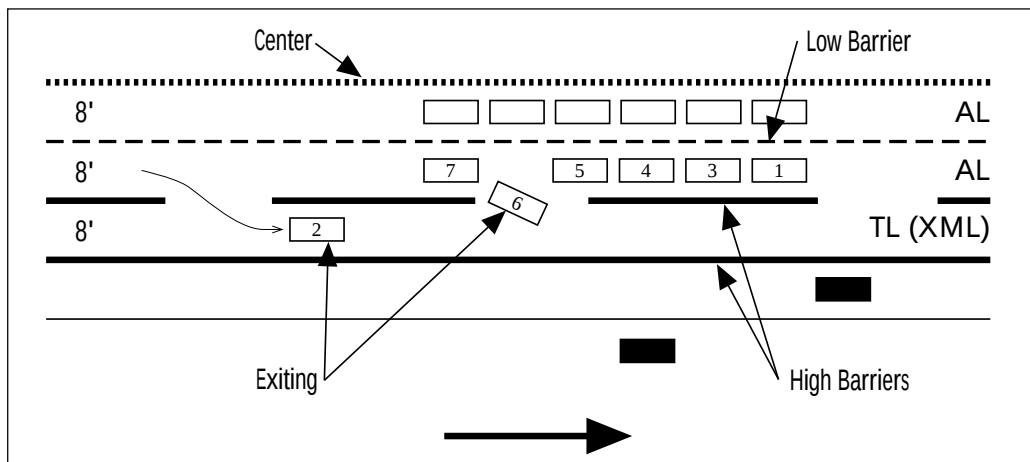


Figure 1 c



We must first define terms. Operation in *platoons* means that vehicles follow one another very closely (our nominal close intraplatoon spacing is 1 m), in groups of between 2 and about 20. Between platoons there is a gap of 60-80 m or more, which is such that vehicles in a following platoon can brake to rest if a leading one stops as quickly as it can. *Dividers* are physical barriers between lanes. They contain *gates*, gaps in the dividers (no moving parts!) through which vehicles can change lanes. We permit two kinds of dividers. The first is a high divider, probably 0.7-1.2 m high, which will resist cars approaching perpendicularly. The second is a low divider, which will permit a car door to be opened over it, and is ankle-high. Dividers must be designed not to present a danger if struck end on at a gate. Their design and use is discussed below. The term *merge* is used to describe a maneuver in which two platoons in the same lane become one. If the platoons were initially in different lanes we refer to this as *entry*, *change-lane* or *joining*.

In the preferred design automated vehicles operate, in *platoons*, on one or more automated lanes (*AL*) from which manual vehicles are excluded. Entry and exit are from a transition lane (*TL*), which is separated from the ALs by a *divider*. (It should be noted that the present definition of “TL” differs from that implied in earlier work—see below.) Entering vehicles join at the immediate rear of a existing platoon: if more than one has to join the same platoon, they do so as a *preplatoon* which has been formed, at low speed, on the TL. As figure 1(b) shows, acceleration of the preplatoon occurs on a stretch of the TL called the entry maneuvering length (*EML*), of which at least part is separated from the manual lanes by a high divider, while between EML and AL there is a low divider (permitting communication and sensing). The EML is probably of AL width, narrower than the parts of the TL open to manual vehicles.

Figure 1c shows the corresponding exit maneuvering length (*XML*). Again it is separated from the manual lanes by a high divider and is of a width appropriate to automated vehicles. Often the XML will be immediately downstream of the EML: if some failure prevents a preplatoon from entering, the preplatoon will be broken into individual automatically controlled vehicles before the XML starts. A vehicle leaves the AL by moving directly out of its position in a platoon through a gate. There may be a need for some minimal opening of the spaces between the exiting vehicle and its neighbors in the platoon before it leaves.

If more than one vehicle in a platoon wants the same exit, they do so by separate gates. Otherwise the platoon will be left with several gaps or large gaps. As we shall see, this would violate safety criteria. After the first vehicle has left, it decelerates, and the gap in the platoon is closed. The next vehicle to leave does so by a subsequent gate. The first exiter is now safely separated from the next.

At the end of the XML the lane widens to normal width, and the high barrier between it and the manual lanes is replaced by one between it and the AL. Here control is offered to the driver. This part of the TL is called the control-change length (*CCL*) and is shown in figure 1a. If manual control is resumed, the vehicle is free to leave the TL before the next EML is reached: if not a *dormitory* area is provided where the vehicle comes to rest. If, in a fault condition, a whole platoon must leave the AL, it can do so as a platoon, and break up on the XML.

If the AHS is on its own structure, and access is from ramps, then entering vehicles are tested and, if accepted, brought under automatic control while entering the on-ramp. The main length of the on-ramp thus becomes equivalent to the EML of figure 1b. Only a small length runs parallel to the AL. All that part of the XML which contains the exit gates, on the other hand, must

clearly run parallel to the ALs, as shown in figure 1c. However, as vehicles enter the off ramp, the lane width increases to that found on manual lanes: this is where drivers are invited to resume manual control. If they do not they are brought to rest at the further end of the off-ramp. In this configuration there is no need for high barriers, but the low barriers remain necessary between ALs, if there is more than one, between ALs and XML, and at the entry end of the on-ramp.

In the preferred scheme, platoons never join or divide on an AL. This is required, as we shall see by the need to conform to safety criteria. We shall not discuss this here, but the length of the EML is reduced, easing constraints if the number of platoons per kilometer remains constant. We shall adopt this assumption here, though it is not a necessary part of the preferred scheme. Even if all vehicles in one platoon leave, the gap is not closed but remains, as a “platoon of zero length”, ready to receive entering vehicles. If there is more than one AL, platoons of equal length move on each AL side-by-side. There are continual exchanges of vehicles between platoons on parallel ALs to keep lengths equal, those leaving first being in the lane adjacent to the TL. It is easy to prove that, under the conditions described here and in the absence of congestion on the AL, the number of platoons per kilometer is a constant; that the distribution of platoon lengths is Poisson, and that as flow increases, so does the mean platoon length.

