Safety Evaluation of Intelligent Transportation Systems

Workshop Proceedings

Sponsored by
ITS America Safety and Human Factors Committee
and the National Highway Traffic Safety Administration

Reston, Virginia
May 1-2, 1995

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ITS America

ITS America is a non-profit educational and scientific association incorporated in August 1990 to plan, promote, and coordinate the development and deployment of intelligent transportation systems in the United States. The association is designed as a utilized Federal Advisory Committee to the US Department of Transportation (US DOT). Members of ITS America include the transportation, communications, and electronics industries; government agencies at the local, state, and federal levels; academic institutions and related associations. The Society is open to international membership, both public and private.

Abstract

Improved safety is presented as an important potential benefit of intelligent transportation systems (ITS). Systems are emerging and are under development that are designed to reduce the number of accidents and the severity of those accidents that cannot be prevented. These systems, as well as those developed to achieve other goals (such as congestion reduction) may have both positive and negative impacts on safety.

Safety evaluations of ITS must include a consideration of the safety consequences of specific ITS technologies for the driving public. This workshop, jointly sponsored by ITS America and the National Highway Traffic Safety Administration, was held to foster better understanding of the process of evaluating the safety benefits and impacts of ITS. Tutorial papers and case studies were developed to provide an overview and discussion of the goals, considerations, methods, and lessons learned in the safety evaluations of ITS demonstration projects and field tests.

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A Workshop on The Safety Evaluation of Intelligent Transportation Systems

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Introduction

Improved safety is an important potential benefit of intelligent transportation systems (ITS). Systems are emerging and are under development that are designed to reduce the number of accidents and the severity of those accidents that cannot be prevented. These systems, as well as those developed to achieve other goals (such as congestion reduction) may have both positive and negative impacts on safety.

The Evaluation of ITS must include a consideration of the safety consequences of specific ITS technologies for the driving public. This workshop was held to foster a better understanding of the process of evaluating safety benefits and impacts of ITS. Tutorial papers and case studies were developed to provide an overview of this area, and break-out groups provided a forum for discussion of the goals, considerations, methods, and lessons learned in the safety evaluations of ITS demonstration projects and field tests.

Acknowledgments

The Workshop and this proceedings was jointly sponsored by ITS America and the United States Department of Transportation National Highway Traffic Safety Administration (NHTSA). The workshop organizing committee consisted of Louis Tijerina *(Workshop Chair),* Gene Farber *(S&HF Committee Chair)*, August Burgett *(S&HF Committee Secretary),* Mark Freedman, and Donna Nelson (ITS *America Committee Coordinator).* Breakout session leaders were: Bob Clarke, Dick Bishop, Gene Farber, Mark Freedman, John Hitz, and Rick Pain. A number of individuals also assisted by providing written material used in the Breakout Session Reports. The Workshop Organizing Committee, the Safety and Human Factors Committee, and ITS America wish to acknowledge the important contributions of the organizers, presenters, breakout session leaders, and others who contributed to the success of this workshop.

The Proceedings

These proceedings are organized in four sections.

Section I - Introduction and Overview
Section II - Tutorial papers
Section III - Case studies
Section IV - Breakout session reports

Section II

Tutorial Papers

Section II consists of a series of invited tutorial papers. These papers, listed below, discuss the challenges and opportunities associated with performing safety evaluations of ITS.

Overview and Methodologies of the ITS Safety Evaluation Process
Alison Smiley, Human Factors North

Moving from Measures of Performance (MOPs) to Measures of Effectiveness (MOEs)
Thomas A. Dingus, University of Iowa

Estimating Safety Impacts of Full Deployment of an ITS
MicheI Van Aerde, Queen's University

DOT's Approach to ITS Safety Evaluations
August Burgett, NHTSA Office of Crash Avoidance Research

Discussion Paper - For Meaningful Evaluation of the Safety Impacts of ITS Products
Robert Ervin, University of Michigan Transportation Research Institute

The first paper, by Smiley, sets the stage for the workshop. The author outlines the appropriate scope of ITS safety evaluations and the criteria that may be used determining system safety. The paper presents a range of methods and approaches for safety evaluation of an ITS from concept to prototype to actual system, raises fundamental feasibility issues in ITS safety evaluation, and concludes with recommended research to further the state-of-the-art in ITS safety evaluations.

The second paper, by Dingus, addresses the issues associated with using dependent measures associated with driving (termed measures of performance or MOPs) to address constructs that theoretically impact safety (termed measures of effectiveness or MOEs) for safety evaluations. This paper lays out important questions and provides general guidelines for addressing each question. The questions include: How should measures of performance be selected for a particular evaluation? What are the scientific bases for establishing the safety relevance of measures of performance collected in a safety evaluation? What are the limits to establishing a transformation from measures of performance to measures of safety effectiveness or impact? What are candidate measures of effectiveness that quantify safety impacts of an ITS product? What are the prospects for development of safety “red lines” (the criteria for measures of performance beyond which the ITS product is considered an unacceptable safety hazard)? What future research is needed to facilitate the process of moving from measures of performance to measures of effectiveness or impacts?

The third paper, by Van Aerde, addresses the evaluation task of estimating the safety impacts associated with full deployment of an ITS. Using the TravTek safety evaluation as an example, Van Aerde explains the challenges regarding estimating accident risks associated with exposure, facility type (i.e., rural versus urban road type), and the use of in-vehicle devices (dubbed the “gadget factor”). The author describes the use of risk surrogate measures, the fusion of multiple safety surrogate measures into a dimensionless safety index, and the application of the INTEGRATION simulation model to assess safety impacts. The results indicate that net impact of ITS on accident risk is both complex and non-intuitive. The paper concludes that while the TravTek evaluation demonstrated that safety inferences can be drawn from such modeling, many further enhancements are needed, particularly in the area of linking field measurements to modeling studies.

The fourth paper, by August Burgett of NHTSA, presents a concise overview of the logic of NHTSA’s approach to ITS safety evaluations. The discussion is framed around a theoretical construct for a safety evaluation measure. The paper includes discussions of a wide range of NHTSA programs.

The discussion paper, by Ervin of UMTRI, provides a succinct overview of the previous papers and presents a conceptual scheme for anticipating the safety record of motor vehicle traffic in the future given ITS products.

OVERVIEW AND METHODOLOGIES OF THE ITS SAFETY EVALUATION PROCESS

Alison Smiley, PhD

Human Factors North Inc.

1. INTRODUCTION

The ITS goal of reducing accidents is challenging indeed. Although driver attention and perception errors are a major cause of accidents, on an individual basis drivers are remarkably reliable. The risk of a lateral collision, for example, is estimated at once every 60 years for a given driver. To reduce such a low risk further will be no mean feat.

The task of reducing accidents through ITS is also challenging because of severe driver limits in information processing capacity. As the number of ITS systems increases, drivers may be inundated with information and warnings, potentially overloading, rather than aiding them. This will be particularly a problem where ITS systems are optional extras, and are not integrated in an “intelligent” driver interface which prioritizes information and warnings depending on the driver’s task. Safety evaluations of each new device, as well as their impact in the context of other such devices, will need to be undertaken to determine the effects of this change in driver task on safety.

2. SCOPE OF AN ITS SAFETY EVALUATION

ITS safety features should reduce accidents. An analysis of the NASS accident database (Bishop et al, 1984) shows that “in all collision accidents in which the vehicles were under way and a driver response might have conceivably avoided the collision or lessened the severity of the collision, 38% of the drivers took no avoidance action”. Thus, low alertness and collision warning systems should improve safety by warning the driver of problems while there is still time to respond. Having support systems, such as navigation and guidance systems, vision enhancement systems, and automated highways should also reduce the mental demands of the driving task.

However, there is one important caveat. A fundamental characteristic of human operators, which makes them valuable as system controllers, is their adaptability. This is seen at the most fundamental level, in the crossover model describing steering behaviour (Krendel and McRuer, 1974). This model describes how the operator’s strategy changes according to the vehicle dynamics. Driver strategy is equally likely to change as vehicles are equipped with ITS devices.

This adaptability has a downside, commonly known as behavioral compensation. A major report on the subject by the Organization for Economic Co-operation and Development (1989) has defined this as “those behaviours which may occur following the introduction of changes....which are not consistent with the initial purpose of the change”. Human operators have a penchant for trading off some of the potential safety benefit of improved vehicles or highways for a mobility benefit. For example, drivers equipped with studded snow tires were found to drive faster on slippery surfaces than drivers without such a feature (Rumar et al, 1976). Despite this adaptation there was still a significant accident reduction with the tires. Similarly, test track studies of drivers with ABS systems showed that they drove slightly faster than drivers equipped with standard brakes (Smiley and Grant, 199 1).

Thus the scope of an ITS safety evaluation is broader than simply looking for improved performance, reduced mental workload and reduced conflicts or accidents. It must also include an examination of adaptive changes in driver performance which may lessen the safety improvement.

3. CRITERIA FOR DETERMINING SYSTEM SAFETY

Before describing the various levels and methods by which a system can be evaluated for safety it is important to define the criteria that should be used. A regulator may wish to require that a system is demonstrably “safe” before it goes on the road. This is difficult. Accident statistics are the golden measure of safety. because they reflect driver-vehicle performance across representative drivers, in representative traffic and road conditions. Such statistics obviously cannot be collected until systems have been on the road for several years. and safety must be assessed before systems are marketed.

This means that safety criteria must be defined in terms of driver performance. There are a few absolute performance criteria that can be set. It is easy enough to say that safe performance means no lane exceedances or no falling asleep while driving. But if a navigation system demands 15% of driver eye glances, is this safe? What if it demands 30%? Based on our knowledge of the precursors of accidents, it is very likely that high visual demand will increase accident risk. However, we cannot be absolutely certain that it will, nor predict by how much, until systems are in widespread use.

The best fallback position is to say that the criteria for safety should be a relative one. Performance with the device should be as safe if not safer than performance without the device. Assessing whether or not this is the case, is complicated by the fact that driving involves multiple control and monitoring tasks. The use of an ITS device will no doubt affect the total amount of attention paid to driving as well as the tradeoff between attention paid to vehicle control tasks and attention paid to monitoring the road environment. Analysis of human factors causes of accidents makes clear the predominance of perceptual and attention errors over vehicle response errors (Treat et al, 1977). Thus the most critical performance issues are attention paid to the road environment and perception of hazards (both those detected and not detected by the ITS system).

Safety evaluation is a multi-step process, in which confidence about safety impact increases as performance is assessed in more and more naturalistic settings. It starts with ensuring a device meets driver needs in the conceptual stage of design. Prototypes should be assessed for useability. Once useability has been assured, performance can be assessed with typical drivers in safe settings - simulators and test tracks. If performance is acceptable, based on expert judgment that the driver is performing at least as safely with the system as without it, then devices can be assessed in on-road experiments and in naturalistic studies. Once a system is on the road, safety evaluations should be carried out to ensure the expected reductions in accidents have occurred. Details of how a safety evaluation should be conducted are discussed below.

4. SAFETY EVALUATION OF THE CONCEPT

Safety evaluation involves both engineering and human factors considerations. Issues which are predominantly engineering include adequate functionality (e.g. does a side object detection system detect all hazards, bicycles as well as other vehicles, in a specific zone to the right and rear of the driver), reliability, and durability. While these issues are predominantly engineering concerns, it is obvious that a system which detects only some of the objects of concern, or is unreliable, is just as unacceptable from a human factors standpoint as from a strictly engineering standpoint.

A safety evaluation from a human factors perspective involves ensuring that driver needs and limitations have been considered. This is achieved by a using systems approach to design which starts with a systematic analysis of the driver tasks to be carried out with the system, and an identification of driver information requirements and driver outputs. A powerful method of identifying driver needs is to examine the characteristics of accidents. For example, case studies of rear-end accidents show that the main problem is not the steady state close following situation where a driver becomes inattentive. It is rather the situation in which there is a high velocity differential and a driver catches up to another vehicle very rapidly (Knipling et al, 1993). This analysis should influence the parameters and thresholds on which collision warnings are based.

To take another example, let us consider a collision avoidance system which operates when the vehicle is in reverse. A case study analysis of accidents will assist in defining those situations in which drivers need assistance. Such an analysis will aid in determining the various tasks the driver will be carrying out when using this system (e.g. backing into a garage, a parking space, down a one-way street), as well as the type of object that should be detected (e.g. all vehicles including bicycles, pedestrians, curbs, barriers and obstacles over a certain size). The inputs to the device (should it be possible to turn it off and on) and outputs from the device (warnings, distances) need to be considered in terms of human requirements and limits.

Design always involves tradeoffs, between aesthetic, human factors, and engineering demands. To ensure that human limitations receive adequate consideration in the earliest stages of design, human factors professionals need to be part of the design team from its inception, and need to be supported by managers. Once design has advanced to a prototype stage, so many decisions have been made that the ability of human factors personnel to ensure human limitations are adequately considered is severely compromised.

5.0 SAFETY EVALUATION OF THE PROTOTYPE

Once a concept is formulated, a prototype is then built. The prototype will be evaluated, modified and evaluated again. Design is an iterative process, involving many versions and variations before a final product results. Safety evaluations should take place at several points during this process.

A. Useability Assessment

The first level of evaluation should involve a useability assessment. This refers to such matters as determining, for typical installation locations in a vehicle, whether all displays can be read from driver's position, whether all controls can be reached, whether warnings can be heard clearly and so on. Drivers aided by ITS will still need to monitor the roadway and perform some control tasks. Information processing capacity is severely limited - the less demand an ITS device places on a driver already occupied with other tasks the better. While a useability assessment considers issues broader than safety alone, it is generally true that a system that is easy to operate supports safety.

To take navigation systems for example, safety will be supported by displays that have character size appropriate for viewing distance, legible fonts, judicious use of colour etc. Such displays can be read more quickly and accurately by drivers in motion. Most important, displays intended to be read by drivers in motion must be restricted to a small amount of information, because of the demands of the driving task. Eye movement studies show that drivers do not go for longer than a couple of seconds without looking at the road ahead (Rockwell, 1988). An early version of a vehicle information system ignored this driver limitation. This system allowed access to status information on a variety of vehicle systems, coolant, electrical etc. To access a particular one the driver had to hold down a switch and watch the display showing successive systems until the one of interest came into view. This could take as long as 30 seconds. At the insistence of human factors personnel, concerned with the visual demand, an interlock was added preventing the driver from using this device while the vehicle was in motion.

Controls should operate according to population stereotypes. Then they are more likely to be operated accurately and quickly, especially in panic situations. If any controls will be used by drivers while they are in motion, such controls should be tactilely distinct from one another so that the driver can operate them correctly without looking.

With respect to collision warning systems, safety will be supported by warning sounds which are at frequencies and amplitudes which have been demonstrated to attract attention and which are not masked by typical noise in the in-vehicle environment. Many factors affect the auditory environment: windows open or closed, operation of the radio, conversation with passengers, road surface, weather. Warnings must be clearly audible in a range of environments.

An ergonomic assessment should be carried out even for an early prototype so that **the direction the design takes** is guided by a consideration of physical, perceptual and cognitive limitations of the range of drivers expected to use the device. At this early stage in the design process, an ergonomic assessment can be made by an expert who will use numerous established guidelines, for example, on reach limitations for 5th percentile females, display height appropriate for drivers with 95 percentile seated height, force required to operate controls for elderly drivers etc.. It is more cost-effective to carry out this early assessment with experts who can point out such problems as inappropriate warning frequencies or display contrast inadequacies without requiring a representative sample of drivers to do so. These obvious design problems should be corrected before more costly evaluations of more refined prototypes involving a representative sample of drivers.

Each time substantial changes are made in the prototype, an ergonomic assessment should be repeated. This is to ensure that the changes that arise from engineering and aesthetic concerns do not create unacceptable ergonomic changes. Once obvious problems such as inadequate volume for warnings, or too high force requirements for control operation etc., are corrected then driver performance testing can be carried out.

