# Intelligent Vehicle-Highway System Safety: Approaches for Driver Warning and Copilot Devices

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Estimates of accident savings ascribed to the intelligent vehicle-highway system (IVHS) and IVHS devices have been published by Mobility 2000. These estimates were obtained through the use of expert judgment applied to various configurations of accidents, for which data are available in standard sources. Similar work has been done in Europe. The availability of in-depth data sets and other more detailed sources enabled estimates to be made on a quantitative basis. Methods used in European and U.S. work are discussed, and results are compared. An account is given of a possible development of the evaluation technique that can provide greater precision and might facilitate the choice between different realizations of the same requirement. Finally, the possibility of interactions among different devices on the same or different vehicles that might hinder safety is identified. The need for systematic configuration management of IVHS is emphasized.

Techniques developed in Europe for the examination of intelligent vehicle-highway system (IVHS) safety are described. The use and extension of these systems in U.S. conditions are discussed. The lack of certain data is identified as a barrier. Specific topics covered include the following:

- Reevaluation of the conclusions of the Mobility 2000 evaluation of IVHS (*1*) in light of some European results and discussion of the availability and collection of suitable data in the United States;
- Proposals to extend the methodology to enable quantitative evaluation of specific designs; and
- A discussion of the interaction between faults and of the need for an appropriate configuration management technique.

## COST-BENEFIT ANALYSIS OF IVHS SAFETY

### Accidents Avoided by New Technology—U.S. and European Approaches

The Mobility 2000 group desires to bring together practitioners involved in the development and exploitation of the IVHS. The group recently issued a series of reviews and an initial cost-benefit analysis of IVHS (*1*), which addressed the impact of the introduction of the IVHS on highway deaths and injuries. Several possible IVHS devices were hypothesized, and five classes of accident were identified as susceptible to change. Estimates of the effect on each were made on the basis of expert opinion. The five classes were related to relative motion at the time of collision: off-road, head-on, rear-end, angle, and sideswipe. In forming their judgments, the experts clearly had to picture the mental processes by which drivers make the errors that lead to such accidents. They then had to judge to what extent a warning (or preemptive control action) would be beneficial.

This approach raises a number of questions:

- Have all the routes by which accidents of each type can occur been considered or identified?
- Is the approach not highly subjective? Is it reproducible?
- Is the approach not open to accusations of bias?
- Might the approach not be biased by the choice of accident classification (which is constrained by the form of the existing statistics, chosen for other purposes)?

These questions can be robustly answered by the observations that work must begin somewhere, that it is more important to obtain answers correct to order of magnitude now than pedantic precision next year, and so on. Indeed, the questions are necessary and timely; because expert opinion will be the immediate source of decision making, it is best that it be expressed.

However, the Mobility 2000 authors were apparently unaware that a quantitative method for tackling this problem had been employed by Hitchcock (*2*) to provide a similar preliminary estimate of the potential impact of the European IVHS project, PROMETHEUS. An account of this project has been published (*3*). The technique requires fewer heroic subjective assumptions, although it is not free from subjective elements. Further papers on this technique have been published by Broughton (*4*) and by Fontaine et al. (*5,6*). The latter developed the technique usefully.

These sources refer to the types of device being developed in PROMETHEUS, which the Mobility 2000 reports call the advanced vehicle control system (AVCS). AVCS-1 devices fall short of full automation and are therefore applicable on all roads, both in urban and in rural areas. [AVCS-2 involves full automation of the driving task on certain freeway links, whereas AVCS-3 adds strategic routing and scheduling functions to an automated freeway network (*1*).] Discussion here is largely restricted to AVCS-1 devices.

Hitchcock (*2*) used the U.K. at-the-scene data base, which consists of observations made by professional observers at the

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scene of accidents within half an hour of their occurrence, supplemented by interviews with those participants in the accidents who consented to them. A tolerable response rate was achieved, with full sets of interviews being conducted in about 60 percent of all cases. Some 1,300 full records were used. Hitchcock also gave a rather general description of the way in which PROMETHEUS would achieve unprecedented safety, placing insufficient emphasis on advice to drivers as opposed to direct control action.