The reason for this scheme is that the safety criteria require that any changes of lane between ALs must take place without a merge over a length greater than the headway between two adjacent vehicles in a platoon. Thus to change between ALs, two platoons lie adjacent, a gap is opened in one opposite the vehicle which is to change lanes, and this switches lanes when a gate is reached. Since there will be one vehicle changing lanes between platoons several times in two or three miles, it is clearly convenient that the platoons remain adjacent all the time, instead of re-aligning themselves whenever a vehicle has to change lane. This maximizes capacity. Indeed if the criterion of Hall (1993) is applied, it appears that with this configuration, the complexities of lane-changing, entry and exit offer do not constrain the capacity of the system. This has been confirmed by unpublished work by the author.

PRINCIPLES OF DESIGN

This design has been chosen because it meets the following criteria:

Economy and safety. Even allowing for the TL, which bears little through traffic, the capacity per unit width can be made high— twice or three times that for manual lanes. The system can thus be economic. The casualty rates per 100 MVMT that are acceptable are not currently defined. We suggest that AHS must *appear* to be less dangerous to car occupants than the manual traffic (on freeway) that it replaces. In fact such accidents as do occur are likely to make newsworthy photographs: many will involve many vehicles, and when, as will be true in most cases, the injury rate is low, the public is more likely to ascribe this to luck than to sound engineering. When fatal accidents do occur, they are likely to be multi-fatality ones. Thus an AHS will *appear* more dangerous than it is. We suggest here that safety criteria, if they are to be publicly, politically and legally acceptable will require that the injury rate due to any one kind of accident should be less than 10% of the present rate on freeways. Further, suppose there are two alternative designs, “A”, and “B”. “A” produces several times more casualties than “B” following the same initiating event. If, we suggest, it is wished to argue that the difference is unimportant, it will be required that the casualty rate of

“A” is less than 1% of the present rate. “A” could, however, be acceptable with a larger value if there are compensating advantages in air quality or capacity. In what follows we shall assume that this position is adopted. Ultimately the decision about what is acceptable here is for legislatures.

Separation from Manual Traffic on freeway. The requirement above that safety be increased by a considerable factor over the present situation implies that there be no manual traffic on the high-density ALs. Otherwise human errors will occur at the same rate as at present, and produce accident rates which are likely to be significantly larger than at present, since speeds and densities will be increased on ALs. This means, incidentally, that full economic advantage may be taken of automation, and lane widths can be narrowed—we suggest to 2.5 m. There must be manual and automated traffic co-existing on the CCL, but this is at low density and reduced speed. It has sometimes been suggested that, for example, platoon leaders might operate with manual control of interplatoon spacing. Under such conditions freedom from interplatoon collision would be lost in many fault conditions—each such event could be a multi-fatality catastrophe.

Platooned operation for least casualties in failures of longitudinal control. In Hitchcock 1994, our modeling technique is applied to systems with different modes of operation, with this in common, that they have the capability of supporting 6000 vehicles per hour per lane. The critical failure, it is argued, arises when a control system failure results in a vehicle applying full braking without warning. Close-spaced platooning turns out to be robust against a number of variables which are difficult or impossible to control, and to have casualty rates per incident lower by a factor of 5 - 500 than the competitors. Thus our preferred system operates with platoons of minimal intra-platoon spacing.

The competing modes of operation considered here are the following. We are not aware that any other modes of high-capacity automated operation have been proposed.

- a. Platoons. Vehicles move in groups of 2-20 communicating vehicles. Intraplatoon spacing about 1 m. Interplatoon spacing 60-80 m or more.
- b. Point Follower Control (*PFC*). There is a series of “slots”, 10-20 m long, moving down the AL. Each may or may not contain one vehicle. All vehicles communicate with the infrastructure.
- c. Autonomous Intelligent Cruise Control (*AICC*). Each vehicle detects a vehicle ahead, and remains a desired distance behind it. No communication between vehicles. The slot lengths used here are such that the capacities necessary for economic viability are achieved. It would be possible to operate a lane with such vehicle spacings that multiple collisions never occur, but these would have capacities less than existing lanes.
- d. Cooperative Intelligent Cruise Control (*CICC*). Same as *AICC* with communication between adjacent vehicles.

The mode of operation of *AICC*-only and *CICC*-only lanes will be affected by driver behavior, and here assumptions must be made. It seems to us likely that most drivers will attempt to press forward as far as possible, just as observation indicated that they do today. This will result in very long lines of vehicles with the *AICC*-system-determined headway, separated by large gaps headed by a driver who does not think it worth-while to close the gap. Clearly this will not apply to

very low flows, and at intermediate flows other behavior may eventuate. However, although other behaviors would produce results that are numerically different the changes are not so large as to affect our conclusions.

The model, and the results of this work are described in greater detail later.

Dividers to avoid unacceptable casualty rates in secondary accidents. Anwar & Jovanis (1993) enumerated “relevant accidents” on a section of the Santa Monica freeway. These are accidents on the manual lanes as a result of which a vehicle is projected on to the leftmost lane, where the ALs would be. Hitchcock (1993a) calculated that the death rate in automated vehicles per 100 MVMT on an AL on this freeway due to secondary collisions after a relevant accident in the absence of a divider. With platooned operation the death rate would be around 1 times the present rate due to all causes. Work reported below indicates that with other control modes, the effect is even worse. The figures are given below.

Since the death rate without AL/TL dividers is unacceptable, any system meeting safety criteria must have them. It is not immediately apparent, however, that barriers can be made safe. It is clearly possible for a barrier to be struck end-on by a vehicle which is changing lane through a gate. If the barrier is a Jersey beam, or the familiar corrugated-metal barriers seen on freeways, this is known to be extremely dangerous. The barrier must be designed in such a way that it will resist penetration by a vehicle striking its side, but will yield, giving a deceleration of between $1/2$ g and, say, $21/2$ g when struck end-on. This can perhaps be achieved by making it of metal beams much thicker across the barrier than parallel to it, as shown in figure 2. Another possibility applies between ALs, or at the entry-gate (see figure 1b), where the barrier has only to contain vehicles to a narrow lane. Here a low barrier, which will pass under the vehicle and slow it by causing it to plow through sand (see figure 3) may perhaps be acceptable. Neither of these design concepts has yet been tested. It seems unlikely, however, that no acceptable design can be found.

Safe Mechanism of platoon formation. Hitchcock 1993b shows that if the critical failure—brakes on—occurs in the first of two platoons which are merging, the injury rate is some 10 times what it would be if there were no merge. Such figures also apply if one vehicle is merging with a platoon from a great distance. The effect is present, but small, when the merge is across a separation of one car length only, but is two or three times larger than this if the merge is over two car lengths.