B. Driver Performance Assessment

The second level of evaluation is concerned with driver’s performance of the various driving tasks that will be altered by the system. For safety reasons, initial evaluations involving representative drivers should take place in simulators or on test tracks. Various aspects of driver behaviour should be measured:

- monitoring and control performance
- mental load associated with carrying out the task
- conflicts
- accidents

By equipping drivers with aids, whether vision enhancement, collision-warning, low alertness warning, or navigation and guidance systems, we subtly or not so subtly in some cases, change the nature of the driving task. With this change in task will come changes in driver strategy, and hence changes in behaviour. Some new behaviours will be desirable, others will be inconsistent with the intent of the device.

To take collision warning systems as an example, behaviour consistent with the intent of the device would be a better awareness by the driver of other vehicles on potential collision paths with her own vehicle. This improved awareness ought to reduce instances of attempted lane changing where another vehicle is in the adjoining lane, or instances where brakes need to be applied abruptly to avoid collision with a slower vehicle ahead. Mazzae et al (1994) assessed the impact of various side object detection systems, in comparison to standard mirrors, on truck driver awareness of vehicles within a defined detection zone. An accompagning experimenter asked the driver without warning for assessments of whether the zone to the right was clear. Interestingly, the radar based systems did not improve awareness over that obtained with standard mirrors; a fender mounted convex mirror, which offered richer information, did.

For behaviour to be consistent with the intent of the device, means that some behaviour should remain the same with or without the device. With an adjacent lane collision warning device, desired driver performance involves drivers continuing their usual checks over the shoulder and with rear-view mirrors before pulling out. Visual search, in terms of location, frequency and duration of glances prior to pulling out should be at the same level with the system as without it. The propensity to change lanes should be the same with the system as without it. The system should add to safety by providing a warning of a vehicle in the adjoining lane on the minority of occasions when the driver is inattentive or the vehicle is in the driver's blind spot.

If visual search prior to lane-changing is reduced or the number of lane changes increases then safety may be compromised. This safety problem arises because current electronic systems, though more reliable, have much less capability than the driver, and cannot fully replace him. The driver who looks over his shoulder or in his rear view mirror to pass, will see the vehicle approaching at high speed, out of the range where a side object detection system would be set to detect it. The driver equipped with the warning system may on occasion not bother to check, and move into the path of a high speed vehicle that the system has not yet warned about. In such a case the presence of the system has resulted in an accident because the driver relied on it inappropriately.

Not only must performance be evaluated, but so must the mental effort required to attain that performance. ITS could not be said to improve safety if driving with a ITS-equipped system changed the level of mental workload in a negative manner - either increasing mental workload so that the driver has to make more effort to obtain the same level of performance, or decreasing mental load so much that the driver becomes inattentive.

Measures of subjective mental workload include primary task, secondary task, physiological and subjective measures, all of which have been used in ITS evaluations. For example, a number of studies have examined the impact of cellular phones (Nilsson and Hakan, 199 1) and navigation systems (Antin et al, 1990) on primary task behaviour such as lane and speed maintenance. A driver who is occupied with such devices may focus less attention on lane keeping, or more slow down or keep a larger headway with the vehicle in front, in order to reduce information processing load.

A secondary task, of monitoring an instrument panel display, was used in a simulator study by Walker et al (199 1). Older drivers in particular were found to miss many signals when they used a map-based navigation display. Such secondary tasks are important indicators of the driver's ability to continue monitoring the roadway environment while engaged in using devices such as navigation systems, driver information systems, cellular phones etc. Significantly poorer performance on monitoring type secondary tasks with an ITS device as compared to without the device would be of concern.

Physiological measures of workload include measures such as eyelid separation (related to blinks), EEG, heart rate variability. Some researchers contend that the best measure of subjective mental workload is the subject's own estimate. Such an estimate must be gathered using validated workload scales such as SWAT and NASA-TLX. These allow the subject to separately weight various aspects of mental workload including time pressure, task difficulty, and effort. Using the SWAT workload index, Verwey and Janssen (1988) showed that paper maps had higher workload ratings than simple visual or auditory displays.

Testing human performance related to warning systems poses a difficult problem because there are seldom situations in which drivers genuinely need a warning. Accidents which could be prevented by warning systems are numerous for the driving population as a whole but rare for the individual driver. Conflicts which do not result in accidents, but in another driver making an avoidance maneuver and or sounding the horn, are more frequent. It is generally accepted that reducing conflicts should reduce accidents. Safety evaluations can use such reductions as measures of effectiveness.

Once ITS systems become implemented, case control studies should be carried out to determine device effectiveness in reducing accidents. Such case control studies have been completed for anti-lock brakes and have yielded, what for many, are surprising and disappointing results. Initial test track studies of anti-lock brakes showed they were highly effective - on wet surfaces stopping distances were shortened and steering control was maintained (Rompe et al, 1988). As a result many auto manufacturers have begun implementing these brake systems.

In 1994 the Highway Loss Data Institute carried out a case control study, comparing the number and amount of claims for vehicles with and without ABS. No differences were found. A statistical analysis by Evans (1995) shows a troubling increase in rollover accidents associated with ABS. Much of this lack of positive effect is no doubt due to the fact that only a limited percent of collisions will be impacted by ABS. These are limited for the most part to collisions on wet roads where drivers attempted to use the brakes.

Test track studies, designed to examine behavioural adaptations suggest that a second reason for the lack of effect may be the tendency for drivers to change their strategies in a way which offsets the benefit of ABS. In these studies, subjects practiced with ABS and standard brakes on wet and dry surfaces. After becoming accustomed to the brakes, drivers with ABS drove just slightly faster than those without ABS. The result was that the emergency stopping distances on wet pavements for the two groups were indistinguishable (Smiley and Grant, 199 1).

C. Test Scenarios

Test scenarios should be derived from a task analysis of the driver task being aided. If the tasks and conditions under which the tasks will be carried out have not been delineated in the early part of the design stage, they should be, before driver performance testing is carried out. For intelligent cruise control, test scenarios will centre on vehicle following situations; for navigation systems, performance studies will centre on navigation in unfamiliar areas, for rear-obstacle warning systems, performance studies will focus on situations involving reversing and so on.

For collision warning systems, test scenarios need to include various alarm thresholds. This is because the criteria for sounding a warning, and the assumptions made about driver reaction time, will have a major impact on the effectiveness of the device. An all-purpose warning interval that will give all drivers sufficient time to react before collision is difficult to imagine. A warning interval that is set for the 5th percentile reaction time will result in many nuisance alarms. A warning interval that is set for a 50th percentile reaction time will be too **short** for half the population. Safety may actually be compromised because of the “crying wolf’ effect if too low a warning threshold is used. If, to circumvent this problem, warning intervals are selected by the driver, their appropriateness vis a vis the driver’s actual ability to respond in time to warnings needs to be examined.

A related safety concern, which requires assessment, arises from drivers becoming inured to alarms because they will anticipate the majority of them. A collision warning system based on time and headway will produce an alarm every time a driver catches up to a vehicle ahead just prior to pulling out to pass. The alarm that sounds on the one occasion where the vehicle ahead has non-functioning brake lights, and has started to slow down, producing a dangerous situation, may be treated by the driver as other anticipated alarms which can be ignored. Crying wolf too frequently can result in the system being ineffective when a real danger exists. Thus test scenarios should include situations such as the above where the driver may not recognize an unanticipated danger.

A third concern relates to inevitable, but hopefully infrequent, system failures. Once drivers have some experience with a warning system, they may become dependent on it and fail to respond if the device fails to give its usual warning. Drivers’ response to system failures should be considered as part of a safety evaluation.

One of the problems of testing devices which guard against driver inattention is that the test situation is inherently alerting. A number of approaches can be used to reduce the driver’s level of alertness to that more likely to be found in the real world. Experiments need to last for an hour or more; the number of stimulating events needs to be kept low: drivers may start the experiment in states likely to induce lowered levels of arousal: after consumption of alcohol, after sleep deprivation, at circadian low points of the day, after many hours of driving. In addition, threats may be introduced which are less obvious than threats likely to be encountered in the real world - obstacles which are very difficult to detect, cars that approach very rapidly from the rear and then sit in the driver’s blind spot.

D. Test Methods

Each of the various types of studies - simulator, test-track, on-road experiments. and naturalistic experiments - has an appropriate place during the evaluation process. Each has drawbacks (e.g. different driver motivations) which are countered by advantages (e.g. safety).

Simulators

Simulators allow safe testing of performance in hazardous situations. The driver's use of a collision warning system raises important questions that are too dangerous to answer with field tests, for example the question of driver response to system failures, raised earlier. With respect to the impact of a device on driver mental load, simulators allow designers to test driver performance at the limits. The complexity of a navigation and guidance system can be raised until the driver is overloaded and responds too late to a hazard. The impact of increasing automation on alertness (as with automated lane and headway control) can be observed. The data required for designing a low alertness warning device can be gathered in safety (Richardson et al, in press).

Simulator studies can be carried out before all the bugs are worked out of a prototype. For example, it is simple to provide a driver with automatic lane position control in a driving simulator, or collision warnings that only and always sound when a potential accident situation exists. It is much easier to make a simulated device function perfectly than to do this is the real world.

Simulators of varying degrees of sophistication can be used. The main criteria determining level of sophistication required is that there must be adequate visual representation of other vehicles. That is the driver must have the visual information about the presence of another vehicle at the same distance away, and with the same level of conspicuity as she would on the road. This does not necessarily require high resolution graphics, only that stimuli equivalent in contrast, size, and path to those in the real world be presented. Useful studies on navigation systems (e.g. Shekhar et al, 1991; Walker et al, 199 1) have been carried out on simulators that do not have state of the art graphics or motion-base systems.

Sometimes those interested in the measurement of driving performance feel that the only valid measures are those obtained in field tests. Such feelings ignore the reality of most field tests as well as the record established by simulator studies in predicting performance in the field. On the first point, on road experiments are also simulations of driving. To reduce variability, subjects are given very specific instructions about how to perform the driving task (e.g. drive at the speed limit, in the centre of the lane, without the radio on and so on). To maintain safety, potential conflicts with other cars and pedestrians are severely limited. On the second point, studies, particularly of drug effects, have shown that behavioural changes found in simulator studies (such as speeding up, following too close to the car in front) have been replicated in field studies (Smiley, 1986; Smiley, 1987).

For reasons of safety and practicality, simulator studies should be used to evaluate the safety of support systems before such systems are tested by average drivers on the road.

Test Tracks

Test tracks add reality to the driving task, although driver motivations are quite different from those in real-world driving. First, safety is as much the responsibility of the experimenter as the driver. Second, the pressures of getting to a particular destination are absent. For safety reasons, interactions with other vehicles are highly circumscribed.

Test tracks are a reasonable approach for testing devices warning of low driver alertness, where the issues of interest: accuracy of the detection device and driver response to warnings can easily be tested. For devices which assist the driver in coping with other traffic, like collision warning systems, test tracks are very limited in terms of safety evaluations. Elaborate choreography is required to set up safe traffic interactions on a test track, making such experiments time consuming and expensive. Even more important, drivers in such a situation are likely to be very alert, a state in which it would be difficult to detect any reduction in conflicts because of a collision warning system.

On-Road Experiments

The next step in coming closer to real world driving is to examine driver behaviour in on road studies. Here the traffic and road environment are identical to real-world driving, though motivation is still very different. The destination is not of the driver’s own choosing and the presence of an experimenter is alerting. For safety reasons, test conditions must be well controlled, and drivers cannot be tested to the limit.

As in simulator studies, a prototype device can be tested before all the technical problems have been solved. Using a “wizard of Oz” technique, an experimenter can cause information or warnings to be presented to the driver at appropriate times during a drive. This has been used successfully by Dr. Paul Green at UMTRI to study driver use of navigation and guidance systems. Similarly a vision enhancement system might be made to produce simulated targets, when there is no potential for an accident if the driver brakes suddenly. This technique would be less suitable for collision warning systems where rapid calculations of time to collision are required.

Naturalistic Driving Studies

Before implementation can occur, safety evaluations must take place under naturalistic conditions to determine the impact of devices on real-life driving behaviour. Such studies would involve representative groups of drivers driving in a variety of typical driving conditions. The costs of instrumenting cars to collect performance data has declined greatly in recent years, making such studies more possible than they have been in the past. In addition, portable instrumentation packages are available so that the driver’s own car can be instrumented. Naturalistic studies may reveal areas where further modifications to the design are required. Most importantly, they will provide the necessary, and final, convincing evidence that the ITS prototype is an implementable system.

Naturalistic studies overcome many of the major disadvantages of test-track, simulator or on-road studies. Traffic, road and motivational conditions are real world. The study can last long enough that the driver's performance becomes stabilized, in contrast to other types of studies where a driver is exposed to a new device for a few hours at most.

The major disadvantages of naturalistic studies are the lack of control over the conditions in which the device is tested and the volume of data produced. One way to handle the data problem is to set video recording and data collection systems to collect data or to conserve data only when certain criteria have been met, for example, a pass has been completed, or the collision warning system has sounded an alarm.

E. FUNDAMENTAL FEASIBILITY ISSUES

The basis of a safety evaluation is the performance of a limited number of drivers (possibly several hundred) using a single ITS device with which they have had very limited experience. From this basis we attempt to predict the direction and amount of change in accident risk, that is the safety impact, for a large population of drivers using a variety of devices including the device of interest, with which they will have had several months or more experience. Clearly this presents fundamental feasibility issues.

First, it is difficult to predict exactly how drivers will adapt over time to the new systems, and therefore the likely impact on safety. The high mounted rear light provides a good example of this. Initial studies using vehicle fleets indicated that reductions of 50% in relevant crash types could be anticipated. Consequently, legislation was introduced to make them mandatory in vehicles manufactured after September, 1985.

A study a year after the introduction found that the actual decrease in relevant rear-end crashes was 15%, much lower than the 50% anticipated. Studies by NHTSA after this showed continuing declines in effectiveness.

What happened? To date there has been no research to examine this, but one form of adaptation is likely. If a driver can see through the windows of the car ahead to the car in front of him, he n;ay follow closer to the vehicle in front, given that he has an advance warning of the traffic slowing ahead from the car ahead of the one he is following. However, this closer following will negate some of the benefit of the advance warning. A second likely adaptation is that the high mounted lights are less attention getting now that many vehicles have them, than was the case initially when only a few were so equipped. Although there was a lessor effect than anticipated, the safety benefit is still considerable.

Other safety interventions which showed great initial promise have not been as successful, ABS being an obvious example. The difference between initial expectations and actual safety achievements for high rear-mounted lights and anti-lock brakes are equally likely to occur with collision-avoidance and intelligent cruise control systems. Safety assessments with prototype systems need to consider the possibility of behavioural adaptation and explicitly look for the ways in which this might occur. It is not enough to look at reaction time to warnings or accidents avoided in simulator settings. One must also look for the inevitable adaptations that occur. Do drivers drive faster, do they follow more closely with an obstacle avoidance system than they did without one, are drivers more apt to lane change without looking, particularly when a vehicle in front suddenly slows to turn? How does behaviour change over several hours or several weeks of experience with a new system? Can undesirable behaviour be reduced through design changes?

It is feasible, though difficult, to evaluate the safety impact of giving an individual driver a single ITS device over the short term. Evaluating safety over the long term is much more problematic. Car and aircraft manufacturers can determine physical changes in products over the long term by subjecting their products to life time stresses over a few days or weeks. Humans are more complex. We do not know whether short but intense exposure to an ITS device is sufficient to reveal long term adaptations. While this may be feasible for looking at adaptations to ABS (as in Smiley and Grant, 1991), and intelligent cruise control, it may not make sense for collision warning systems where the driver state of interest is that of inattention. A driver who is exposed to a raft of potential collisions is likely to be very alert, not a state in which the safety value of a collision avoidance system will be evident.