Each relevant accident record was read, and a judgment was formed about whether, in the circumstances described, the IVHS devices specified could have affected the course of the accident. By totaling the number of successes for each device, an upper bound to the efficiency of the devices can be obtained, after making some corrections arising from the nature of the sample.

Broughton (*4*) used the same data, but provided much more precise descriptions of the functions offered by possible PROMETHEUS devices. He also employed less restrictive assumptions than did Hitchcock, who had been concerned that IVHS devices should not perform in ways that led them to be mocked, such as stopping at green lights to avoid collision with traffic approaching a red or declining to leave the road to enter an owner's driveway.

Fontaine et al. (*5,6*) also gave more precise descriptions of 14 possible PROMETHEUS functions, but, lacking an in-depth data base, used the precise police reports of accidents known in France as *procès-verbaux*. These authors appreciated better than their predecessors the importance of precisely stating the assumptions made about the scope of action open to the device, thus avoiding unexplained differences such as those between Hitchcock and Broughton. Fontaine et al. also describe an alternative method for typifying accidents, but it does not add to the quantitative results.

Conditions are different between Britain and France, but they are probably more similar than either is to the United States. At full penetration of the devices, Hitchcock found an upper bound to the reduction in accidents to be approximately 25 percent, Broughton found 60 percent, and Fontaine et al. found 45 percent. Each recognized that the figure was an upper bound on the basis of the following assumptions (*4*):

- All devices work as intended;
- All drivers react as intended; and
- There are no unintended side effects, particularly no behavioral changes.

The devices assumed by these authors are not the same, however. In particular, Broughton assumed a device that could advise the driver of the speed "most appropriate to the conditions," varying with congestion, traffic pattern, weather, light, and so on. It is not clear that anyone could arrive at a consensus, before the accident, on this speed. It is even less clear that the speed could be specified mechanistically. Hence, drivers might be more reluctant to accept its guidance than that of other copilot devices. Without this assumption, Broughton's figure would be approximately 20 percent less—more in line with that of Fontaine et al. whose less optimistic speed control has an effect in only 3 percent of cases.

Fontaine et al. and Broughton find that nearly half of the remaining effect (i.e., 20 percent of all cases) can be ascribed to devices in which active elements in two vehicles determine the likelihood of collision by communicating their positions and intended trajectories. Such devices are clearly not effective until penetration of the market is nearly complete. Hitchcock did consider such devices, but, under his more restrictive assumptions, its effect was only 5 percent.

These large corrections bring the three results into line to an unjustified extent. There are other smaller differences that, if corrected, would take them further apart. Nevertheless, the three European studies are much less at variance than appears at first sight. It seems right, at full penetration, to reject Hitchcock's restrictive approach to intervehicle communication. It seems best, too, to reject Broughton's so-called "wise" speed indicator. The conclusion, then, is that the effect under European conditions of PROMETHEUS is a reduction of 45 percent or so in injury accidents.

There is some agreement that a cooperative trajectory-indicating anticollision device—perhaps as advanced an application as considered—would reduce accidents by only 20 to 25 percent. The U.S. workers also considered an advanced robust collision prevention system, which reduced all categories of accident, at full penetration, by 70 percent. This variation may reflect optimism in the United States or actual differences between U.S. and European conditions.

Although all authors, European and American, recognize that it is possible to mount devices in a vehicle that can detect the presence of alcohol, none listed such a device. Those who do include an impairment detector based on erratic behavior consider that it will not detect alcohol use.

### Application to U.S. Conditions

Although it is relevant to draw attention to large discrepancies (as with the robust collision prevention system mentioned previously), little consideration is needed to demonstrate that European numbers are not transferable to U.S. conditions. In the United Kingdom, for example, roughly 15 percent of vehicle-miles traveled (VMT) is on freeways. In California, by contrast, some 40 percent of VMT is on freeways. Equally, in both Britain and France about 40 percent of those killed (to compare numbers injured is unwise because of differences in definitions) are either pedestrians or pedal cyclists. The corresponding figure for California is 20 percent.