We therefore need, in order to meet safety criteria, a mode of operation in which merging over a distance anything from two car lengths to the full interplatoon separation is excluded in normal operation. This has consequences on entry and exit and on the co-ordination of movement on two or more ALs. We accept that in fault conditions it may be necessary to isolate a vehicle which is faulty but can still move under its own power, and, after it has left the AL, reform the platoon by a merge. Under these conditions the merge would be prolonged by limiting the relative speed of the two components, even though this results in a marginal increase in congestion. If such prolonged merges were accepted as part of normal-operation lane-change, lane-changing would constrain capacity very severely, according to the criterion of Hall (1993), as confirmed by unpublished work by the author.

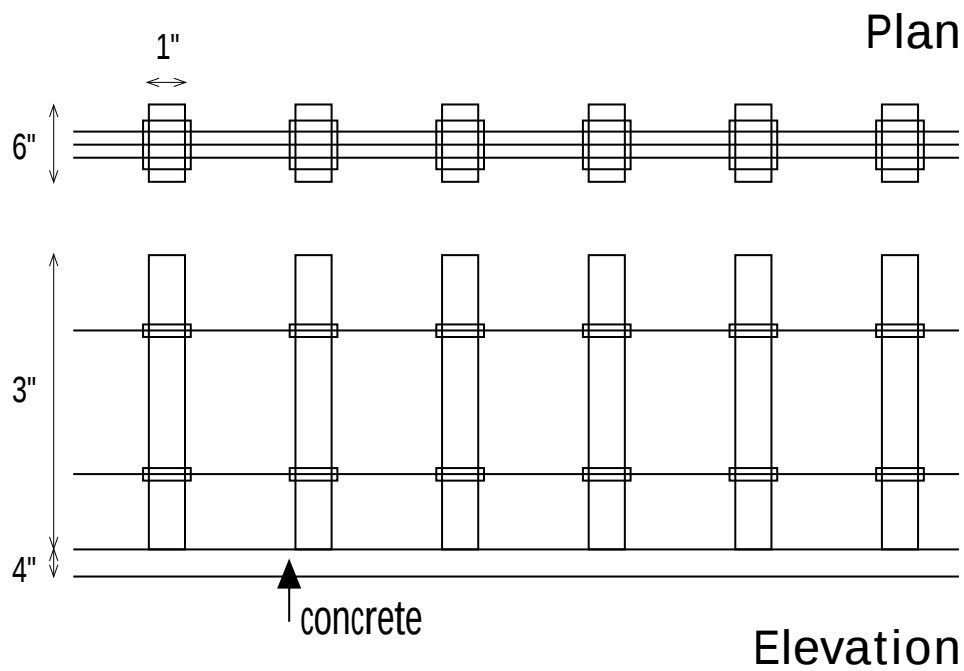


Figure 2 Conceptual design of high barrier. The horizontal links are intended to resist twisting if the barrier is struck obliquely.

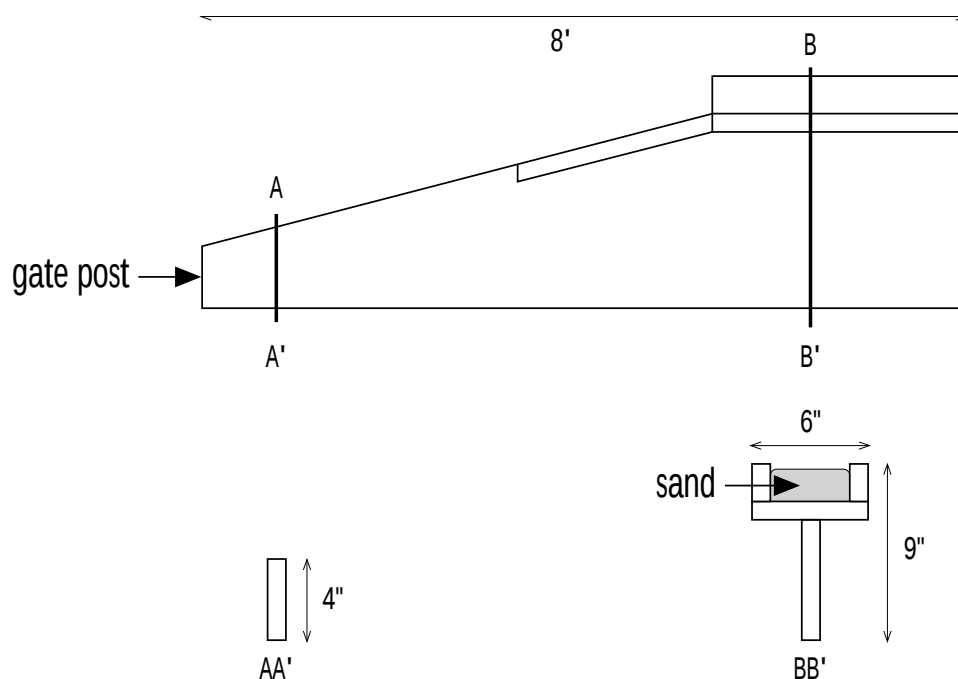


Figure 3 Conceptual design of low barrier. The box containing sand is intended to slow down a vehicle which straddles the barrier.

MOTION OF VEHICLES AND OCCUPANTS

“*Coefficients of friction*”. In the accidents we discuss, lines of vehicles respond to the initial incident by braking. Nevertheless collisions occur. One of the factors affecting the severity of injuries is the variability between vehicles. In any of the longitudinal control schemes, if vehicles were all identical there would be fewer or no collisions. In fact, however, 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 tires which are sufficiently worn to affect maximum deceleration in the wet.

In this paper 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 over a small range, while the minority ranges down to a small value. Figure 4 shows the distribution of f -values for our standard “dry” conditions. (Higher values are not realistic with asphalt or concrete road surfaces.) Fuller details are in Hitchcock 1994. The results reported here and elsewhere use the standard dry and wet values described there.

It may or may not be technically and economically possible to ensure that all vehicles on an AHS have good tires and brakes. However, even if it is technically possible, it may be doubted if it is politically possible (witness the present laws about old vehicles which cannot meet air quality regulations).