The complexity of a safety evaluation increases further if one begins to consider group behaviour. To date most human factors measurement of driver behaviour has involved individual drivers rather than groups of drivers. We have been more concerned with “psychology” rather than “sociology”. Yet drivers influence one another. Informal rules about how to interact with other traffic abound, and differ from urban to rural areas and from one urban area to another. There is no doubt that as the number of drivers equipped with ITS devices increases, the interaction between drivers will change. Drivers may rely on other drivers having collision warning systems and have less regard for the potential impact of behaviour such as sudden slowing or abrupt lane changes.

The task of predicting safety is difficult and the methods are not as adequate as we might wish. Research is required to further the state-of-the-art in safety evaluation.

F. RESEARCH TO FURTHER STATE-OF-THE-ART IN SAFETY EVALUATIONS

In order to assess safety before a system is in widespread use, one must rely on performance as a predictor of accident risk. We need a better understanding than we currently have of the relationship between performance variables such as standard deviation of lane position, eye glance duration, monitoring performance and conflicts, and the relationship between conflicts and accident risk.

It will not be possible to establish simple correlations; human performance measurement is far too complex for this. Measured values depend on operator variables (age, sex, experience), road environment variables (lane width, traffic density etc.), experimental values (number of subjects, instructions etc.). It is possible to associate behavioural patterns with particular types of conflicts. For example, complex signing at highway exits may be shown to lead to increased glance durations, slowing, and increases in the number of late exits (conflicts). Number of late exits may then be associated with accident risk.

Performance data collected in naturalistic settings is also needed to establish normal ranges under standardized conditions. This would assist in determining whether a new device changed behaviour significantly, and would assist in establishing how drivers currently carry out various tasks. Information on typical following distances, gaps accepted for overtaking, typical lane position deviation will assist in the design of ITS devices as well as in the evaluation of their impact on performance.

Finally, we need a better understanding of how drivers adapt to changes in the vehicle and road system over time. There are very few studies which have looked at such effects. The few that have, such as studies on the impact of transverse lane striping in slowing drivers approaching turns (Denton, 1973; Shinar, 1977), have basically looked at two points on the curve, immediately after the change and a short time later. Study of how adaptations change over time are required. For example, a study of driver performance with high mounted brake lights which examined changes in behaviour (not simply in accident risk) after implementation would assist in revealing where initial assumptions about the safety impact were over-optimistic.

G. SUMMARY

ITS safety evaluations should occur at the design concept stage, when the first working prototype is produced, each time substantial changes are made in the prototype and after implementation.

Performance should be evaluated in terms of behaviour consistent with the intent of the device, as well as adaptive behaviour which lessens the safety effect. Mental effort required to produce the performance should also be evaluated. A system which results in equivalent performance by dint of greater mental effort, cannot be said to have improved safety. Because accident data cannot be obtained before production, a surrogate variable, conflicts, should be assessed in naturalistic studies. Assessment needs to continue after production to determine whether the expected safety benefits have materialized.

If the driver's task is changed he will adapt - the form of the adaptation will determine how much safety can be achieved with a support system. There is a limit to our ability to assess safety. The more influences that are considered, the more difficult it is to determine or predict safety. Drivers equipped with several warning systems may respond differently to a given warning, than would a driver equipped with a single warning system. Drivers influence one another; as more drivers are equipped with ITS systems, interactions between drivers may change. Research is needed to improve our ability to predict safety risk on the basis of performance.

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Moving from Measures of Performance to Measures of Effectiveness in the Safety Evaluation of ITS Products or Demonstrations

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1. INTRODUCTION

The purpose of this paper is to address issues associated with converting practical measures of performance to measures or metrics of the safety impact of intelligent transportation system (ITS) products and demonstrations. For the purposes of this discussion, the dependent measures associated with driving will be termed "measures of performance" and the associated constructs which theoretically impact driving safety will be termed "measures of effectiveness." The paper focuses on the empirical, proactive evaluation of ITS safety prior to fleet-type evaluation studies and, ultimately, mass deployment. Therefore, the methods described in this paper attempt to predict safety utilizing measures that are removed from the direct, epidemiological assessment of safety (i.e., numbers of crashes), since achieving sample sizes to accurately predict actual crash rates is often impractical.

The state-of-the-art in the proactive measurement of safety enables direct comparisons between the relative safety of an ITS configuration and an appropriate control condition to be accomplished with some level of confidence. In other words, it is practical to ordinally rank a set of matched configurations from least to most safe. Currently, however, the magnitude of any safety differences between conditions, as well as the accurate prediction of accident rates once deployment is achieved, cannot be derived. A recent example of the state-of-the-art is the center, high-mounted stop light (CHIMSL). Empirical research and substantial fleet testing showed that the CHIMSL would benefit safety. This finding was correct, but the magnitude of the benefit was predicted to be higher than determined by subsequent epidemiological research.

Several methods show promise for advancing proactive safety prediction capabilities, and a logical progression of research will substantially improve the state-of-the-art if it is undertaken. One set of methods discussed in this workshop is integrative study and modeling, which utilizes several aspects of safety, including:

(1) Relatively small samples compared with a control sample and national databases.

(2) Detailed incident and accident analyses.

(3) Models to simulate network-wide effects assuming that a larger percentage of cars were equipped with ITS products.

(4) The investigation of the potential for distraction and information overload via the conduct of instrumented vehicle studies.

This paper focuses on another set of methods, which include the micro-measurement of driver behavior on a smaller sample basis via specially instrumented vehicles, external devices such as cameras to record and measure the interaction of vehicles passing a fixed point, and driving simulation. Specifically, this paper will describe what to measure, how to measure it, and how to relate the findings to the goal of assessing safety costs and benefits. Several major questions must be addressed in order to move from measures of performance to measures of effectiveness for the assessment of safety and advance the state-of-the-art so that accurate proactive safety predictions can be made for ITS products and demonstrations. These questions are raised and addressed in each of the following sections.

2. HOW SHOULD MEASURES OF PERFORMANCE BE SELECTED FOR A PARTICULAR EVALUATION?

This question can best be answered by providing several general guidelines based primarily upon previous research experience.

Guideline # 1. Spend significant effort a priori to lay out the issues, hypotheses, and measures of effectiveness as a foundation for the research problem. At this stage, it is important to understand the potential for selected measures of performance to measure constructs related to, but not redundant with, the goal of safety measurement.

The answer to the above question depends largely upon the underlying theoretical constructs and hypotheses of interest for a particular safety evaluation. In other words, there is no fixed set of measures for the empirical evaluation of safety that applies to all problems. For example, both the measures of effectiveness and measures of performance will be quite different for the evaluation of the attention demanded by an advanced traveler information (ATI) system as compared to the evaluation of the potential benefits of a collision avoidance system (CAS).

The first step in selecting measures for a safety evaluation is the application of sound empirical research principles. The empirical approach to addressing a hypothesis emphasizes direct observation and controlled experimentation. A critical aspect of experimentation is the accurate measurement of a theoretical construct associated with the hypothesis. A key concept in this approach is the development of a clear operational definition to describe the theoretical construct, An operational definition explains a concept solely in terms of the operations used to produce and measure it. For example, an operational definition of safety may be the number of accidents observed under a given set of circumstances.

Although the discussion above is a review of basics for most who are interested in this topic, it is not unusual for even the “seasoned” researcher to lose sight of the complex relationship between a safety hypothesis, underlying construct, operational definition, measures of effectiveness and measures of performance. The following example illustrates this point. Let’s say the goal of the research is to determine the relative safety costs and benefits of a variety of navigation techniques, including several AT1 system configurations. The hypothesis is that techniques which do not overload the driver’s visual processing resources will not result in a safety cost. The theoretical construct is “safety,” which must be defined operationally in order to be measurable. The definition of the measures of effectiveness and measures of performance describe the operational definition of safety and the means for measuring safety for a given study. In this example, driver workload or attention demand could serve as the measure of effectiveness that operationally defines the safety hypothesis, and a variety of individual measures such as eye glance dwell time or subjective workload could serve as the measures of performance.

It is not uncommon for a safety evaluation study to falter and neglect to provide an effective safety measurement due to poor operational definitions of the measures of effectiveness and measures of performance. A case study of such an evaluation is provided below. The authors are not cited since the problems outlined are commonplace and the study is taken somewhat out of context for the sake of brevity.

Case Study # 1

This case study was a simulator study in which the primary objective was to measure the relative safety of a number of different navigation systems, including several AT1 system devices. The measures of performance were average speed, average lateral placement, variance of lateral placement, heart rate, and reaction time when confronted with gauge changes. The results showed that subjects in a complex visual navigation condition missed gauge changes, had slower reaction time to gauge changes, and drove more slowly than they did under other conditions, with the exception of a paper map control condition. Lateral position measures were not statistically different across conditions. Subjects in the visual conditions drove more slowly than those in auditory conditions. The authors concluded that auditory devices are somewhat safer than visual devices and that moderate levels of complexity are preferable to higher ones.

The study above, while very well-done from a manipulation and control standpoint, was actually measuring *driving quality or performance and alertness* and not *safety* per se. Many empirical researchers treat these constructs as synonymous, when in fact they are often only mildly correlated. An analysis of one of the measures of performance illustrates this point. When drivers are heavily task-loaded, they naturally take steps to reduce the load. One way to reduce the overall task load is to reduce vehicle speed, which was the assumed relationship in the case study mentioned above. However, one might also hypothesize that drivers will reduce speed in circumstances where they are less sure of the correct navigation action to take, regardless of task load. This means that drivers will proceed more slowly if the navigation information is more complex, but that this may have little impact on safety.

An example of how vehicle speed can provide deceiving data with respect to safety is illustrated by the TravTek Camera Car Study (Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman, 1994). Figure 1 shows the average vehicle speed for six navigation configurations. Interpretation of this result based on the hypothesis stated above would indicate that the paper map condition resulted in the highest driver task load and therefore was the least safe configuration. As Figure 2 shows, however, this interpretation is erroneous. The paper map resulted in the fewest safety-related driver errors, as classified by an in-vehicle experimenter and subsequent videotape analysis. Looking more globally at the TravTek measures, it was evident that the paper map was indeed difficult to use and resulted in a large number of navigation errors, high workload ratings, and long trip-planning times. However, drivers compensated for this difficulty by driving more slowly and stopping more often (almost always in a safe location) to read and interpret the paper map as necessary.

As the case study illustrates, the empirical, proactive assessment of safety is quite complex and it is easy to lose content validity and actually measure a construct that is not directly predictive of safety.

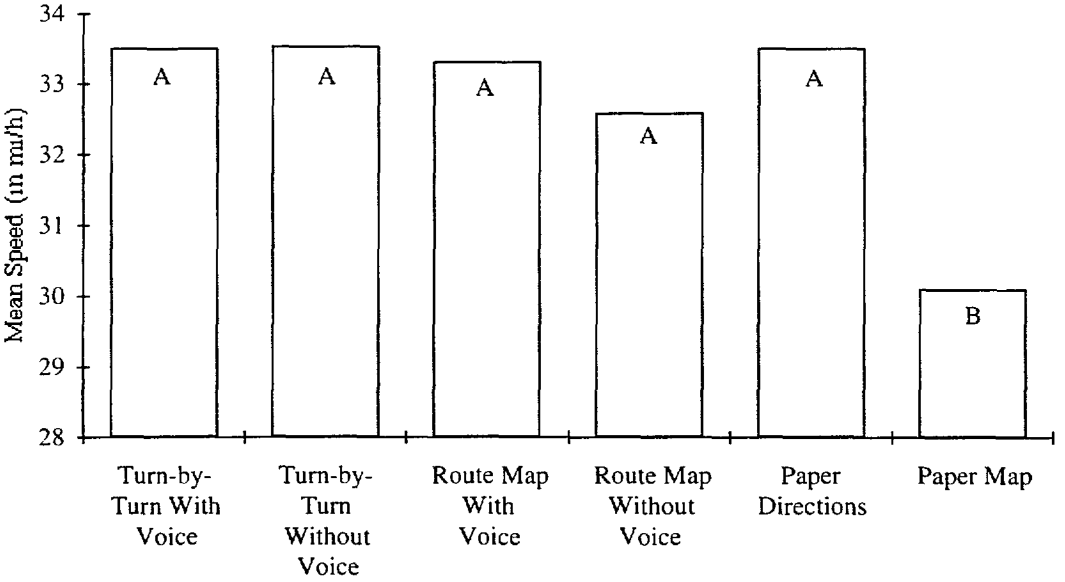

Figure 1. Mean speed for each navigation condition. (1 mi/h = 1.61 km/h)

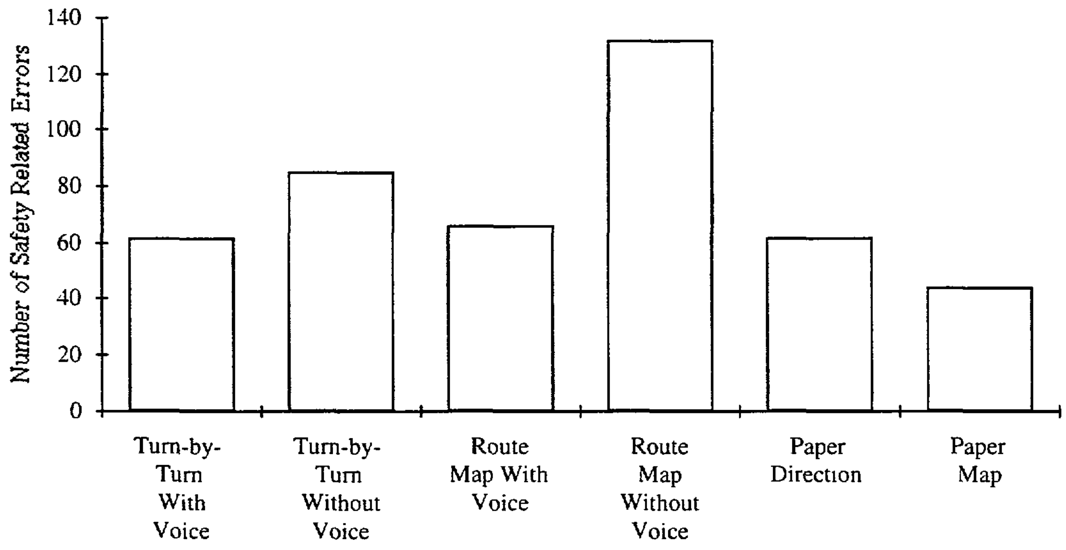

Figure 2. Number of safety-related errors for each navigation condition; no hazard present and minor severity incidents excluded.

Guideline # 2. Select a number of measures of performance to provide corroborative evidence that the ultimate goal of safety assessment is being successfully addressed. In addition, measures of performance which provide content-valid evidence of safety should be well-represented in the constellation of measures selected.

An example of a content-valid measure that is commonly utilized is the number of unplanned deviations outside of the lane boundaries. Unplanned lane deviations provide a valid measure in that, if the driver can not maintain the vehicle within the lane, the probability of a crash increases. As guideline above implies, however, it is a mistake to rely too heavily on a single measure of performance, regardless of its apparent validity.

This point is illustrated in an evaluation of the attention demand associated with the Etak navigator (Dingus, 1986). The number of unplanned lane excursions was calculated to determine if the drivers' visual channel was overloaded during the use of a moving map display relative to several control conditions. In the study, the traffic density was classified by an in-vehicle experimenter as either low or moderate. Data runs were not conducted during conditions of high traffic density to help minimize the risks to the subjects and other drivers. The rate of unplanned lane excursions was 1.44 per 20-minute trip in the low traffic density circumstances and 0.73 per trip in the moderate traffic density circumstances. This was by far the most powerful effect. Thus, with equivalent routes, tasks, and experimental circumstances, drivers were clearly adopting a lower lane-keeping standard when fewer cars were present in the immediate vicinity.