Hitchcock (*2*) indicates that the IVHS devices he considers will avoid a larger fraction of freeway accidents than of all accidents. No doubt, other, subtler factors related to differences in terrain, law, and social custom are involved, but it would not be useful to pursue them here.

It is not immediately possible to apply the techniques directly to U.S. conditions because of a lack of necessary data. In Britain an in-depth data base was used. A publication by the Organization for Economic Cooperation and Development (OECD) (*7*), reviewing data bases of this type, refers to only two such data bases in North America, although its time scales preclude reference to the pioneering Indiana trilevel data (*8*), which are of the required type. The Indiana data base dates from the early 1970s and therefore may lack the power to enforce conviction.

One data base referred to by OECD (*7*) is the Canadian work done along with the trilevel work, which was concluded in 1979 and therefore may suffer the same lack of power to convince. The other is the National Accident Sampling System (NASS) (*9*).

NASS data are detailed but emphasize the crash and post-crash phases of an accident, as expected, given the primary responsibility of its sponsor for vehicle safety standards. In the form in which NASS data are available, their value in this context may be limited. Work is in progress to determine to what extent they can be used.

Equally, there is no U.S. equivalent of the *procès-verbal*. Although U.S. police records of accident investigations were not examined, they are said to be extremely variable. Indeed, that the levels of emphasis of good reporting vary from police force to police force and, no doubt, from officer to officer is a matter of record.

However, there are also records that are complete. There is no a priori reason to suppose that the quality of the police record (regarded as a source for research of this kind but not written for that purpose) is closely correlated with any other relevant characteristic of the accidents. Tolerably quantitative results could possibly be obtained by using a selection of existing police records.

There are obstacles to this approach. Records that identify individuals, their statements to police, and police opinion for situations in which prosecution is possible are rightly regarded as confidential. The police would carefully examine the protocols proposed by any researcher before allowing access to such data.

There may, however, be ways of avoiding this difficulty, at costs in time and money. Perhaps someone who was permitted to view such data could sanitize it by removing names, addresses, and the like, passing only extracts to the researcher, or could arrange for letters to be sent to those involved seeking permission for data to be passed after being made anonymous. If the number of records to be examined were large, such expedients would be costly. However, if the researcher were content to examine 1,000 or so accidents, which would certainly suffice for the first stage, the cost would not be prohibitive.

Another possibility would be to work in an area where the police could be persuaded to make their records more complete for a limited period. Unfortunately, it would not take long to assemble records of 1,000 accidents in a small area.

It is unlikely that a fully representative sample of accidents could be assembled by such methods, but the experiment of assembling data could be useful. (The representativeness of the European data can also be questioned.) It would perhaps be appropriate, in view of the European findings, to take separate samples of freeway and nonfreeway accidents.

## EFFECTIVENESS OF ALTERNATIVE DESIGNS

The evaluation technique can also be developed for use at later stages of design. It can probably be modified to select the more efficient alternative realization of a specification and to examine the significance of engineering tolerances in the specification. The basic tool required is a computer simulation shell that can represent the movements of several vehicles on a road or on roads of variable geometry. It must be possible to insert varying control algorithms. In such a simulation the human driver must be represented as a controller whose objective function is a particular space-time trajectory (initially the one actually followed). The driver is represented as being able to change the objective function on receipt of an external stimulus (personal observation or IVHS-generated warning) with a variable time lag.

The computer shell is then used to simulate a series of actual accidents, the course of which is known either because the accidents are recorded in an in-depth data base or in some other way, as discussed previously. As in the earlier case, it is assumed that one or more IVHS devices, including the one being tested, are installed in one or more of the vehicles in the simulation. One or more alternative assumptions are entered about how the driver's control-objective trajectory will change if a warning is received. These assumptions must be consistent with what is known about the way in which the driver actually behaved. Alternatively, if the IVHS device is one that overrides the driver, the user must feed in the device's behavior.