However, it is possible that the fraction of vehicles with poor stopping ability either is or will be different from what is assumed here. Some sensitivity analysis has been carried out. The numerical results of our calculations are sensitive to the numbers chosen to describe f -values. The relative magnitudes of the results for different control modes, and the absolute values for the secondary effects of relevant accidents, are less sensitive. The conclusion that the principles stated above are necessary if safety criteria are to be met remains valid, but if the fraction of vehicles with reduced stopping power is very different than what is assumed, the reliability requirement may change.

Equally, the effects of aerodynamic forces have been ignored, (largely because data on them is not yet available). This will affect the magnitude of the results, but seems unlikely to affect relativities. It would be desirable to remedy this defect.

Warning of need to brake. There will be delays in initiation of braking, which vary with the mode of operation. The i th vehicle in line will start to brake at time

$$t_i = a + b \cdot i$$

1. In the *platooned* condition, and also in CICC, a message is passed back from vehicle to vehicle in the platoon. There is then a delay before brakes are applied. We take $a = 0.09 \text{ s}$ and $b = 0.01 \text{ s}$.
2. With AICC, each vehicle can only detect the vehicle ahead of it. We take $a = 0$; $b = 0.09 \text{ s}$. This is optimistic with present del. brake technology, but we are advised that it may become pos-

sible. Thus the generally negative conclusions we reach about AICC later are not due to pessimism here.

3. *PFC* systems are controlled from the infrastructure. We therefore take $a = 0.09$ s, $b = 0$.

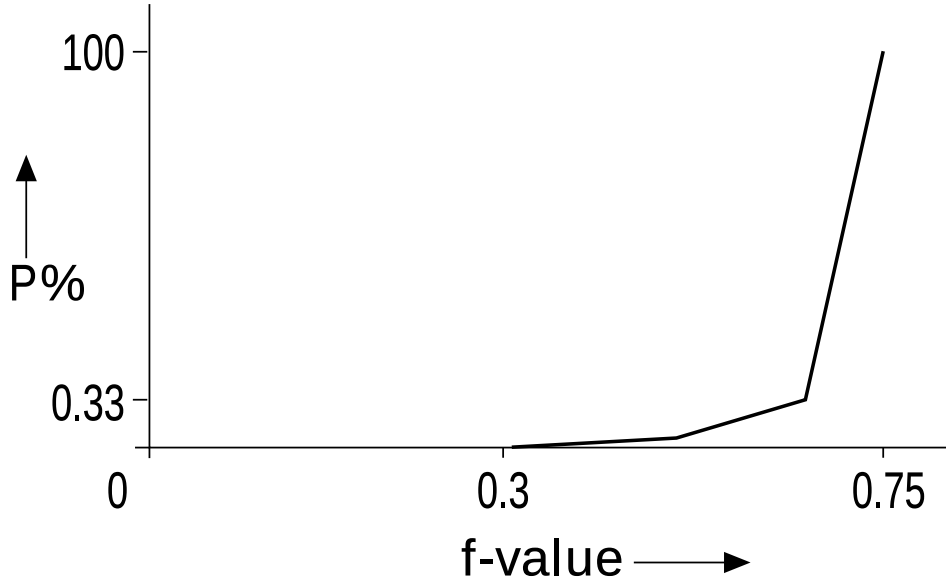


Figure 4. Probability distribution of coefficients of friction. Dry condition.

In all the modes of operation except platooning, long lines of vehicles can be formed, whose length is limited only by the size of the AHS area. If the response to the incident is in all cases full braking, the consequences will stretch back to a theoretical infinity of vehicles, and casualty rates will be also infinite. One way to resolve this is to assume that driver intervention limits the spread of the incident—this is perhaps reasonable for AICC and CICC, especially if no barriers are present, so that vehicles can steer out of trouble. We consider cases in which such intervention is supposed to limit the number of vehicles affected to 10 or 20 vehicles, and others in which a few drivers adopt interplatoon-like spacings. Alternatively, one might assume that less than full braking is applied. One possibility in the *PFC* case would be to arrange that the n th vehicle will come to rest n car lengths behind where it calculates its the failed vehicle will stop. Similar criteria for what we term *graded braking* can be found for AICC and CICC. This reaction requires that the n th vehicle is “aware” of the coefficients of friction and other parameters of the failed vehicle. We investigate the effect of getting these parameters wrong.

There is another problem here: when the vehicle ahead is braking, the safest response for a vehicle’s occupant is to apply the brakes fully. As we have seen, this can increase the total number of casualties, but it reduces the risk to the individual with a choice. There are moral and legal issues which are not relevant here.

Model of vehicle motion. 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 statis-

tically. In the cases studied here, the means of 25000 cases are taken.

The basic configuration which is modeled is a line of vehicles, each behind the next. Barriers are present: vehicles remain in line whatever happens. At time zero all vehicles have the same speed: the initial incident causes messages to be sent to vehicles behind, starting braking at a maximum or graded rate (if the latter is less).

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. All collisions are inelastic, so that *v-masses*, once formed, move as a single rigid body. The value of *delta-V* is recorded. *Delta-V* is the change in speed of the vehicle on impact, and hence the relative speed of vehicle and occupants after impact.

Probability of injury. The mechanism by which an occupant may be injured by contact with the inside of a vehicle after a sudden change in speed is clearly dependent on many variables, such as the occupant's age and the precise position he/she assumed at the moment of impact. We cannot know these things but if we make observations of many similar past impacts, the probabilities deduced will apply in the future, since the occupants' and vehicle's characteristics are drawn from the same population. As explained above, the severity of the impact is measured by the magnitude and direction of *delta-V*. Provided the passenger compartment is not breached and the occupant stays in it, no other parameter can be relevant.

The National Center for Statistics and Analysis (an office of NHTSA) provided data for all vehicles with front damage only involved in accidents recorded in the Crashworthiness Data System (CDS) in the years 1990 and 1991. This related numbers of vehicles involved in accidents with given *delta-V* to the maximum severity of injury suffered by any occupant. Severity was measured in the clinically-attested Abbreviated Injury Scale (AIS) (see AAAM, 1980). In what follows we mostly count what the clinicians term "moderate injuries"—AIS 2. These, very roughly are injuries which cause hospitalization for several days but are not life-threatening. A compound fracture, in which broken ends of bone are exposed to the air, is AIS 2. A simple fracture is not. AIS 2 injuries are roughly one-seventh of injuries described as "serious" in Police Accident reports.