This example illustrates an important point regarding even the most valid of safety-related measures of performance: if the circumstances in an experiment, field study, or demonstration are not well-controlled and well-understood, the wrong conclusions regarding the safety costs or benefits can easily be drawn.

Eye scanning measures are another example of a heavily relied-upon class of measures of performance. Such measures include, among other things, the total number of glances away from the forward roadway and the number of long glances away from the forward roadway. These measures are appealing to researchers since a driver who is not looking at the forward roadway when an unexpected event occurs presumably has a greater risk of a crash. As with lane deviations, however, great care must be taken to interpret eye glance data in the proper safety context.

An example of the potential problems associated with relying heavily on eye scanning data to predict driving safety can be seen in the TravTek Camera Car Study results. One of the comparisons made in the study was between local residents and visitors to the test area. Both groups were novice (although instructed) TravTek users unfamiliar with the destinations under test, and were matched for age, gender, driving experience, and spatial ability. Thus, the primary difference between the two groups was their familiarity with the testing area.

Figure 3 shows the total number of glances to each of the navigation aids tested by area familiarity group. Visitors to the testing area glanced away from the roadway more frequently. Therefore, it might be expected that the visitors would have a higher number of safety-related errors. However, as Figures 4 and 5 show, this was not the case. The local drivers had more safety-related errors overall, and more unplanned lane deviations than the visitors.

Analysis of a number of driving performance measures showed that the visitors drove and navigated more cautiously and, in general, more safely than the local drivers despite glancing at the navigation aids more often.

Another issue associated with relying heavily on eye scanning data to predict safety is illustrated in the following case study.

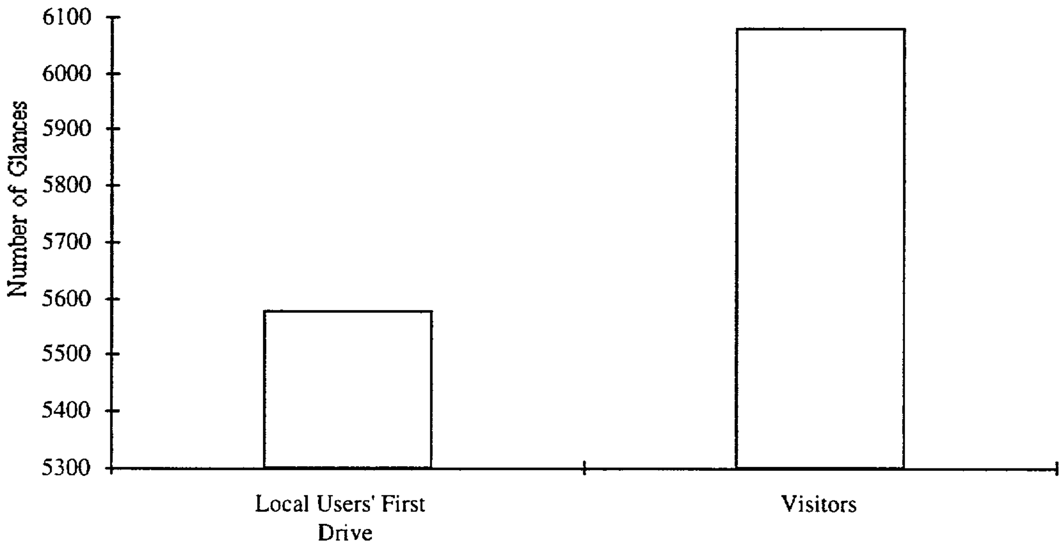

Figure 3. Number of glances to the navigation display for drivers of differing area familiarity.

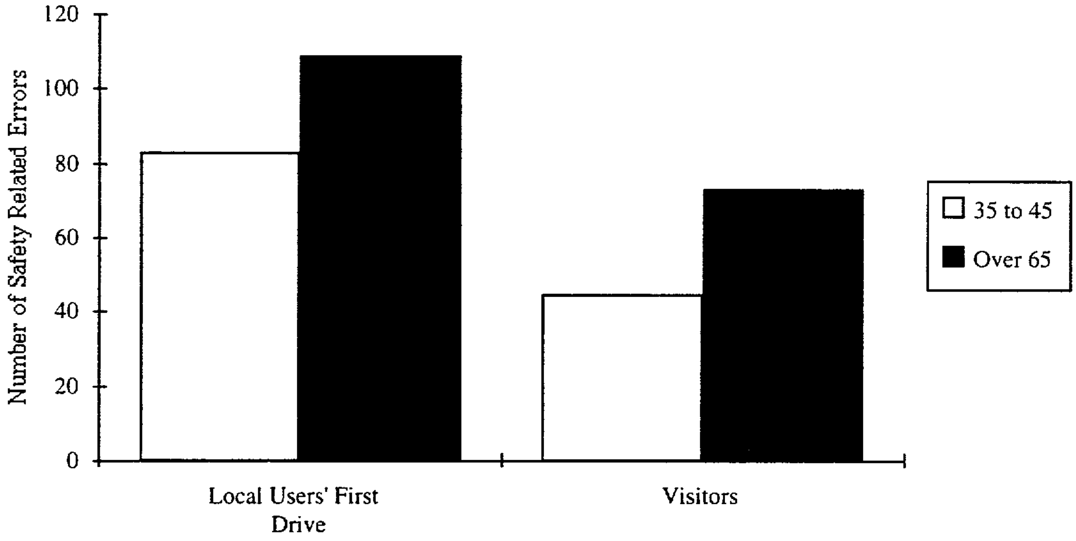

Figure 4. Total number of safety-related errors compared across drivers of differing area familiarity and age.

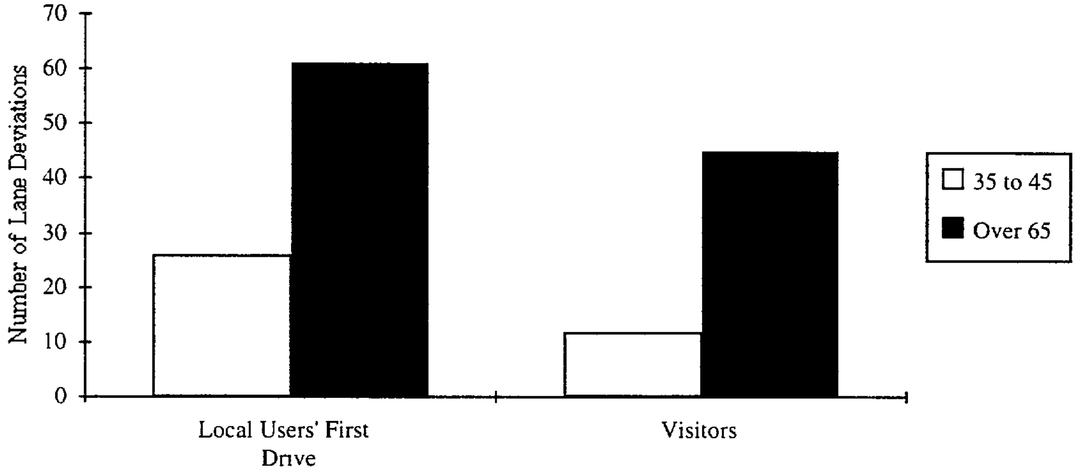

Figure 5. Number of lane deviations compared across drivers of differing area familiarity and age.

Case Study # 2

This example focuses on an on-road instrumented vehicle study that compared three navigation conditions: a moving map navigation display, a paper map, and a memorized route control condition. Eye scanning and driving performance measures were collected. The probability of a glance to the paper map was 7%, while the probability of a glance to the navigator was 33 %. The probability of a glance to a driving task related location was 82% for the paper map and 60% for the navigator. Steering reversal rate was lower for the navigation system compared to the paper map or memorized route. There were no differences in lane deviation, brake usage, or accelerator measures, and no collisions or near-collisions during the experiment. The authors concluded that the visual demands were drawn largely from "spare visual resources," and that the drivers "adapted successfully to the demands of both navigation methods." It is also stated, however, that "it remains to be determined how additional attention demands might effect driving performance in areas such as detection of salient visual cues."

It was apparent that the subjects were looking at the navigator more often than the task demanded. This anecdotal observation was corroborated by the large glance probabilities to the display, without a corresponding degradation in driving performance. This effect was deemed to be a result of the system "novelty," which was presumably less for the paper map or memorized route conditions. As the authors state, however, even though the drivers looked at the display more often, the safety impact of this choice was unknown.

The discussion above illustrates that even the most reliable and valid safety-related measures of performance often cannot be interpreted correctly without additional corroborating evidence. Therefore, the question remains. How should a broad range of measures be selected?

Guideline # 3. Consider issues of orthogonality and redundancy while selecting a broad range of measures.

The following example from the TravTek Camera Car Evaluation demonstrates the process of selecting a comprehensive list of measures of performance aimed at assessing driving performance. Measures were chosen to evaluate differences in driving performance as a result of driving task intrusion caused by the use of various navigation methods. The selected measures represent several broad and somewhat independent categories including lateral vehicle control, longitudinal vehicle control, eye scanning behavior, and workload estimation. The example also shows a logical path to follow from objective to hypothesis to measure of effectiveness to measure of performance that serves as a guide for both study planning and result interpretation.

Example Issue #1: Did any of the navigation configurations tested in the TravTek Camera Car Study result in driving task intrusion?

Table 1 summarizes an evaluation designed to measure driving task intrusion. This approach allows the comparison between experimental conditions, or between an experimental condition and a control condition, based on driving performance measures. These measures do not to directly assess whether or not one or more experimental conditions are unsafe.

Objectives

An important objective of the TravTek Camera Car Study was to provide a detailed assessment of the effects of the TravTek configurations on driving performance. An important aspect of this objective was the assessment of the amount of attention required by each navigation configuration. One reason to provide systems with limited attention demand is that the driving task (including maintaining position in the lane, scanning the environment, and attending to other traffic) sometimes requires almost all of the driver’s information processing resources. Each driving-related task consumes some of these limited resources and, at times, few resources are left over for the execution of navigation tasks. In addition, there are individual factors such as fatigue, arousal, and individual differences that can affect the amount of available resources.

It was not only important to compare different navigation configurations, but to compare all of them to available alternative methods (most notably a paper map and a textual list of directions). It was certain that any navigation alternative would intrude on the driving task to some extent. With this knowledge, the key question then became; “Compared to other alternatives, to what extent do TravTek navigation alternatives affect driving?” Therefore, it was important to assess any difference between TravTek display alternatives and the means of navigation currently being used .

Table 1. Which experimental conditions result in the least driving task intrusion?

OBJECTIVES	HYPOTHESIS	MEASURE OF EFFECTIVENESS	MEASURE OF PERFORMANCE
Assess driving task intrusion associated with each configuration	Driving performance will vary depending on which configuration is used	Driving performance	# of unplanned lane deviations Duration of unplanned lane deviations Steering wheel variance # of steering reversals Mean velocity Velocity variance Abrupt lateral maneuvers Abrupt braking maneuvers Percent of time scanning roadway/traffic Navigation aid glance time/# Workload

Hypotheses

It was hypothesized that driving task intrusion would vary as a function of the six configurations used (four TravTek and two non-TravTek alternatives) . Specifically, it was hypothesized that one or more of the measures of performance described below would vary as a function of navigation technique.

Measures of Effectiveness

The measure of effectiveness for this issue was driving performance. Driving performance in this context refers to the primary task of driving (i.e., maintaining position in the lane, scanning the environment. attending to other traffic, maintaining vehicle speed, assimilating environmental information, and executing required and desired maneuvers). Driving performance was defined operationally as a multivariate set of measures which individually addressed one or more aspects of the driving task.

Measures of Performance

The measures of performance collected to assess driver performance for this issue were the following:

- Number of unplanned lane deviations.
- Duration of unplanned lane deviations.
- Steering wheel position variance.
- Number of steering wheel reversals greater than 6 degrees.
- Average vehicle velocity.
- Velocity variance.
- Number of abrupt lateral maneuvers.
- Number of abrupt braking maneuvers.
- Variance in lateral acceleration.
- Mean negative longitudinal acceleration.
- Variance in longitudinal and negative longitudinal acceleration.
- Number and length of brake applications.
- Percentage of time spent scanning the roadway environment.
- Number and length of glances to the navigation aids.
- Subjective measures of driver workload.

All of the measures listed above are described in the following sections.

Number and Duration of Lane Deviations

A lane deviation was defined as any part of the vehicle exceeding a lane boundary. Unplanned lane deviations provided a valuable content-valid measure of driving task interference resulting in performance degradation. Both the number and duration of deviations were measured. Increases in either measure indicated a degradation in driving performance.

Steering Wheel Position Variance and Number of Large Steering Reversals

Research has shown that changes in driver steering behavior occur when driver attention changes (McDonald and Hoffman, 1980). In normal circumstances which require low attention, drivers tend to make continuous, smaller steering corrections to make up for roadway variance and driving conditions. These corrections were typically within the range of 2 to 6 degrees. As attention or workload demands increased, the frequency of steering corrections tended to decrease. Since the small centering corrections decreased, the vehicle tended to drift farther from the lane center, and a larger steering input was required to correct the position. These steering inputs generally exceeded 6 degrees and are sometimes referred to as large steering reversals. An increase in the steering wheel position variance indicates high attention or workload requirements and a reduction in driving performance.

Average Vehicle Velocity and Velocity Variance

Vehicle speed, like lane position, can be considered a vehicle state which has to be maintained in most circumstances. Therefore, variations in velocity are also used to evaluate performance. Drivers are required to make continuous adjustments in pedal displacement to maintain the correct speed. When driver attention is drawn away from the driving task, there is a tendency to maintain accelerator pedal depression. This behavior often, but not always, results in the vehicle traveling too slow. When drivers realize they are going too slow, the accelerator is depressed to a greater degree than is normal for continuous adjustment. Research indicated that velocity maintenance is a sensitive measure of changes in the amount of attention demanded by secondary driving tasks (Monty, 1984).

In addition to the research described above, average vehicle speed is also a valid measure of task demand. Previous research has shown that drivers adapt to increased task demand by modifying their behavior and driving more “cautiously” (Antin, Dingus, Hulse, and Wierwille, 1990). One way in which this modification was exhibited was in a decrease in vehicle velocity as task demands increased.

Lateral Acceleration Measures

Abrupt lateral maneuvers, like large steering reversals, are indicative of a vehicle that is off-track due to driver inattention. Lateral acceleration measures are highly correlated to driver steering input. However, large lateral accelerations provide additional insight into the degree or magnitude the vehicle is off-track. Therefore, lateral accelerations are used to highlight large magnitude corrections.

Longitudinal Acceleration Measures and Braking Data

Braking behavior can also provide a sensitive measure of driving performance (Monty, 1984). If drivers are looking away from the driving scene and glance back only to realize that an unanticipated event is occurring, the brake pedal must be depressed harder and the resulting deceleration is greater than in a normal attention situation.

Time Spent Scanning the Roadway Environment and Navigation Aids

The driving task requires constant scanning of the forward roadway, the left and right of the forward roadway, and the rear (via mirrors) to drive effectively and defensively. Therefore, a reduction in the time spent scanning these locations can be construed as a decrease in driving performance.

It was anticipated that the novelty effects of the two TravTek visual display configurations would be approximately equal. Therefore, the percentage of time spent scanning the roadway and navigation aids was a useful measure for making comparisons between configurations. The comparisons for the paper map and textual direction list conditions required more caution, since neither of these conditions could be considered novel.

A. Concluding Thoughts

The example above illustrates all of the principles described thus far in this section: careful determination of the hypotheses and measure of effectiveness, selection of a broad range of measures including some with inherent content validity, and selection of a number of orthogonal classes of measures. The example also illustrates two issues that require caution on the part of the researcher:

1) Several measures are inherently redundant. Steering variance, steering reversals, and lane position are linked by the physics of lateral vehicle control. However, they measure differing aspects of lateral performance. Placing too much emphasis on the significance of all three of these measures in the absence of any other measure could be an over-exaggeration of the driving task intrusion. In addition, researchers must be cautious when including all measures in multivariate statistical analyses since the weighting of the significance model can be inflated when multiple, highly correlated measures are included.