In practice, a series of variations of a single accident case would be considered, varying driver reaction times, precise initial positions, and speeds of vehicles. It will always be necessary to check that, without warning, the accident occurs as it did. It can then be determined whether the effect of the device under evaluation is always the same. If desired, the behavior of the IVHS device can be varied within its engineering tolerances. This process must of course be done for a series of accidents taken from the data bank in which there is reason to suppose that there will be an effect.

The development of a computer simulation of this kind will be lengthy and complex, and its use in the way described presupposes not only the existence of a significant number of in-depth accident reports but also significant expenditure in setting up each case. Fairly good statistics are required, too—at least 20 and perhaps as many as 100 relevant cases should be run.

However, the proposed method does ensure that design decisions are tested against real data. Experience in the direct use of in-depth data bases reveals how much more complicated most accidents are than appears in a simple statistical record. Vehicle movements and drivers' intentions are affected by the presence of road users and vehicles who are not involved in a crash, have committed no irregular action, and may not have been aware that anything was amiss.

The alternative to this kind of analysis is to design the device to meet simple, common-sense criteria. These criteria are likely to be based on a simple mental model that classifies accidents into a small number of categories and assumes uniformity within each category. However, if the designer believes that the requirement specification is self-justifying, the error will not be detected until application. The remedy for oversimplification of a problem is exposure to fact. No other way of achieving this than the expensive suggestion presented earlier has yet been proposed. People are complicated—there is more than one way to make a mistake.

## INTERACTIONS BETWEEN FAILURES

Most accidents occur after several distinct driver errors or other system failures. However, if all bad driving led to an accident, the roads would be much more dangerous than they are. In the future, it must be expected that most faults in IVHS devices will be detected and corrected before an accident occurs, partly because of the safety-oriented reaction of other drivers and IVHS devices to hazardous behavior caused by a faulty component. A potentially hazardous fault in a component may be cushioned by corrective behavior in the surrounding traffic.

Alternatively, corrective behavior may not be necessary because the IVHS design is such that, although the affected vehicle or road device has lost a capability, no immediate hazard arises. However, when two or more such cushioning groups meet or a diminished-capability vehicle comes across another failure, the level of hazard may increase. If there are active automatic controls (as opposed to warnings) or if false information is being propagated and relied on, the hazard level may exceed the level that would exist in the absence of IVHS devices.

## Freak Waves

Freak waves are a known phenomenon of the oceans, occurring well away from coasts. The irregular movement of the surface of the ocean is a superposition of many separate wave trains of varying amplitude, direction, and phase. Most of the time, interference between waves keeps the mean displacement relatively small, but constructive interference occasionally occurs. Then, a freak wave, 10 or 20 times the mean amplitude, appears suddenly out of a calm sea. Ships have been wrecked by such waves.

The phenomenon can arise because ocean wave trains are dissipated very slowly; hence, a train can readily travel thousands of miles, in deep water, from the storm that generated it.

Could a similar phenomenon occur in traffic under an AVCS? Waves can certainly travel through traffic streams. The shock-wave phenomenon, by which a disturbance in a traffic stream is propagated backward down the road, is well documented both in car-following theory and by observation. A speed disturbance grows as it propagates from front to rear of a close-spaced platoon, unless special care is taken to include stabilizing terms in the control function to damp the waves (*10*). Even without a positive attempt to maintain a fixed distance from the preceding vehicle, some undamped waves could be propagated through a traffic stream if there are devices present that attempt to avoid a close approach to vehicles ahead and to either side.

Advanced AVCS-1 systems may include devices that communicate from vehicle to vehicle, potentially over some distance. These systems might also be designed to cause an automated avoidance response. Again, the opportunity for creation of an undamped wave could arise, although it is not possible to be precise until the intended function of the system is evident.

The freak wave analogy can perhaps be carried too far. It is mentioned merely to suggest one mechanism by which a multivehicle interaction can produce a hazardous situation, so that the investigation of interactions does not seem pointless. In the search for deleterious interactions, however, the researcher should consider if intervehicle communication and subsequent actions can produce waves that would be propagated along or across a highway.