Further information about the treatment of the CDS data, including the formulas relating probabilities of death or injury at different AIS levels to *delta-V* is given in Hitchcock 1993a. It is well attested, e.g. in Ricci 1980, that when the *delta-V* change corresponds to a blow from the rear, injuries are much less serious. Injuries arising in this way were ignored in this work.

RESULTS OF CALCULATIONS

Longitudinal control failure. The only failures of longitudinal control which can generate accidents are ones in which a vehicle's acceleration changes abruptly, or will not change when this is necessary. If a vehicle runs out of gas, for example, it will slow down, but so slowly that following vehicles can also slow without collision. We have already pointed out that proper design of degraded modes can ensure that such violent events as collision of two platoons can be discounted (Hitchcock 1992).

If then, a vehicle accelerates without warning, it may collide with the vehicle immediately ahead. If it is in a platoon, this is not serious, since the relative speed is small. If it is a platoon leader, or otherwise well behind its predecessor, the fault detection mechanism can apply the brakes (an independent function) or switch off the engine. In no case does a serious danger arise.

If a vehicle loses the power to brake, the fault detection mechanism may turn off the engine. If, because there is no immediate effect on the vehicle motion, the fault is not detected, there will almost inevitably be casualties in the accident on exit. It will therefore be important to detect this condition. If it occurs one should switch off the engine. However, the detection mechanism may well fail until the brake is activated. It will therefore also be important to design the automatic braking system in a "fail-safe" manner, so that the failure is dominantly to the other extreme—brakes locked on.

It thus becomes important to examine the consequences when the brakes are fully applied without warning. This is the "fail-safe" mode of the longitudinal control system. As indicated above, should the vehicle accelerate uncontrollably, the failure detection and malfunction management system will adopt this condition.

The results below are expressed in terms of casualty rates per vehicle, $AIS \geq 2$. Where this is meaningful we express the results as functions of flow in vehicles/hr. In the case of AICC and CICC, where long lines are formed, the casualty rates are the same at all flows with a given vehicle spacing: we then express the results as a function of capacity, which also depends on the spacing. If no fatalities occur we shall call the curve "green". If the fatality rate is less than 1% of the casualty rate, $AIS \geq 2$, we shall term the curve "yellow" and otherwise "red".

Effect of speed. The results reported in this paper are for a speed of 30 m/s (≈ 68 mph). Some values for wet conditions are given in the figures but are not always included in the tables. In Hitchcock 1994 results for a speed of 25 m/s (≈ 56 mph) are also reported. together with fuller results in wet conditions. The effect of speed, over the range 25 - 30 m/s is small and may be in either direction. At given capacity, if speed is reduced, the platoon size increases. This increases the number of collisions. The resulting increase in casualties is offset against the reduction which occurs because delta-V values are less.

Platoons. We consider platoons with spacings of 1 m, 4 m, and 10 m, with the numbers of platoons per km chosen to give roughly equal capacities. For the 10 m spacing, in particular, this leads to platoons with numbers of vehicles which are perhaps unrealistic. 6000 veh/hr is, at best, very close to the limit of what is possible with this spacing. Figure 5 and table 1 show the results.

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.

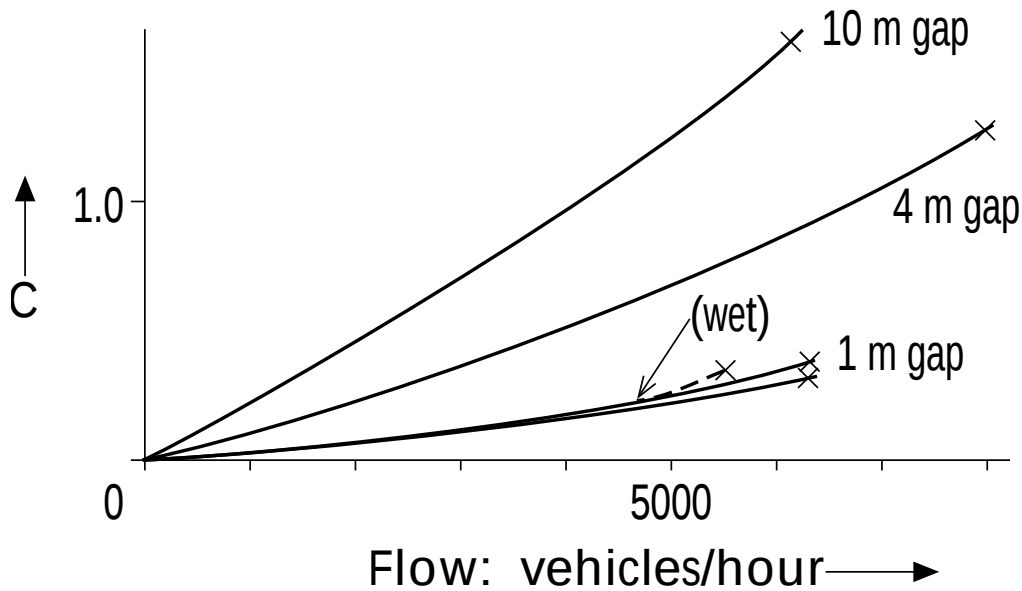


Figure 5. Casualties, C , ($AIS \geq 2$) per 100 incidents, platoons in dry weather. The 1 m gap curve is “green”, the others are “yellow”.

Table 1. Capacity and casualty rates at capacity: platoons.

Spacing (m)	Plats/km*	Speed (m/s)	Capacity (Vehicles/h)	Casualties ($AIS \geq 2$) per 100 incidents	
				dry	wet
1.0	8(7.5)	30	6480	0.27	1.37
4.0	4(18.9)	30	8180	1.18	3.34
10.0	2(28.0)	30	6040	1.55	6.72

The curve for 1 m spacing is green, the others yellow.

* No of vehicles per platoon

PFC. Figure 6 shows the results for PFC configurations. Some of them are also shown in table 2, which gives parameters describing the different configurations. We have explained above that in this case we assume that the system imposes “unselfish” braking behavior. Each vehicle, on hearing that there has been heavy braking in vehicles ahead, itself brakes (if it can) with the deceleration it calculates will bring it to rest in vehicle lengths behind the failure.