2) As previously described, the relationship between safety, driving task intrusion, and similar measures of effectiveness is not simple. Therefore, interpreting increases in driving task intrusion as having an adverse effect on safety may not be true. The answer depends on the nominal level of intrusion and the magnitude of increase.

3. WHAT ARE THE SCIENTIFIC BASES FOR ESTABLISHING THE SAFETY RELEVANCE OF MEASURES OF PERFORMANCE COLLECTED IN A SAFETY EVALUATION?

Since safety cannot be practically and directly measured by empirical means, it is important to establish any safety-relevant scientific bases for collected measures of performance. Traditionally, most of the performance measures have been grounded in the theories relating to driver performance. The TravTek example provides several instances of this human performance measurement. For example, the number of large steering reversals has proven to be a sensitive measure of driving task intrusion. If driving task intrusion reaches a high level, safety is adversely affected. As shown in this example, a limitation of principles of human performance used as scientific bases is that they are several theoretical steps and a complex relationship away from a direct safety relationship.

Another class of scientific bases that has been used for empirical safety evaluations are first principles of physics. For example, research on CAS using the Iowa Driving Simulator has used maximum deceleration rate to indicate when a non-antilock brake-equipped vehicle was skidding. Since skidding typically indicates a loss of vehicular control, a skid represents a scientific basis for an unsafe event.

First principles of physics are commonly used to establish criteria for the classification of unsafe events or behaviors. For example, distributions of driver reaction times and the physics of stopping a vehicle on a surface with a given coefficient of friction can be used to establish a criterion for an unsafe driver headway. The TravTek Camera Car study also included eye glance data in such a criterion assessment. A glance away from the roadway for a specific duration (e.g., 2.5 seconds or longer) in conjunction with headway and required stopping distance would result in an unavoidable crash if an unexpected event were to occur in front of the vehicle.

Another example in which principles of physics were used to classify unsafe events was an analysis performed using simulator data where a sudden and severe lead-vehicle braking event was presented in the simulation scenario. "Evasive maneuvers" were operationally defined as brake only, steer only, or brake and steer based on the following criteria:

(1) Brake only was defined as any longitudinal deceleration _ 0.7 g but with no appreciable lateral acceleration.

(2) Brake and steer was defined as any deceleration _ 0.7 g combined with lateral acceleration _ 0.3 g.

(3) Steer only was defined as any lateral acceleration of _ 0.3 g but with no appreciable longitudinal deceleration.

The values of 0.7g longitudinal and 0.3g lateral were chosen because they approach the limits of reasonable control under the circumstances of the test (i.e., traveling on a congested interstate).

It may also be feasible to classify traffic conflicts in the future using principles of physics and automated technology such as the vehicle motion environment (VME) system or a vehicle-borne "black box", which will use data such as vehicle relative positions and accelerations to classify events as "unsafe." The scientific bases for establishing the relevance of such measures of performance will likely include specific limits of vehicle control and known driver performance data. For example, in circumstances where driver error leads to a second vehicle performing an evasive maneuver to avoid a crash, it can perhaps be determined that the vehicles would have collided had the evasive maneuver not been performed.

Archival data such as crash and other databases can also be useful in establishing criteria for classifying and counting unsafe circumstances. For example, data exist showing that relative closure rates induced by speed variance contribute to the number and severity of crashes. Such data can be used to create operational definitions, much like the ones derived from physical principles above, to establish safety-related criteria and measures. An additional use of archival data is in the determination of crash circumstances and causal factors which are used in the design of an empirical study. Such data form the basis of the empirical problem definition in addition to providing a scientific basis for measurement.

Another valuable use of archival data from crash and other safety-related databases is the modeling and integration of safety data to predict safety costs or benefits. Much of the use of these data are beyond the scope of this paper.

Legal and ethical issues are a major concern in the conduct of safety-related empirical research and the collection of scientifically valid measures of performance. For example, there was a hypothesized safety cost in some of the navigation configurations under test in the TravTek on-road study described above. Therefore, the question exists: was it ethical to put these subjects at risk on the road? The answer lies in a gray area where the relative safety risks (minimized to the greatest degree practical) and potential safety benefits must be carefully weighed. In this case, the collection of data in a small, relatively controlled study with the potential of making mass-marketed systems safer was an ethical trade-off.

Potential legal issues associated with the collection of safety data include the potential for invasion of privacy. Examples include “black boxes” or other unobtrusive measurement means to monitor vehicle location. Do such practices represent an unreasonable invasion of privacy? The primary answer is one that every empirical researcher must address: the appropriate treatment of data. In other words, black box data, location data, eye glance data showing subjects’ faces and all other data must be protected so that subject anonymity is preserved.

4. WHAT ARE THE LIMITS TO ESTABLISHING A TRANSFORMATION FROM MEASURES OF PERFORMANCE TO MEASURES OF SAFETY EFFECTIVENESS OR IMPACT?

A primary limitation in establishing a transformation from measures of performance to measures of safety effectiveness is that safety can never be directly empirically measured, at least as I have defined it. Thus, the empiricist attempting to proactively assess safety on a smaller scale is forced to make an intermediate step. This requires a detailed understanding of potential causal factors inherent in the introduction of an ITS product and the creation of a testable hypothesis regarding the safety cost or benefit.

A number of measures of effectiveness related to safety can be measured directly in a proactive empirical study. Some examples of these include:

- Driving performance or quality
- Driving behavior (e.g. average speed)
- Attention demand
- Workload
- Situation Awareness
- Driver Impairment (Fatigue, Alcohol, other Drugs)

The assessment of these measures, while more practical than the direct assessment of safety, is not a simple task. Furthermore, relating them directly to safety by accurately predicting crash rates has never been successfully accomplished. Thus, great care must be taken in selecting, measuring, and interpreting results, since none of these measures of effectiveness are independent from one another, and none of them are directly and simply related to safety per se.

The following analogy is a description of the problem. Driving-related measures of performance can be likened to a network of roads which can provide a path to addressing one or more measures of effectiveness. Measures of effectiveness can therefore be likened to a set of cross-roads (i.e., as in a town or city). Such measures of effectiveness have traditionally included issues such as driving performance, attention demand, situation awareness, and even less well-established constructs such as driver impairment. In the scheme of this picture, safety is an island surrounded by coastal towns (i.e., the measures of effectiveness), but with few and difficult paths to the island (e.g., an occasional ferry).

The following type of empirical study is commonly performed and illustrates the problem. A degradation in driving performance may result if the attention demands of a secondary task interfere with the driving task, such as the use of a poorly-designed AT1 system device. Attention demand and driving performance can be successfully measured in-vehicle or in-simulator. However, if a task results in higher attention demand and poorer measurable driving performance, will safety be adversely affected? The answer. as in most human factors and safety applications. is that it depends. It depends upon the degree of intrusion. Drivers, despite what driving safety researchers read about them on a daily basis, are generally highly reliable and adaptable subsystems. An example is the paper map condition in the TravTek Camera Car Study which was illustrated in the previous section. This method of navigation was clearly the least usable of those tested as far as time required. number of errors, and workload ratings, but drivers adapted by driving slower and more cautiously and stopping under safe circumstances to read the map.

I offer the following hypothetical relationship between attention demand and safety as shown in Figure 6. Drivers can devote “spare” attention resources as total attention demand increases up to some level, and safety is not heavily impacted. At some point, however, the driver is depleted of attention resources and driving performance and safety will begin to decrease significantly. As more demand is imposed, greater driving task intrusion results in decreased levels of safety. What occurs when attention demand is very high is not clear. Based on some of the studies we have conducted (e.g., the TravTek Camera Car), it appears that, at some point of task difficulty, drivers simply do not attempt to accomplish all tasks in a dual task environment. They exercise their option to conduct the tasks serially by stopping the vehicle. This is illustrated in figure 6 by the upturn in safety at the highest levels of attention.

The point illustrated by Figure 6 is that the relationship between measures that have been traditionally used to evaluate safety are complex. Most of them are certainly non-linear, and some may not even be monotonic. Perhaps even more disturbing is that the relationship between these safety-related measures of effectiveness and actual safety as measured in number/severity of accidents is not known.

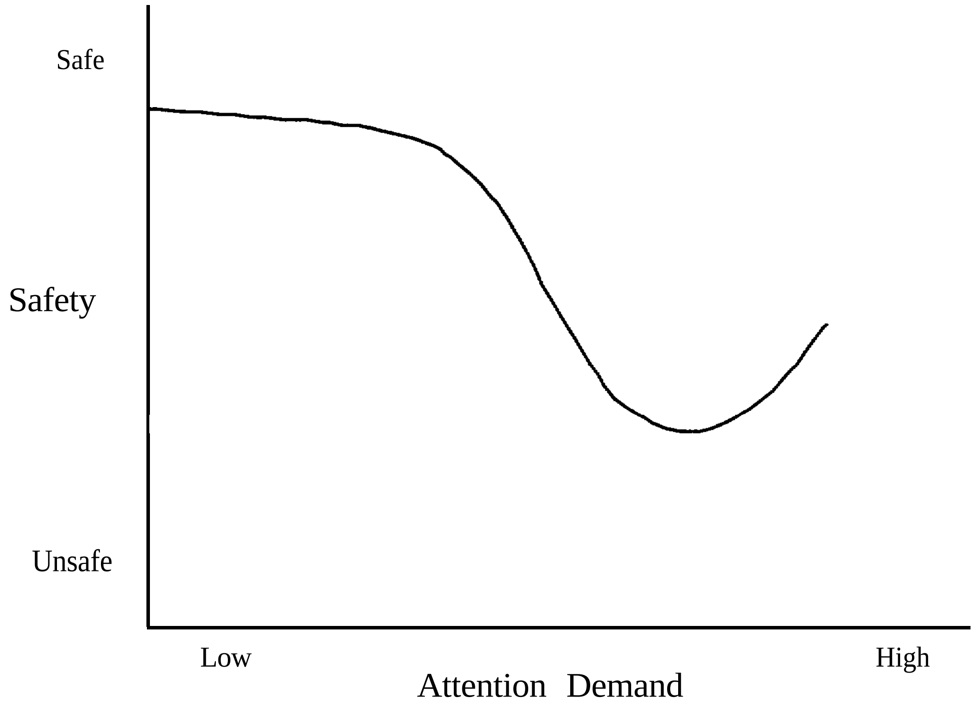

Figure 6. Hypothetical Relationship between Safety and Attention Demand

In the analogy used above, a ferry or bridge to safety island is needed to alleviate this primary limitation . I believe that the bridge consists of the analysis of near collisions and/or traffic conflicts. Another possible solution is the systematic study of the relationship between safety-related measures of effectiveness and the number and severity of crashes. If used appropriately, a large-scale ITS operational field test may help provide much-needed data relating empirical measures to crashes in addition to its primary goal of safety assessment. These potential solutions are discussed in the following sections.

Another set of limitations in the transformation from measures of performance to measures of effectiveness include those involved in the process of conducting empirical study. If one conducts an instrumented vehicle study with an experimenter present or a simulator study in a laboratory, drivers will typically be alert, attentive, and on their best behavior. Therefore, causal factors such as inattentiveness are rarely seen in such experimental circumstances. Solutions to this limitation include the simulation of inattention by the introduction of realistic secondary tasks (i.e., tuning a radio) and unobtrusive data collection of subjects in specially instrumented vehicles (perhaps even their own). The ITS operational test environment may provide a particularly unique opportunity to collect safety-related data unobtrusively.

5. WHAT ARE CANDIDATE MEASURES OF EFFECTIVENESS THAT QUANTIFY SAFETY IMPACTS OF AN ITS OR IVHS PRODUCT?

It is necessary to determine the appropriate measures of effectiveness on a case-by-case basis. The measures of effectiveness are necessarily driven by the specific issue that must be addressed as part of the safety evaluation, as well as the availability of instruments or apparati to sufficiently assess the required measures of performance. However, as the question implies, there is a recurring set of measures of effectiveness which will be particularly useful in the safety evaluation of ITS and IVHS systems.

The following sections provide two examples of ITS issues, objectives, hypotheses, measures of effectiveness, and measures of performance. The examples represent two common ITS evaluation problems while illustrating the treatment of some important and recurring safety-related measures of effectiveness.

Example Issue #2 attempts to establish the relative safety of several ATIS configurations by analyzing near-crashes and safety-related errors. This example illustrates the use of measures of performance to count and classify near-crashes as opposed to using measures of performance to provide support for a hypothesis associated with an intermediate theoretical construct. This is an important distinction, given the complexity of moving through intermediate constructs as a means to assess safety.

Example Issue #3 evaluates the effect of introducing a CAS on safety. This example utilizes measures of performance which rely on principles of physics and driver performance as scientific bases for safety assessment. In addition, it illustrates a CAS-unique approach to the assessment of near-crashes.

Example Issue # 2: Did any of the navigation configurations tested in the TravTek Camera Car Study result in unsafe driving behavior?

Table 2 summarizes the TravTek camera car approach to determining which (if any) navigation configuration resulted in unsafe driving behavior. The purpose of this issue was to determine, with the greatest degree of accuracy available in the measurement state-of-the-art, whether any of the navigation configurations tested resulted in unsafe circumstances.

Objectives

An important objective of the Camera Car Study was to assess in detail whether any of the TravTek configurations affected driving safety. Drivers should have been able to use any navigation configuration or perform any required in-vehicle task without jeopardizing driving safety. In addition, during critical driving situations or emergencies, drivers should have been able to redirect and focus their attention towards the driving task. As long as the demands imposed by a configuration leave sufficient resources for driving in all situations, driving safety should not be reduced

Table 2. Do any of the navigation configurations result in unsafe behavior?

OBJECTIVES	HYPOTHESIS	MEASURE OF EFFECTIVENESS	MEASURE OF PERFORMANCE
Determine if any of the navigation configurations result in unsafe driving behavior.	Navigation configurations may cause unsafe driver behavior	Crashes	# of crashes Assessment of crash causal factors Single eye glances > 2.5 s
		Near crashes Unsafe acts	Abrupt lateral maneuvers Abrupt braking maneuvers Unplanned lane deviations Dangerously close headways Turn tracking errors Unsafe intersection behavior Late/inappropriate reaction to an external event Unplanned speed variation > 16 km/h (10 mik) Stopping in unsafe circumstances Subjective workload ratings for overload

Furthermore, it was expected that the TravTek system would enable the driver to avoid getting lost and to find gas stations and emergency services when required. In this manner, TravTek could enhance safety and security.

In order to determine if navigation system safety benefits outweigh the risks, all foreseeable uses should be considered. Designers cannot rely on drivers to use the system safely and only in the manner intended (Sanders and McCormick, 1987). Therefore, each available navigation configuration was evaluated to determine if it could be safely attended to or manipulated while driving.

Since some driving tasks require more attention than others, a broad cross-section of driving safety circumstances were evaluated (Mourant and Rockwell, 1970). In the context of navigation systems, circumstances include vicinity-of-turn situations (close enough to a turn or decision point that maneuver preparation was necessary), mid-route situations (a greater distance away from a turn or decision point), and anomalous situations (including presentation of off-route, congestion, and action information by the system) (Burgett, 1992). Other driving circumstances that required consideration include two-lane streets, which require more attention than interstates; curved roads, which require more attention than straight roads; and heavy traffic which requires more attention than light traffic. It then follows that composite driving task attention and workload must be measured to ensure that drivers were allocating resources appropriately in circumstances with high resource demands (i.e., that the driver was effectively ignoring navigation in some situations).

As discussed in the driving task intrusion example above, any navigation alternative will intrude on the driving task to some extent because it creates a secondary task (Antin, Dingus, Hulse, and Wierwille, 1990). However, the key safety objective was to determine whether any alternative configuration results in unsafe driving performance or behavior.