Hazardous interactions might also occur among different devices on the same vehicle, although in this case the freak wave analogy would not apply.

It is relatively easy to postulate credible pairs of IVHS devices that could interact in a hazardous way, even without faults. One vehicle might have a lane-keeping device that, when there is another vehicle alongside, keeps it a distance $x$ from it. Another could have an anticollision device that causes it to veer away if another vehicle comes within a distance $y$ of its side. If $x < y$, there will be a hazardous interaction.

Another possibility is that two such lane-keeping devices, with compatible steady-state objectives, could interact to produce divergent oscillations because their control functions had been designed independently (which could happen even with two different devices from the same manufacturer). More complex, more likely, but less readily imaginable combinations no doubt also exist.

## Configuration Management

Techniques for looking for interactions among AVCS devices are not discussed. Part of the data for such an analysis are clearly specifications of the devices concerned.

Some devices currently being produced will still be in service 25 years hence. If a new device is designed at that time and the designer wants to search for interactions, he will have to research the devices placed on cars in 1991. It does not seem likely that these data are being retained. Indeed, if an engineer today wished to carry out an analysis of the safety of existing IVHS devices, the engineer may find that some of the necessary specifications have already been lost as staff changes and record holdings are reduced.

In other fields involving complex systems, such as spacecraft or aircraft, a technique known as configuration management is used to maintain comprehensive records of interacting components. The system monitors whether individuals concerned with one component have been informed about changes to the other component; modifications, updates, and improvements to hardware and software; repeat analyses of the safety-critical part of the system following such changes; and so on. In these cases, of course, the whole system is the responsibility of one body, which is in a position to exercise such control and has an interest in doing so. Otherwise, if the system doesn't work, the reason cannot be determined. In IVHS the legal situation is different. The components have various owners, and not all of them have any interest or responsibility for system safety. But the need for the ability to determine the configuration is no less. The owners expect that someone has accepted responsibility for determining that the system as a whole is not excessively hazardous. They believe they have a right to be assured that any proposed addition to the system does not make it more hazardous. The courts are likely to identify those "individuals" after an accident, if no one does so earlier.

No attempt is made here to suggest where responsibility should lie or by what procedures it should be discharged. However, this task will not become easier as time passes.

### Specifications

A first step in rectifying these deficiencies is to determine what the content of a formal specification of an IVHS device should include. What needs to be recorded so that analyses of safety-critical systems containing the device will be possible and valid? This task will require additional analyses, as well as a good deal of communication among the involved groups.

It is suggested that entries will be necessary under the following headings:

1. *Initiation.* What stimulus causes the device to function?
2. *Modes of Operation.* Under what conditions (e.g., vehicle in motion, crashing, traffic lights red, official emergency) does the subsystem function and under what is it inhibited?
3. *Effect.* What does the device do?
4. *Changes.* What can the device modify externally (e.g., heading of vehicle or aspect of traffic light)?
5. *Outputs.* Does the device signal that it has completed its task? Does it give intermediate signals? Are there any fault signals?
6. *Faults.* How does the device behave in foreseen fault conditions?

## CONCLUSIONS

A number of suggestions have been made. It is hoped that the data needs identified will be met, that it will be possible to demonstrate that quantitative approaches to the evaluation of IVHS safety are possible, and that the use of these systems will result in increased safety.

The following are suggested:

- To collect a small set of in-depth accident reports applicable to U.S. conditions, would be useful especially for freeway accidents, for use in these kinds of analyses.
- Advances in determination of the relative effectiveness, from a safety viewpoint, of different realizations of the same IVHS requirement specification are possible by constructing suitable shells for computer models.
- As IVHS devices multiply, the possibility of interactions among them will loom larger. Thus, full functional specifications for all IVHS devices present on the roads must be available to analysts in a standard form. A first step would be to initiate consultations about standardization, with the objective being to define effective configuration management protocols. The alternative approach—waiting for accidents to occur—may cost lives and is likely to be expensive for manufacturers and highway authorities.

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