This rule implies that the control system uses an implied f -values for the failed vehicle to compute its own deceleration. Figure 6 is drawn on a logarithmic scale because of the very large differences that errors here can make.

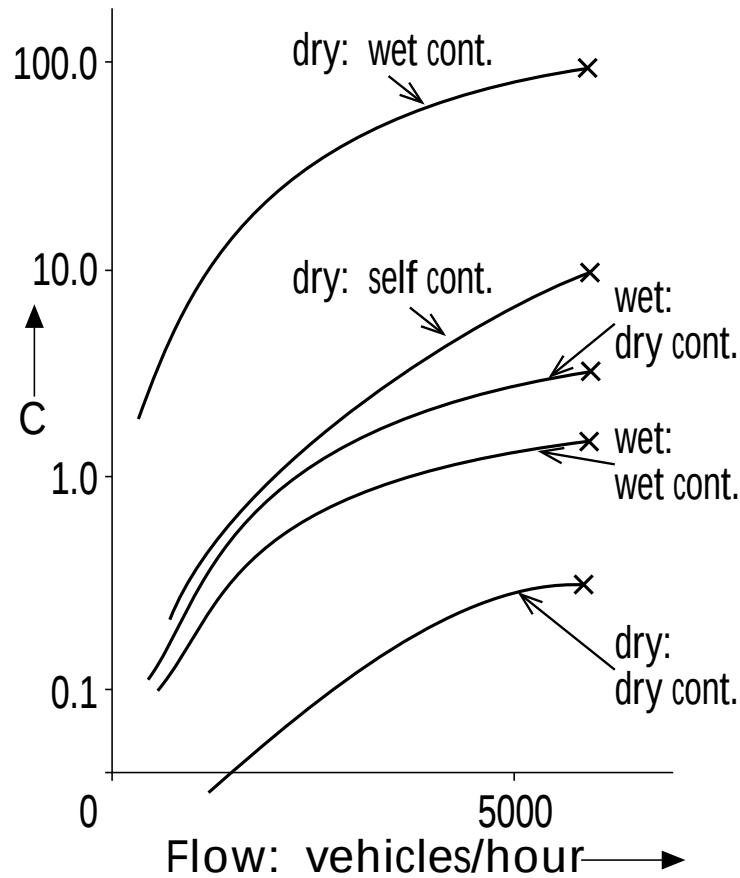


Figure 6. Casualties, C, (AIS ≥ 2) per 100 incidents. Point follower control, slot length 15 m. The cross indicates capacity. See text for meaning of labels.

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, (wet: dry cont.” in figure 6) the casualty rate is more than doubled over the well-organized “wet” conditions—a ten-fold increase over the “dry” values. This curve is red. In the reverse condition, where conditions are in fact dry, but the control system calculates on the basis of a “wet” range (dry: wet cont.” in figure 6), the increase in casualty rates is over 250-fold, and, again, the curve is red.

In practice, it may be difficult for the central system (and PFC is controlled from the infrastructure) to “know” just what are the appropriate conditions at every point in the network. The large effects of errors here, are therefore not academic. There may be solutions 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 the casualty rate and a red curve (“dry: self cont.” in figure 6). There may be better solutions: we have not been able to find them.

Table 2. Capacity and casualty rates at capacity: PFC

Slot length (m)	Speed (m/s)	Capacity(1) (vehicles/h)	Casualties (AIS $\geq$ 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	30	5760	93.0		(2)
# 15	30	5760	..	3.04	(3)
# 15	30	5760	9.44	8.44	(4)

indicates that fraction of casualties (AIS $\geq$ 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.

AICC. Figure 7 and table 3 present results and some details of the configurations considered. Our assumption of long lines means that, for any one inter-vehicle spacing, the casualty rates are independent of flow. This is clearly unrealistic at low flows. Changing inter-vehicle spacing changes both the casualty rates and capacity, so that the different points on the curves in figure 6 correspond to different vehicle spacings.

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” or “10 in line”. 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 results are not shown in a figure: they 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.

**Table 3. Capacity and casualty rates at capacity: AICC.
(These values apply at all flows.)**

Veh'e Speed Cap'y(1)			Casualties (AIS ≥ 2)					graded braking
spacing			per 100 incidents					
(m)	(m/s)	(veh/h)	20	line of vehs 10	voluntary gaps 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	**
Wet Conditions								
#50	30	1570	1.84	0.87	0.43	0.92	1.41	
#45	30	1730						0.17
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	**

Notes:

(1) An allowance of 20% is made to allow spaces to enter.

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).

* These values are less than present manual capacity.

** “Infinite”—see text.

3. We also consider the possibility of an 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 choose 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. The curve is red.

There may be other automated strategies which are superior to the “graded” one chosen. Our search for one was not successful.

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.

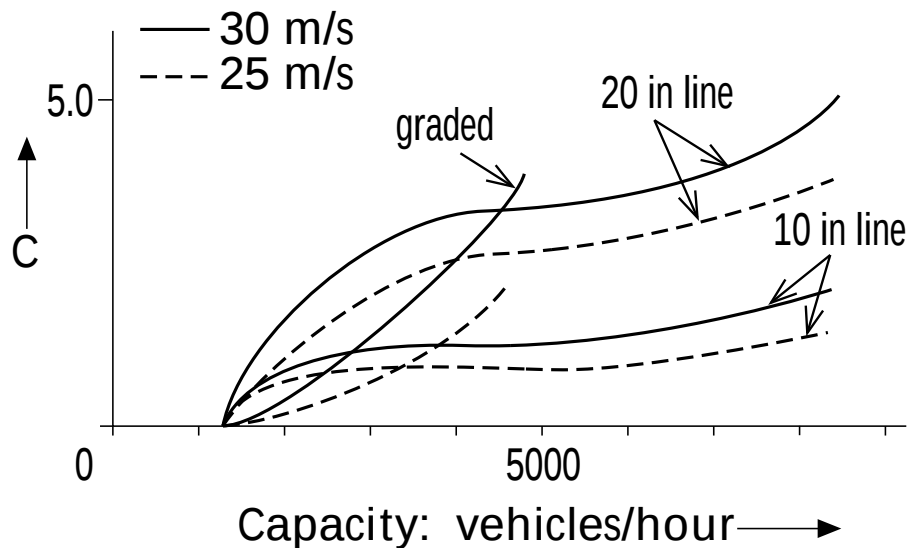


Figure 7. Casualties, C , ($AIS \geq 2$) per 100 incidents. AICC. Dry conditions.