Navigating an automobile is more difficult for most drivers than driving to a known destination and it is often not done well because it requires a significant investment of information processing resources (Lunenfield, 1989). It is much more difficult to navigate to an unknown destination than it is to commute and monitor traffic in a familiar area. Therefore, the priority for the Camera Car Study was to evaluate the safety of drivers navigating to unknown destinations rather than commuters driving on familiar routes.

Hypotheses

It was hypothesized that safety would degrade for one or more of the six navigation configurations (four TravTek, paper map, and direction list). Specifically, it was hypothesized that one or more of the measures of performance would indicate unsafe driving behavior as a function of navigation technique and driving circumstance.

Measures of Effectiveness

There are two measures of effectiveness related to the issue of safety; crashes and near-crashes. Crashes that can be attributed to use of a navigation configuration provide hard evidence of a potential safety risk. Such crashes, however, must be taken in context with respect to exposure. There is a risk of a crash regardless of whether or not a driver is using a TravTek configuration to navigate to a destination. The key issue then becomes, “Is there a greater risk of a crash while navigating with a TravTek configuration than with an alternative navigation configuration?" As discussed earlier, navigation is a difficult task to perform while driving. It requires searching the environment for cues and landmarks, memorizing or referring to maps or direction lists, and maintaining spatial orientation, all of which can interfere with the driving task. In attempting to proactively evaluate safety, crash data are often of limited use. Fortunately, estimates of the relative crash risk associated with a system can be established through the analysis of near-crash data. A near-crash is defined as "any navigation-related act which, in and of itself, creates the potential for a collision."

Near-crashes occur more often than accidents of any severity, as illustrated in Figure 7. This figure, known as Heinrich's Triangle, is used in other safety applications to estimate the future accident rate by counting near-misses. By counting the number of near-crashes associated with a given configuration and driving circumstance, it is sometimes possible to estimate the number and severity of crashes that would occur at given levels of market penetration. Unfortunately, the numerical tie between crashes and near-crashes does not yet exist for driving. The concept is useful for comparison of navigation conditions, since no crashes occurred while driving the camera car and differences in numbers of near-crashes will reflect ordinal differences in crash rates at some level.

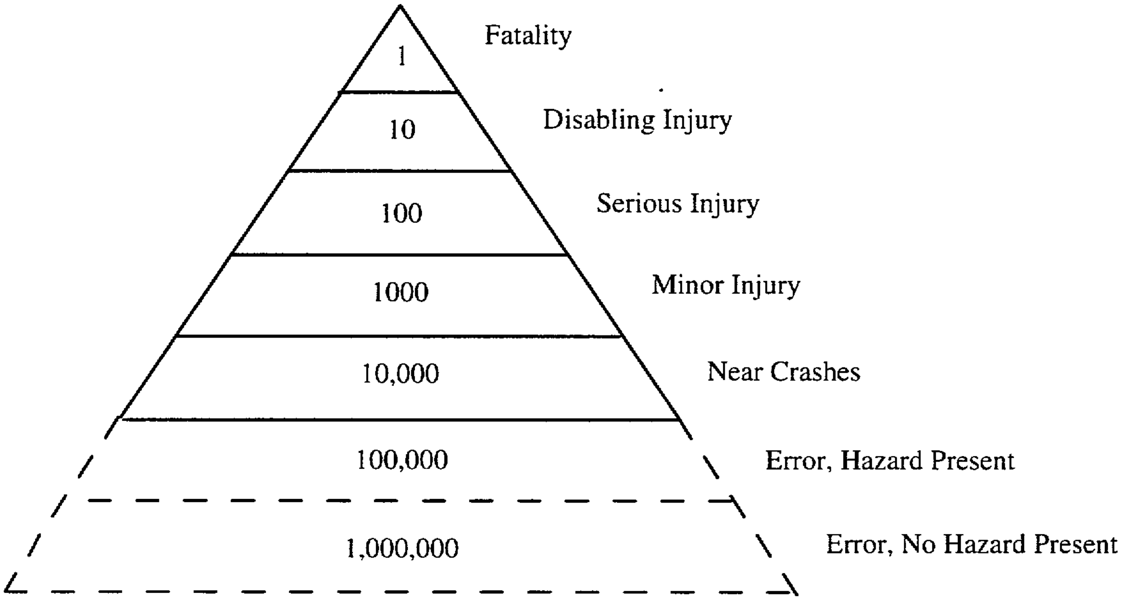

Figure 7. Example of a Heinrich's triangle with hypothetical relative frequencies for driving.

Figure 7 also shows two levels below near-crash which are not commonly assessed as part of this method. These levels, dubbed "error, hazard present" and "error, no hazard present" refer to driving errors which do not constitute a true "close call." These categories were analyzed along with true near-crashes to provide additional safety-related data for comparison. The relative magnitudes of the levels shown in Figure 7 are hypothetical. However, regardless of their relative frequency, these measures provide a valuable means for direct comparison between the navigation conditions tested.

The classification of an event as a near-crash was systematically evaluated using a priori criteria. These criteria were used to establish the severity of an unsafe act based on the potential accident consequences. The criteria used included the type of potential crash and associated injury potential, vehicle speed, presence or absence of proximal traffic, and roadway type including the presence of proximal obstacles.

Potential crash consequences were established by two independent raters who used the above criteria. The classification scheme was based on the most severe, reasonably probable potential outcome, including fatality, disabling injury, serious injury, minor injury, and no injury.

Measures of Performance

The measures of performance collected to assess safety included behaviors that indicated the presence of an unsafe act. These measures of performance actually served as criteria for further assessment of the presence and severity of an unsafe act in laboratory analyses, as opposed to direct measures of a safety-related construct. These “trigger” criteria, for which additional analyses were performed, included the following:

- Single display glances greater than 2.5 s
- Abrupt lateral accelerations
- Abrupt braking behaviors
- Unplanned lane deviations
- Late/inappropriate reaction to an external event (including inadvertent failure to observe related safety signs and signals and closeness of approach to other vehicles, such as actions that cause another driver to take evasive action)
- Unplanned speed variations greater than 16 km/h (10 mi/h)
- Stopping in unsafe circumstances
- Unsafe intersection behavior
- Turning track and other turn errors
- Dangerously close headways
- Subjective workload ratings indicating overload

Any point in the data stream that had a trigger event mark associated with it was subjected to detailed analysis. This analysis included detailed review of the videotape record generated by the camera car.

The activation of the trigger criterion was automatic for cases in which the data were flagged by the computer. and manual for cases that required the judgment of the in-vehicle experimenter. A description of each trigger criterion is provided below.

Single Display Glance Time

Glance duration was recorded so that data reduction in the laboratory resulted in the duration of each driver glance to the nearest 0.1 s. The duration of single glances to the display (or map) configuration in question were of particular relevance to the safety of utilizing the system. Bhise, Forbes, and Farber (1986) have stated, based on speed and travel distances, that any single display glance greater that 2.5 s in a moving vehicle is inherently dangerous. Based on this research, the value was used as a criterion to assess instances of unsafe behavior. Note that although this criterion value has been described as "inherently dangerous," it is not known how long glances away from the roadway correlate with crashes. It is clear, however, that in many circumstances such glances are inappropriate and increase the potential for crashes.

Abrupt Lateral and Braking Maneuvers

Lateral and longitudinal accelerations were automatically recorded by camera car sensors. Abrupt lateral and longitudinal accelerations could be indicative of driver inattention and are therefore an unsafe act. Accelerations above 3.9 m/s^2 (0.4 g) served as a trigger for subsequent event analysis. This value was selected since it represents an unusually high acceleration for normal driving circumstances.

Unplanned Lane Deviations and Turning Track Errors

An unplanned lane deviation is a content-valid indicator of driver inattention and collision potential. In the laboratory, lane deviations were classified and timed from the vehicle's lane-track camera record. A turning track error is similar to a lane deviation except that it occurs in turns where no lane markers are typically present. Each unplanned deviation served as a trigger event for further analysis.

Late/Inappropriate Reaction to an External Event

Because an inappropriate reaction to an external event creates the potential for a collision, it was used as a trigger event. The in-vehicle experimenter provided a record of inappropriate reactions via the "event" button available on the experimenter control panel. To minimize the probability of missing important safety data, the experimenter used the event key somewhat liberally. All trigger events were reviewed on videotape to establish the causal factors.

Unplanned Speed Variation in Excess of 16 km/h (10 mi/h)

Unplanned speed variation indicates driver inattention to the driving task and creates potentially unsafe circumstances. The criterion of 16 km/h (10 mi/h) was selected as a trigger value for two reasons. A variation of 16 km/h (10 mi/h) indicates driver inattention for a relatively long period of time, and such a variation means that the closing rate between the camera car and proximal traffic was relatively high (increasing the crash potential). This criterion level was pretested to determine if, in fact, it appeared reasonable in the field. Speed variations were automatically determined by the in-vehicle computer.

Stopping or Slowing in Unsafe Circumstances

If a subject stopped or slowed to an unsafe speed in a location that created the potential for a collision, the in-vehicle experimenter treated this as a trigger event. "Unsafe" was operationally defined as any circumstance where slowing, stopping, or accelerating created the potential for a collision. The in-vehicle experimenter assessed whether stopping or slow driving circumstances were unsafe and recorded the occurrences via the "event" key on the experimenter control panel.

Unsafe Intersection Behavior

Any circumstance where unsafe behavior occurred in the vicinity of an intersection was flagged by the in-vehicle experimenter on the videotape. Such circumstances included improper visual scanning, failure to appropriately yield right-of-way, and improper reaction to a traffic control device.

Dangerously Close Headways

Utilizing the videotape record from the forward-view camera, a laboratory assessment of the appropriateness of vehicle headway (given driver visual scanning behavior) was performed. Those instances where headway was too close to allow the driver to react appropriately to an unexpected event were treated as triggers and subjected to further analysis.

Mental Workload

During each camera car data collection run, a subjective workload measure was collected on a periodic basis. The subjective scale used required the subject to rate three dimensions (time stress, psychological stress. and mental effort) as low, medium, or high. Any workload response that indicated subject overload was treated as a trigger event and subjected to further laboratory analysis.

Example Issue #3: Is there a measurable safety benefit provided by a front-to-rear-end crash avoidance system?

Table 3 illustrates the relationship between the objectives, hypotheses, measures of effectiveness and measures of performance for the issue of evaluating the safety benefit provided by a front to rear-end CAS which includes a graded headway maintenance/warning display.

Table 3. Does a front-to-rear-end CAS provide a measurable crash avoidance benefit?

OBJECTIVES	HYPOTHESIS	MEASURE OF EFFECTIVENESS	MEASURE OF PERFORMANCE
Determine if any CAS safety benefits are present.	The presence of a CAS will result in a measurable safety benefit.	Driver Situation Awareness.	Accelerator release distance Accelerator release time Initial brake press distance initial brake press time Max brake pedal pressure Max vehicle deceleration Initial steering input time Min headway distance Max deviation from lane center
		Number of Near Crashes.	# of skids # of very close headways
		Number of Evasive Maneuvers.	# of braking only evasive maneuvers # of steering only evasive maneuvers # of braking and steering evasive maneuvers
		Number of Crashes.	# of crashes
		Severity of Crashes.	relative velocity at impact classification of crash severity

Objectives

An important objective of the evaluation of a CAS is the degree of safety benefit and absence of safety cost that drivers gain while using the device. A primary advantage of evaluating a CAS in a simulation environment is that scenarios can be created which place drivers in circumstances where they must respond quickly and effectively to avoid a crash. Furthermore, an alerted driver is a very reliable crash avoidance system. Thus, it is feasible that a CAS might actually increase the probability of an accident if it is not designed appropriately and/or the driver does not use it appropriately. Therefore, the evaluation of potential accident-inducing circumstances is also part of this issue

Hypotheses

It was hypothesized that situation awareness would be improved for at least one of the CAS configurations tested (graded visual head-up display, graded visual head down with auditory supplement display) over a baseline control condition. This improvement in situation awareness was hypothesized to result in a reduction in the number of near crashes. It was anticipated that even though the circumstances in the simulation scenario included several events which required timely braking on the part of the subject, insufficient numbers of simulated crashes would be present to reliably analyze any differences between conditions.

Measures of Effectiveness

Number and severity of crashes and number of near-crashes were used as measures of effectiveness for this research. Crashes that can be avoided due in part to the presence of a CAS provide hard evidence of a potential safety benefit. If a driver can be placed safely in simulated circumstances requiring a severe maneuver to avoid a crash, a key issue then becomes, “Is there a greater risk of a crash without the presence of the CAS?” Even in simulation environments, crash data are often of limited use due to their infrequency. Fortunately, estimates of the relative crash risk associated with a system can be established through the analysis of near-crashes which occur several orders of magnitude more frequently than an actual crash.

Driver situation awareness was also analyzed as a measure of effectiveness for this research. Situation awareness was operationally defined as the timeliness and accuracy of the driver awareness of a stopped or slowing vehicle on the roadway ahead. If a driver is made aware of the presence of a close or closing vehicle sooner or more effectively due to the presence of a CAS, then a safety benefit (i.e., a reduction in number or severity of accidents) may result.

Measures of Performance

Near-Crashes

An analysis was conducted to classify near-crashes based on subject response. Each near-crash was classified into four driver responses:

(1) Left-lane deviation (defined as any crossing of the left-lane boundary)

(2) Right-lane deviation (defined as any crossing of the right-lane boundary)

(3) Close headway (defined as a minimum headway _ 0.3 seconds)

(4) Driver-induced skid (defined as any deceleration _ 1 g)

In addition to driver responses, a separate analysis was conducted on any evasive maneuvers performed by the drivers. Evasive maneuvers were classified as:

(1) Brake only (defined as any deceleration _ 0.7 g)

(2) Brake and steer (defined as any deceleration _ 0.7 g and lateral acceleration _ *0.3 s>*

(3) Steer only (defined as any lateral acceleration of _ 0.3 g)

Situation Awareness

Accelerator release distance/time

The point at which the accelerator is released prior to brake activation provides data on the initial subject response to an external event. The distance between the subject and the lead vehicle when the driver first releases the accelerator pedal in response to a slowing or stopped lead vehicle is indicative of the timeliness of the driver's situation awareness. The time between the vehicles (measured in headway seconds) at the point of accelerator release also provides a valuable measure of this initial response. Although headway time and distance are related, headway time contains the subject vehicle's speed as a component. Thus, the two measures provide somewhat different information.

Initial brake press distance/time

The point at which the brake is first initiated in response to a slowing or stopped vehicle is also indicative of the driver's situation awareness. The headway, measured in time, at the initial brake press also provides a valuable measure of this initial response. As described above, these two measures provide somewhat different information.

Max vehicle deceleration

The maximum vehicle deceleration achieved during a slowing or stopped vehicle event is also indicative of driver situation awareness. That is, a driver can make a more controlled stop, thus reducing the maximum deceleration, given that a CAS provides more timely status and warning information than the driver has without the CAS.

Initial steering input distance/time

As with the accelerator release time, the point at which the driver makes an initial steering response provides a measure of performance for situation awareness.

Min headway distance

The minimum headway distance, at least in circumstances where heavy braking is required, can indicate the time that it took the driver to brake. Therefore, the situation awareness is at the point of slow-down or recognition of the presence of a stopped vehicle.

6. WHAT ARE THE PROSPECTS FOR DEVELOPING SAFETY "RED LINES", I.E., CRITERIA FOR MEASURES OF PERFORMANCE BEYOND WHICH THE ITS PRODUCT IS CONSIDERED AN UNACCEPTABLE SAFETY HAZARD?