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.

The results are given in table 4. 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 those shown in table 2.

Intruders from a relevant accident. In order to demonstrate the need for dividers, we calculate the casualty rates due to “relevant accidents” (Anwar & Jovanis, 1993) on that 12-mile section of the Santa Monica freeway which was studied by those authors. The model used to calculate the effects was basically the same as that discussed above for longitudinal control failures. The same correlations between casualty probabilities and Δv was used as discussed above, the same distribution of coefficients of friction, and same delay times on braking in the different control modes. The configuration studied was of a freeway whose manual lanes are similar in geometry and flow to the Santa Monica Freeway on 17 Sept 1992 (the date for which data was obtained) However an automated lane has been added, on which there is a traffic flow equal to 40% of the manual flow, hour by hour throughout the day. We report deaths on the AL per 100 MVMT on the AL due to second-

ary accidents following a “relevant accident”. The calculation is for each control mode. Speed on the AL is 30 m/s (67 mph). We allow for 20 wet days per year, which is believed to be roughly correct for Los Angeles. Further details are reported in Hitchcock 1993a.

Table 4. Capacity and casualty rates: CICC

Veh'e Speed Cap'y(1) spacing			Casualties (AIS ≥ 2)					
			line of vehs		per 100 incidents groups (2)			graded braking
(m)	(m/s)	(veh/h)	20	10	10	15	20	
10	30	7200	2.14	1.02	0.50	0.76	1.06	0.38
15	30	5400	2.18	1.09	0.53	0.83	1.13	0.26
20	30	4320	2.19	1.09	0.51	0.75	0.57	0.17
#30	30	3090	1.40	0.69	0.37	0.57	0.79	0.10
#40	30	2400	0.71	0.34	0.18	0.28	0.37	0.06

Notes:

(1) No allowance for flexibility for entry: values for vehicle groups somewhat less, depending on inter-group spacing.

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).

The results are given in table 5. It will be seen that the effect of increasing the length of the line affected is not great. The initial collisions of the first and second vehicles which strike the intruder are severe, and the bulk of the deaths occur in these two. After that, the v-mass has acquired a significant speed along the line of the AL, and subsequent collisions are less often fatal. The platooned case has a lower casualty rate largely because there are gaps between platoons, and if the intruder enters the AL here the platoon has a chance to slow down.

It may be asked why a similar death rate is not observed now. Deaths in secondary collisions following a relevant accident do occur now, but in smaller numbers because:

- Speed in the left lane of the Santa Monica freeway does not always exceed 60 mph.
- Flow on this lane is not 6000 veh/h now.
- A manual driver will receive earlier warning of an intrusion than the AHS. The latter can only detect (or so we assume) intrusion on to the AL. A driver will hear the accident, and will take avoiding action if the debris is crossing his/her path.

The intruder is taken, in the calculations, to be a car. Anwar & Jovanis do not report the number of intruders that were trucks. In private discussion, the authors explained that the number was around 5 per year: too small to be statistically satisfactory for prediction, but not zero. Calculations indicate that with a 40,000 lb truck the death rate per incident increases between five- and ten-fold. The increase depends on the weight of the intruder. The extent to which a barrier would contain a truck, however, is uncertain, and a great deal more data about relevant accidents would be needed to work this out.

Table 5. Deaths per 100 MVMT on an AL on the Santa Monica freeway following “relevant accidents”.

Control Mode	Vehicle Spacing (m)	Platoons per km.(2)	Number in Line	Deaths per 100 MVMT(1)
Platoon	1.0	6	..	0.84
Platoon	1.0	4	..	0.72
Platoon	4.0	4	..	1.01
Platoon	10.0	2	..	1.39
PFC	10.0	..	..	1.39
PFC	7.0	..	..	1.42
CICC	10.0	..	20	3.12
CICC	10.0	..	10	3.12
CICC	20.0	..	10	2.08
CICC	40.0	..	10	0.76
AICC	10.0	..	20	3.31
AICC	10.0	..	10	3.31
AICC	20.0	..	20	2.13
AICC	20.0	..	10	0.76

Present death rate on urban freeway in California, all causes:- 0.61 per 100 MVMT.

Notes:

(1) per 100 MVMT on the AL.

(2) this number is kept constant, and flow changes reflected in the mean platoon size. See text.

We conclude that without a barrier the increase in deaths would be unacceptable. With a barrier it may not be.

“Brakes-on” failure during platoon merge. If the brakes-on failure discussed above occurs in the forward platoon while two platoons are merging the mechanism which prevents violent collisions following a sudden deceleration is no longer operative. The gap can be large enough to permit significant change of relative speed, and there is significant relative speed initially, when the failure occurs. Hitchcock 1993b describes the model and programs used to calculate casualties during the merge period. The model is essentially the same as that described for the other investigations reported here: the casualty rate is calculated for a series of separations and corresponding relative speeds, and a numerical integration is carried out. The relative speed profile assumed for the maneuver consists of a series of segments which may be jerk-limited, acceleration-limited or relative-speed limited. The limitations on jerk (0.2g/s) and acceleration (0.2g) are those recommended by Caywood, Donnelly & Rubenstein (1979) as appropriate for seated passengers facing forward. The recommendations are based on extensive experiment.

Table 6. Casualties during merge per 100 incidents

Platoon Speed (m/s)	Max. rel. speed. m/s	Gap to close m.	N	Merge Duration s	Deaths	AIS ≥ 2
30	None	80	12	13.7	0.08(0)	15.6(1.36)
30	None	80	10	14.6	0.08	13.7
30	None	80	8	14.6	0.08(0)	11.9(1.06)
30	5	80	10	19.5	0.01	3.6
30	2	80	10	42.0	**	1.3
30	None	120	10	16.5	0.23	16.5
30	5	120	10	27.5	0.01	2.8
30	2	120	10	62.0	**	1.2
30	None	6	10	4.6	0	2.7
30	None	12	10	6.0	0	4.3
10	None	48	3*	8.8	0	0.9
5	None	48	3*	8.8	0	0.2
2	None	48	3*	8.8	0	0

* one vehicle merging with two ahead.

** less than 0.01.

N is the total number of vehicles involved: leading and trailing platoons are each of N/2 vehicles. Number in brackets is number with no merge: for N = 10, speed = 30 m/s; Deaths = zero, AIS ≥ 2 = 1.14.