In general, the establishment of safety red lines will require a better understanding of the relationship between measures of effectiveness that relate to safety and the direct measure of safety itself (i.e., numbers of crashes). As illustrated throughout this paper, traditional, effective, heavily relied-upon measures of performance such as lane deviations or number of long glances do not relate simply to safety. Thus. a detailed understanding of the relationship between safety and any existing measure of performance does not exist.

Measures of effectiveness which are designed to be a step closer to the direct measurement of safety, including numbers of near-crashes and traffic conflicts, hold the greatest promise for the development of hard "red lines." Previous research has established and validated ratios of near-crashes or traffic conflicts to actual numbers of crashes. However, a substantial research database will be required before such relationships can be established in a wide variety of circumstances.

An additional problem exists even if the empirical safety measurement problem is solved. Even if measures of performance which provide accurate counts of near-crashes and reliable ratios between near-crashes and crashes can be established, where does one draw the safety red-line? The answer must be where the introduction of an ITS device will not result in an overall safety cost relative to pre-ITS circumstances. Thus, any ITS product which can be shown under such hypothetical circumstances to provide a safety benefit will fall within the red line.

This case creates several interesting issues. First, if a collision warning device is projected to neither provide a safety cost nor a significant safety benefit, it falls within the "red line" per se. But should it be introduced? From a marketing and sales perspective the answer may be yes. If no projected safety detriment is present, the answer probably will be yes.

A second interesting issue is the standard set by the concept of “do no harm” and the associated affects on any safety red line. For example, SRS airbags save lives overall, but for some passengers (e.g. small children) the airbag deployment itself can result in injury or death. Thus, existing safety devices “do harm” even though they result in an overall safety benefit. An ITS example would include an AT1 system that provides route guidance and incident warning. Such a device may increase driver workload, and therefore increase accidents in some circumstances. However, it may also provide a safety benefit in alerting drivers to hazards ahead and reducing workload under circumstances when a driver is lost. Therefore, the appropriate criterion for a safety red line is the point where the overall costs and benefits in the equation result in either no safety effect overall or a safety benefit.

7. WHAT FUTURE RESEARCH IS NEEDED TO FACILITATE THE PROCESS OF MOVING FROM MEASURES OF PERFORMANCE TO MEASURES OF SAFETY EFFECTIVENESS OR IMPACTS?

I believe that the most fruitful path in advancing the process of moving from measures of performance to measures of effectiveness involves building a bridge between empirically measurable constructs and the direct prediction of safety. One approach to achieving this goal is to further develop both the ties between performance measures and near-crashes/traffic conflicts and the ties between near-crashes/traffic conflicts and crashes.

Analysis of traffic conflicts is not a new concept. The Traffic Conflict Technique (TCT) was initiated in the United States in the 1960s. Interest developed quickly in the international arena of traffic safety analysis and the technique became widely accepted and implemented. There is currently an Association for International Cooperation on Traffic Conflict Techniques that consists of researchers and safety administrators whose aim is to promote and organize the exchange of information and unify the data collection and validation of results. There has been a lot of recent activity in Europe. Fairly recent technical reports describing data from Holland, Sweden, France, and Portugal are in existence. These data, in conjunction with other existing data, have provided some valuable insight into the relationship between near-crashes and crash rates.

Essentially, TCT looks at near-crash or potential crash situations in order to provide more timely information regarding hazardous roadways and conditions than can be provided by epidemiological accident histories. The technique utilizes intersection observation of crash avoidance situations, or near-crashes, to extrapolate recommendations about hazardous intersection and appropriate corrective action. Traffic conflicts have conventionally been defined as a potential crash situation involving one or more vehicles, in which drivers take evasive actions such as braking or weaving in order to avoid a collision. The evasive action must result from an unusual or unexpected situation (Perkins and Harris, 1968; Asmussen, 1983; Risser, 1985).

Data acquisition has historically taken place over a short period of time utilizing multiple trained observers and/or motion picture cameras to provide a continuous record of all of the events taking place. Observers quantify factors such as time to avoid collision, severity of evasive action, type of evasive action, and proximity of vehicles involved. This manual means of data collection is very labor-intensive. I believe that this is one reason that TCT has not provided a more positive safety impact over the last 35 years. However, with emerging technologies such as machine vision (including the VME tool), automated near crash data can potentially be collected more efficiently.

Results utilizing the traffic conflict technique consistently show that high-crash frequencies are always associated with high-conflict frequencies. Study results concentrating on specific intersection types indicate a 0.80 correlation between serious conflicts and high crash rates. However, according to Older and Spicer (1976), the ratio between accidents and serious conflicts is highly dependent upon intersection demographics, the exact technique used by the conflict rater, and the type of vehicles involved in the conflict. Urban area intersections have shown a serious conflict-to-injury crash ratio for four-or-more wheeled vehicles to be approximately 2000: 1. Crash situations involving motorcycles, bicycles, and pedestrians are much lower, between 500: 1 and 300: 1.

As described in previous sections, a methodology similar to TCT was employed in the TravTek Camera Car Study. This approach analyzed near-crashes in a vehicle on-road as opposed to analyzing conflicts from a stationary point. Such an environment, particularly in the case of large-scale ITS demonstrations, might serve both as a means to generate data to tie measures of performance to near crashes to actual crashes, and as a testbed to predict safety effectiveness.

Based on the above discussion, the primary research that I recommend to address the issues presented in this paper include:

(1) Establishment/validation of a standardized method for the collection of near crash data for instrumented vehicle studies (including the use of DASCAR)

(2) Establishment/validation of a standardized method for the collection of near-crash data and crash data for high-fidelity simulation environments (like the NADS)

(3) Establishment/validation of a “black box” methodology to unobtrusively record both near-crash and precursor crash data in large numbers of vehicles as part of ITS safety evaluations

(4) Investigation into the use of the VME to collect automated traffic conflict data

(5) Research aimed at collecting measures of performance and measures of effectiveness utilizing the above-referenced standard techniques during the conduct of safety evaluations for a variety of systems

(6) Research that attempts to integrate the data from the above sources to predict crash rates from measures of performance

(7) Systematic epidemiological studies which evaluate and validate various predictions made using the techniques described above once ITS devices are deployed

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ESTIMATING SAFETY IMPACTS OF FULL DEPLOYMENT OF AN ITS

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ABSTRACT

The implementation of Intelligent Transportation Systems (ITS) has many objectives. The most common of these is the improvement of network efficiency and the reduction of navigational waste. However, equally important are the impacts on fuel consumption, vehicle emissions and the overall accident risk. It is anticipated that base efficiency levels are such that some of the initial ITS deployment efforts will be able to provide improvements in all of these measures. However, as the overall system gets optimized further, it is expected that further improvements in one of the above measures may only be possible at the cost of negatively impacting one or more of the others. An overall benefit assessment, therefore, needs not only to consider the potential impacts of ITS on one of these measures in isolation, but also needs to consider the concurrent impact on the various other measures that may be impacted indirectly. This analysis is further complicated by the need to consider these impacts for mature systems

The first objective of this paper is to indicate how the potential impacts of ITS on accident risk can be estimated for an initial system deployment. These numbers are key to establishing a reference framework from which the impacts at larger levels of market penetration can be estimated. Secondly, the paper explores how the impacts on safety are likely to change as the level of market penetration of ITS technology increases. This analysis is typically performed using simulation tools. Finally, the interaction between safety and the above other measures of performance (e.g. fuel consumption) is considered. The latter comparison illustrates the trade-offs involved and the potential implications of alternative priorities on different benefit streams.

The following paper addresses these issues from a general perspective, and therefore concentrates on findings which have implications for a wide range of different ITS configurations. However, many specific examples are based on experiences gained during the TRAVTEK operational test safety evaluation. The use of this study is important in making the findings both more tangible and concrete. Finally, it is argued that ITS safety assessments are much more complex than most realize, but that at the same time considerable advances have been made in bridging the gap between what is needed and what is possible.

1. INTRODUCTION

The most direct measure of safety is often considered to be the frequency or probability of the occurrence of an accident. It is therefore desired that accident risk be directly measured during any operational tests for both the subjects participating in a prototype deployment and for a comparable base case group that are equal in all respects except for the use of the ITS technology. Unfortunately, the limited resources that are usually available for performing an ITS field test preclude setting aside a sub-population of drivers which are put under surveillance yet are not utilizing the ITS technology. The tracking of a comparable reference group is, however, critical to making any statements about the ITS equipped population.

The second difficulty associated with tracking accident risk as a safety measure is the fact that not all accidents are equivalent. For instance, it is well known that accidents that occur at lower speeds typically have fewer fatalities associated with them than accidents that occur on higher speed roads. Consequently, an accident on a low speed road is not the same as an accident on a high speed road.

Furthermore, depending on the accident environment, accidents in urban areas tend to involve more vehicles per collision than do accidents in rural areas. Again, some correction should be made to account for this differential. Finally, if one considers for example. monetary equivalents, one finds that severe injuries represent higher financial liabilities to societies than do fatalities, resulting in a less than ideal situation in which fatalities might be preferred to severe injuries.

The above analysis of ITS related accident risks needs to be viewed in a context of what is and is not known about the main factors that influence accident risks. One of the main factors influencing accident risks is drinking and driving, and while one might eventually conceive of some ITS technology that might prohibit drunks from driving or take control of the vehicle driving, for now it must be acknowledged that ITS is likely not to have an impact on one of the main sources of accidents. Consequently, if ITS is to provide some small impact on accident risk with respect to a subset of all causes, the variance associated with the rate of occurrence of accidents due to non ITS impacted accidents will likely mask many small to medium trends.

2. COMPUTATION OF BASE VALUES OF ACCIDENT RISK

Based on the above, one must then consider what effects can be estimated and the limitations of this estimation process. For example, it is known that accident risk is correlated to exposure. Consequently, any ITS measure which reduces exposure, while keeping all other factors equal, will likely reduce accident risk. However, some debate exists as to whether exposure should be measured in terms of distance, i.e. vehicle miles, or in terms of time, i.e. vehicle hours, or some combination of both. The distinction between distance and time exposure becomes quite critical when some congestion avoidance measures may reduce travel time through diversions which increase travel distance.

A. Facility Accident Risk Component

A second major factor influencing accident risk is facility type and facility environment. On a lane mile basis, rural roads are much less safe than urban roads. However, on a vehicle mile basis, the trend is reversed. This leads to a scenario in which someone taking a drive of a certain length in an urban environment will encounter many more accidents than traveling the same distance in a rural environment, but will actually be personally involved in fewer accidents in the urban setting.

This ratio of urban to rural rates for comparable facility types is in the range of a factor of 2 to 3. Superimposed on this relationship is the fact that within a given setting accident risks vary by facility type by a factor of 1:3 or 1:5. For example, access control freeways are much safer than either arterials, collectors, or local streets.

A ‘further complication arises from the fact that accident rates on a given facility are traffic volume dependent. In other words, the level of accident risk varies depending on the degree of facility utilization and or the level of congestion. A simple analysis of this effect is precluded by the fact that traffic volumes within a day are correlated with night versus daytime conditions, as is the prevalence of drunk drivers. Furthermore, as the level of non-congested traffic volume changes, the mix of single versus multi-vehicle accidents changes while the onset of congestion and the consequence reductions in speed also change the severity of the accidents. Some have attempted to analyze the impact of congestion by comparing similar facilities with different AADT’s, however, this analysis is not the same as analyzing the impact of changing traffic volumes on the same facility. The reason for this is that in using the AADT no account is made for the actual flow variation on the facility.

The final complications associated with determining accident risk arise from the fact that on arterials the factors influencing accident frequency are quite different mid-block than they are at intersections. Similarly, accident causes are different within basic freeway segments versus those segments which are considered ramp or weaving areas. It is likely that navigational tools will have the most pronounced impacts at intersections and weaving or ramp areas as in these areas routing decisions need to be acted upon. Unfortunately, little is known about how accident risk will vary as a function of the type of turning movement that is performed, as a function of the type of turning movement control that is being applied and or the level of prevailing traffic congestion.

Within the TRAVTEK analysis of accident risk, safety was modeled as being a variable which is environment specific (rural versus urban), facility specific, (i.e. freeway or arterial/collector/local), and dependent on the presence or absence of traffic congestion. This analysis permitted consideration of ITS impacts on distance exposure such that diversion to a longer route was penalized while the reduction of navigational waste was considered to be a benefit. However, the above analysis needed to further consider to what extent the links on the diversion route and the links on the route diverted to were experiencing congestion.

A sample consequence of this is the fact that the TRAVTEK logic's bias towards use of higher facility types provided a net safety benefit as freeways are typically 2 to 3 times safer than arterials on a vehicle per mile basis. Furthermore, the reduction of navigational waste and/or wrong turns also was allowed to credit a reduction in accident risk. However, when, during congestion, equipped vehicles diverted to a shorter time route along higher speed but longer distance alternate routes, the TRAVTEK system was modeled as incurring increased risk due to both the increase in distance exposure and the utilization of a lower class facility type. On the other hand, non-equipped vehicles were assigned safety credits as the facility on which they remained would, following the diversions of some **TRAVTEK** vehicles, experience less residual congestion.

B. Gadget Factor Accident Risk Component

The above analysis considers the impact on safety of the influence that ITS technology has on guiding vehicles on different facilities under different circumstances and with different levels of exposure. However, it precludes an analysis of the intrinsic benefit or risk associated with the technology which suggests and confirms the routes that are to be taken. This latter impact, that during the course of the **TRAVTEK** experiment, became known as the gadget factor, can only be determined from direct observation of test subjects as will be discussed next.

The differential impact of an ITS technology on accident risk should ideally be measured directly as a difference between the accident risk experienced by a subject group with the ITS technology and a comparable control group utilizing a placebo. Unfortunately. it is somewhat difficult to contrive of a placebo which would not reveal the absence of ITS functionality. The second difficulty is the fact that accident frequencies are still fairly rare occurrences. For example, vehicles are expected to only experience one accident per 1 to 1.5 million vehicle miles. Consequently, the number of accident observations during an experiment, even as extensive as **TRAVTEK,** which involved one hundred vehicles that traveled just over one million vehicle miles during a 12 month period is, therefore, insufficient to prove that the TRAVTEK accident risk was different (better or worse) from the base accident risk by a factor of 2. However, while such low exposure levels could never be utilized to demonstrate that **TRAVTEK** was significantly safer than base conditions (if the base expectation is 1 or 2 accidents), a very high accident rate (5 or more) could have shown that the safety record was much worse. In the absence of a TravTek accident rate which was very different from the base rate, it could only be concluded that the TravTek rate was essentially the same.

The above analysis is further complicated by the fact that accident risk is known to be different when drivers traverse unfamiliar versus familiar territory, when vehicles are driven by renters as opposed to their owners, and when drivers first start driving a new vehicle versus when they have been driving a familiar vehicle for a prolonged period of time. Finally, it should be noted that accident reporting is non-uniform and that by some estimates only one out of every three accidents is actually reported in the accident data bases which are utilized to derive base case accident rates. If it is considered that during the entire **TRAVTEK** experiment as many vehicle miles were driven during the entire twelve month period, as are driven on a busy five mile section of freeway on a typical weekday, one can begin to appreciate the sample size problems that arise even before factors such as the driver's age, gender, experience or vehicle configuration are considered.

In view of the above limitations and complications of utilizing direct accident rates as a measure of relative accident risk for situations in which an ITS technology is present, the **TRAVTEK** experiment considered the reliance on various safety surrogates instead, as will be discussed next.

3. UTILIZATION OF ACCIDENT RISK SURROGATE MEASURES

It is common practice in many industrial and other safety contexts to utilize minor injuries as surrogates for estimating the frequency of much rarer major injuries and of major injuries as surrogates for fatalities. This use of surrogates implies that a reduction in the frequency of the more plentiful but less severe event will be indicative of a comparable decrease in the frequency of the more severe but less frequent event. With this in mind, a variety of safety surrogates were collected as part of the TRAVTEK experiments in order to complement and or to replace a direct accident rate comparison. The most common of these accident rate surrogates were measurements taken using either a human observer in a subject's vehicle or through the use of a camera car. Typical measurements included the frequency of lane deviations, number of steering wheel reversals, number of hazardous movements, number of excessive lateral or vertical accelerations and or the duration and frequency of eye movements. The need for the presence of a human observer and/or the use of the camera car. restricted the observation of these measures to a sub-population smaller than the 100 vehicle TRAVTEK fleet, and for a duration much less than the full twelve month duration of the TRAVTEK experiment.