Table 6 gives some selected results. In some cases a limitation has been placed on the maximum closing speed of the merging platoon. The imposition of a limitation reduces the number of casualties per merge. If the failure can occur at any time, the risk of casualties is proportional to (casualties/merge)•(merge duration). This also decreases as the relative-speed limitation becomes more restrictive, but less markedly.

Even if no merges take place over the normal interplatoon gap, there may still have to be merges over one or more car lengths after a vehicle has left the platoon. The table shows that a merge over one car length is significantly superior to one over two lengths.

The last three entries, with reduced speeds, show that preplatoon formation at the entrance to the EML can indeed be made as safe as is wished by doing it at reduced speed. The precise speed profiles and strategies for preplatoon formation require further study. The ones implied here are probably not the best.

CONSEQUENCES FOR AHS CONFIGURATION AND OPERATION

Our preferred layout (see figure 1) has the properties that the results above demonstrate to be necessary:

- a. It does separate manual and automated vehicles on the high-density AL. Automated vehicles on that part of the TL to which manual vehicles have access have reduced speeds, and for the critical maneuver of preplatoon formation, the speed is very low indeed.
- b. It uses close-spaced platoons.
- c. It has high barriers between AL and TL, and low ones between ALs, which are so designed that they will not generate severe casualties if a failure of lateral control causes a vehicle to hit them end-on. There are no “gates” (no moving parts) in the high barriers, and gates in the low barriers are protected from manual-vehicle accident debris by the high ones.
- d. It can be operated without merging of platoons over distances exceeding one car length, as the following description of the operation shows.

Maneuvers in operation. Since there is no merging of platoons over the interplatoon spacing, the number of platoons per unit distance is constant: variations are reflected in changes in mean platoon size. It would be convenient, though not necessary for safety, if platoons moved so that the distance between platoon leaders remained almost constant. Even if a platoon happened to become empty there would be no changes in relative position of the leaders: entering vehicles could reform the platoon by entering the large gap.

On the ALs, if there were more than one, speeds would be equal in both lanes. Vehicles would move from one platoon to another which lay beside it: a gap, length one vehicle plus spacings, would open in the receiving platoon opposite the mover, which would transfer at a convenient gate. This process is very rapid, and, according to the criterion described by Hall 1993, (and unpublished work by the author) does not limit capacity, even if many changes are needed.

At exit, supposing several vehicles have to leave one platoon there is a succession of gates: the most forward of the vehicles to leave does so by the first gate. The gap is closed before the next vehicle leaves at the second gate. Following exit, vehicles are braked to a speed suitable to the TL and separated by safe distances before leaving the narrow XML (figure 1c), where they are offered manual control.

At entry, the reverse process to exit involves unsafe following distances—vehicles would be accelerating towards each other rather than braking. Therefore as each vehicle enters it is assigned to the first platoon that it can join. Platoons are some 6-10 s apart: it is possible that more than one vehicle will be assigned to the same platoon. Each is brought to a very low speed, or to rest, and following vehicles merge with it (safe at low speed) forming a preplatoon. At the right moment a controller (this may be vehicle- or infrastructure-borne) gives the word to an appropriate number of members of the preplatoon to accelerate. They coordinate with the platoon so that they arrive at an entry gate with the platoon’s speed just as the last vehicle in the platoon has passed. They join, as a platoon, through the gate on to the rear of the AL platoon, which thus does not have to divide to accept them.

Low barriers. The safety case for the low barrier arises only in fault conditions. If one lane has been brought to rest, it is desirable on capacity and fault recovery grounds that the trouble be confined to one lane, so that others can be used. Also, in the same conditions, a lateral control failure in the operating lane would cause death and injury if it led to collision with stationary vehicles in the

adjacent lane. This said, it is clear that the case for these barriers is less strong than for the other features we have described.

CONCLUSIONS

The configuration of the “preferred” AHS, shown in figure 1, and the mode of operation described here, conform to the safety principles which have been demonstrated to be desirable. In the case of the barriers, the danger which is guarded against is external, so that these are always necessary. In the case of the longitudinal control failures, high reliability of the control system is an alternative. It is easily seen that a configuration which gave x casualties ($\text{AIS} \geq 2$) per 100 incidents would generate casualties at less than 1% of the current rate (and so be negligible) if the failure rate per vehicle per thousand years were less than $0.3/x$. This corresponds to a mean time between failures of $4 \cdot 10^5 \cdot x$ hours. We have seen that for configurations other than the preferred one, which have acceptably high capacities, x is typically in the range 1.5 to 5. Vehicle failures of the wrong kind would have to occur less than once per 10,000 vehicle-years. That is, mean times between failures of 10^6 operating hours should be envisaged. Given that the quality of maintenance received by private cars is indeterminate, this would represent a challenge to the automobile manufacturer, which could conceivably be met. Alternatively, the configuration of figure 1 diminishes the required standard of reliability by a factor exceeding ten.

A note on mixed-flow AICC. Mixed-flow AICC may be a precursor to full AHS and is therefore of interest. In this scheme AICC vehicles and normal ones travel in the same lane, and lines of AICC vehicles form behind manually controlled ones. Brake control system failures in an AICC vehicle affect any following AICC vehicles. If the next manual vehicle is following too closely, it, too may be involved in any resulting collisions, but we are here concerned with accidents to automated vehicles, and ignore this.

Mixed-flow AICC does lead to some increase in capacity which cannot approach what is ultimately required unless the fraction of all vehicles in the lane which are AICC vehicles is very high. Casualties per incident also depend on the fraction of all vehicles in the lane which are AICC. Up to a value of this fraction, no matter what spacing is chosen for AICC operation, the casualty rate ($\text{AIS} \geq 2$) in the automated vehicles remains below 0.4 per 100 incidents at 30 m/s. At this value, if the AICC vehicles follow closely, capacities up to about 4000 veh/hr can be attained. As the fraction rises towards one, however, the casualty rates per incident rise rapidly. The $\text{AIS} \geq 2$ rate can exceed 1.5 per 100 incidents at a penetration of 83%.

Mixed-flow AICC therefore does not present the same dangers to its users as AICC on a reserved lane. Mixed flow AICC is not compatible with dividers, and no calculations on these lines have been made.

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