The above reductions in sample size still yielded a reasonably large data set that could be utilized to analyze with and without TRAVTEK configurations as well as several variations in TRAVTEK configurations and further variations in driver characteristics. The real challenge was in determining the nature of the functional relationship between the safety surrogates and the variable of interest, namely accident risk. Little data exists and/or has been analyzed to quantitatively link any of these variables to accident risk and/or to suggest whether the potential relationship is either linear or non-linear in nature.

The second complication arises from the fact that no quantitative data exists to indicate which one of these multiplicity of data sources should be given greater credence or weight when conflicts in terms of the magnitude and/or the sign of the impact arise.

Within the TRAVTEK analysis, the above two difficulties were addressed by a data fusion analysis. This data fusion analysis served two functions. In the first instance, the data fusion scaled the diverse safety surrogates and their corresponding incompatible units of measure into a common dimensionless safety index with common units. Part of this scaling was the conversion to different safety measurements to a single relative risk measure, while concurrently this computation addressed the issues associated with the absence or presence of non-linearities. The second function of this conversion was the selection of weights to be placed on the various data sources. Both of these two steps were performed in the absence of a pre-existing procedure. Instead, the conversions were performed through consultation with a panel of subject matter experts, where these experts provided inputs reflecting both the relevance and the quality of the data.

The above data fusion process also propagated the main first and second order interaction affects through the data fusion process. For example, in some cases it was found that the impact of the presence of voice was different depending upon the vehicle display configuration that was available. Hence, a consideration of the impact of voice in concert with the configuration impact revealed data trends which would have been lost if each of these factors had been considered in isolation. For example, the impact of voice was different for a map versus a turn-by-turn display. Hence, the effect of voice with a map was different than if the effects of map and voice were considered in isolation.

The net result of the above analysis was a derivation of what became known as the TRAVTEK gadget factor. This factor captured the impact of the medium which provided the route guidance and navigational information to the driver independently of the message that was conveyed through this medium. In other words the gadget factor considered the safety impact of how routing instructions were being conveyed whereas the earlier analysis of facility, congestion and exposure effects considered what the implications were on accident risk when the message that was conveyed was acted upon.

The gadget factor focuses predominately on issues which are related to the ergonomics of the vehicle display. In contrast, the non-gadget factors relate primarily to the impact of the route guidance algorithm within the network in which TRAVTEK system was deployed. The above non-gadget related safety factors dominated the net impact of TRAVTEK on safety to TRAVTEK vehicles and was the only means by which non-TRAVTEK vehicles were able to obtain the same benefits from the TRAVTEK system deployment.

Unfortunately, the impact of these non-gadget factors is heavily dependent upon the prevailing network topology, the network loading, and the a priori assumptions about the non-TRAVTEK driver behavior. The further dependence of these relationships on the level of market penetrations required utilization of a traffic simulation model to perform the overall safety assessment.

4. SIMULATION ASPECTS OF ACCIDENT RISK COMPUTATION

The utilization of INTEGRATION in this context provided three main benefits. In the first instance, the INTEGRATION model was able to be utilized as a giant accounting framework within which the accident risk was incurred by each vehicle could be tracked and logged on a second by second basis. Secondly, the INTEGRATION model also provided a means by which the impact of market penetration on network performance and therefore network safety could be dynamically estimated. Finally, the fact that the INTEGRATION model was already utilized to estimate the impact of TRAVTEK on travel time, travel distance, vehicle stops, fuel consumption, and vehicle emissions, also permitted any changes in accident risk to be viewed within a context of the corresponding changes in these other measures of performance. As a bonus, the relative ease with which the calibrated INTEGRATION model can be applied within different urban areas permits a network efficiency assessment to be performed quite readily, but then also permits a safety assessment to be performed automatically. The details of each of these three elements will be discussed next.

The INTEGRATION model tracked accident risk on a second to second basis by first noting the distance that was traversed during the previous second of the simulation. This distance was taken to be a direct measure of the unit of exposure incurred at that instant. Secondly, the facility type of the link being traversed was noted to cross-multiply the above exposure against an appropriate facility dependent accident risk while a further real time assessment of the prevailing level of traffic congestion was utilized to make a further correction to the base accident risk for that facility depending on the presence or absence of congestion. Upon completing a given network link, the accident risk accumulated by a particular vehicle was utilized to update the cumulative accident risk incurred by all vehicles utilizing a given link, while upon completion of a vehicle’s entire trip, the accident risk incurred by that vehicle was utilized to update the total accident risk experienced by all drivers traveling between the same OD. Finally, at the conclusion of this simulation, the total network risk could be computed by either accumulating the total risk across all links or alternatively, by accumulating the total risk across all the OD pairs in the network.

During the TravTek evaluation, the above base accident risk for non-equipped vehicles was adjusted for both equipped vehicles on a second-by-second basis to reflect the impact of the particular type of in-vehicle configuration that was deployed. Consequently. not only was the impact of a particular route guidance system considered on the exposure side of the analysis, but the presence of the in-vehicle display was also incorporated in the risk that was assigned per unit of exposure.

The INTEGRATION model is a dynamic platform on which the evaluation of traffic congestion can be traced for a mixed fleet of ITS equipped and non-equipped vehicles. In particular, INTEGRATION has established a unique niche in being able to microscopically trace the benefits of ITS as increasing proportions of vehicles are equipped with ITS technology. Typically, level of market penetration analyses have demonstrated how the initial fraction of ITS system participants reap considerable travel time savings both in absolute terms and relative to their non-ITS counterparts. However, once levels of market penetration have increased, these marginal benefits have been shown to level of as the system matures. In other words, travel time benefits continue to increase for the entire vehicle fleet, but the additional benefits for each unit increase in level of market penetration becomes less.

The above changes in congestion levels and diversion opportunities have a direct impact on the exposure levels which both TRAVTEK and non-TRAVTEK vehicles experience. especially when this exposure is segregated by facility type and congestion level. The net consequent impact on accident risk is both complex and non-intuitive, yet is estimated implicitly as part of the concurrent simulation of network efficiency and safety benefits.

Finally, it has been noted that network efficiency benefits are not perfectly correlated with either environmental or safety measures. In other words, a reduction in system travel time does not necessarily imply a change in system travel distance which is either equal in magnitude or sign. Similarly, environmental benefits and safety benefits are also not perfectly correlated with network efficiency measures. This has at least two important consequences. In the first instance, one cannot expect that a system which is designed to yield or maximize network efficiency will automatically also yield or maximize safety benefits. Hence, a tradeoff will often need to be performed, once the most obvious navigational waste is removed, to decide to what extent network efficiency must be traded off against network safety. Secondly, in designing an ITS system there exists in the long term the potential to actually create architectures and algorithms which may strive to explicitly optimize a network’s environmental or safety performance rather than simply its travel time efficiency.

5. CONCLUSIONS

In summary, it is possible to systematically estimate the potential safety impacts of ITS systems. These analyses are plagued with limitations within both, the state of the art in our understanding of accident risk in the absence of ITS, and with limitations within the state of the art of measuring ITS related impacts. However, where data exist traffic models and corresponding preprocessors can exploit much of the available data that does exist, and these models could also drive the design of future ITS field experiments from which safety inferences are to be drawn. Efforts, such as those involving the deployment of INTEGRATION to perform the safety analysis for different levels of market penetration of TRAVTEK, have indicated that these analyses are possible and can be shown to be objective. However, many further enhancements and extensions to these type of analyses need to added, in particular related to the linking of field to modeling studies.

DOT's Approach to ITS Safety Evaluations

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1.0 INTRODUCTION

The ability to assess the safety impact of new systems is an important part of the development and deployment of intelligent safety systems. One goal of the NHTSA ITS program is to develop assessment methodologies. A succinct statement of this goal is the requirement in the 1966 Safety Act [1][1] that systems, or performance standards for systems, should "meet the need for motor vehicle safety." One strength of this statement is the concise way in which it identifies the two parts to any safety assessment methodology. The first part is identification of the "need" and the second part is the determination of level of performance and how well that level "meets" the need. The NHTSA program includes projects that support both parts of this requirement.

At the Fourteenth International Technical Conference on Enhanced Safety of Vehicles last year the author presented an overview of safety evaluation and discussed application of the general process to several examples [2]. In that paper, the following three questions were put forward as a common basis for evaluation of the safety impact of any ITS.

- Do drivers drive more safely with the system than without it, in ways related to the system?
- Do vehicles equipped with the system have fewer collisions than vehicles without the system?
- If all vehicles in the fleet were equipped with the system, would there be a decrease in the total number of collisions and collision-related injuries?

The third question is the fundamental question about performance of collision warning/avoidance systems, and other systems that have an impact on safety. However, frequently the data to directly answer this question are difficult or impossible to obtain without fully deployed systems. This paper focuses on concepts and methods for addressing the first question for collision warning/avoidance systems and how these methods can lead to estimates of the answer to the third question. The second question mainly applies to operational tests and provides another source of information for assessing effectiveness.

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[1] Numbers in brackets correspond to entries in the list of references.

2.0 THEORETICAL CONSTRUCT

The relationship between questions one and three is contained in the following basic expression for effectiveness of any safety device:

$$E = (N_{wo} - N_w)/N_{wo} \quad (1)$$

where:

E is the estimated effectiveness of a countermeasure
N_{wo} is the number of collisions that occurred when no vehicles were equipped with the countermeasure
N_w is the number of collisions that would occur if all vehicles were equipped.

If an estimate of effectiveness exists for a system or concept, an estimate of the number of collisions that would occur if all vehicles were equipped with a countermeasure (the answer to question three) can be obtained by rearranging Equation (1) in the following way.

$$N_w = N_{wo}(1 - E) \quad (2)$$

The process for estimating the national impact of potential collision avoidance systems has two steps. The first is to estimate the effectiveness of the system in eliminating or ameliorating the severity of specific types of collision. This estimated effectiveness is then applied to data from national files of collision data to estimate the number and severity of collisions that would have been eliminated had the system been in place when the collision data were collected.

The effectiveness in Equation (2) relates to the number of collisions. However, the measures of performance from laboratory tests and other sources are in terms of measurable quantities other than numbers of collisions. Thus, part of the process is to construct bridging concepts that link estimates of collision reduction with measurable quantities in the laboratory and from field data. A way of expressing this linkage is with a conditional probability tree that leads to the number of collisions shown in the Equation (1). If we work backwards, the number of collisions can be expressed as the product of the conditional probability that a collision will occur given that a specified situation exists and the number of opportunities. If the number of opportunities is denoted as M and the probability of reacting to the opportunity in such a way that a collision with occurs is P, then:

$$N=P*M \quad (3)$$

In this construct, if it is furthermore recognized that the likelihood of a collision occurring is not the same for all situations or opportunities, then Equation (3) can be generalized and expressed as the inner-product of a probability vector and an opportunity vector by the expression

$$\boldsymbol{N}=\boldsymbol{P}*\boldsymbol{M} \quad (4)$$

Where the elements of the two vectors M and P refer to individually identifiable situations and are the number of opportunities and likelihood of a collision for each situation, respectively.

If N is expressed in this probabilistic form and P is used to denote the likelihood of crashes with no countermeasure present and R is used to denote the likelihood of a crash when a countermeasure is present, then the effectiveness E of a system or concept can be estimated by substituting corresponding estimates of number of collisions into Equation (1) with the following result:

$$E = (P - R) - M / \quad P*M \qquad (5)$$

If data are available from collision data files, such as the General Estimates System (GES) or the National Accident Sampling System (NASS), the expression for effectiveness can be written as:

$$E = (P*R)*M/N_{wo} \qquad (6)$$

An extension of this approach is based on the postulation that there is a relationship between the number of near-misses, or close-calls, that occur for a given driving situation and the likelihood that a collision will actually occur in that situation. If this postulate is valid, it offers the potential of using data from less hazardous test conditions and from normal driving for estimating system effectiveness. This approach leads to development of a mapping. or linkage, between the likelihood of a near-miss and the likelihood of a collision. If **L** is the mapping matrix between the probability of a near-miss and the probability of a collision. then either P or R can be expressed as the result of the following matrix multiplication:

$$\mathbf{P= Lv} \qquad (7)$$

and

$$\mathbf{R= L\,w} \qquad (8)$$

where V is the vector of baseline probabilities of near-misses and W is the vector of near-miss probabilities with the countermeasure present.

With the introduction of the concept of a relationship between near-misses and actual collisions, the expression for system effectiveness can be written as:

$$\mathbf{E = L(V-W).M/Lv.M} \qquad (9)$$

or, if crash data are available:

$$E = L(V-W).M/N_{wo} \qquad (10)$$

From Equations (5), (6), and (10) it can be seen that estimation of effectiveness for a system entails combining several elements.

These elements are:

relative probability of a collision	$(P-R)$
relative probability of a near-miss	$(V - W)$
relationship between near-misses and collisions	L
distribution of collision opportunities	M
baseline number of collisions	N_{wo}

The remainder of this paper discusses NHTSA projects which are addressing each of these elements.

ESTIMATION OF RELATIONSHIP BETWEEN NEAR-MISSES AND COLLISIONS: L and (V- W)

Analytical Framework Project

The expansion of the concepts presented in the previous section is the subject of a task order with the University of Michigan Transportation Research Institute (UMTRI) [3]. This project will develop an analytical bridging framework which will be capable of deriving estimates of the change in crash frequency and crash severity. It will help address questions such as: “What is a near-miss?“, “How might it be defined?“, “Why are near-misses important?“, and “What is the relationship between normal driving and crash?” The project will include modeling tools which bridge between data derived from observation of normal driving activities and data derived from investigations of collisions. The data on normal driving will be derived from tools such as the Vehicle Motion Environment system (VME) and the Data Acquisition System for Collision Avoidance Research (DASCAR), both of which are described below. The bridging framework developed in this project will be a refinement of the general concept of a mapping matrix. L. discussed in the previous section.

System for Quantitative Characterization of Vehicle Motion Environment

As noted in Equations (9) and (10) real-world, in-vehicle data from normal driving are an important element of assessing the safety impact of new systems. NHTSA is developing and validating a measurement system that can quantify the specific motions that vehicles exhibit as they move in traffic. The VME system will establish the locations and motions of all vehicles within the field of view of the VME sensors relative to roadway boundaries, other features, and each other [4]. The pertinent variables address vehicles in near proximity to one another, including spatial clearances, relative velocities, and angles of nominal attack vis-a-vis other vehicles and fixed objects. In operation, the VME will gather information on successful collision avoidance maneuvers such as reaction to other drivers cutting in front, normal following distance, typical lane change trajectories, and response to inclement weather will be studied. Ervin has offered the observation that there is “virtually no theory of driving and (that) we are largely impoverished relative to empirical data showing even the most common phenomena that occur in virtually every vehicle trip.“[5] This project should take a step toward reducing this poverty. The development of the VME system is currently being carried out through a cooperative agreement with UMTRI.

Portable Driver Performance Data Acquisition System for Crash Avoidance Research

Another project is applying state-of-the-art technology and methods to develop a portable in-vehicle instrumentation package and a set of analytical methods/tools to allow driver-vehicle performance data to be collected using a variety of vehicle types. The instrumentation suite will be unobtrusive to subjects and inconspicuous to other drivers; thus, it will support “naturalistic” studies of driver performance/behavior on the road. The design and development of this research tool is currently being carried out through an interagency agreement with the Oak Ridge National Laboratory [6].

The design and initial development of both VME and DASCAR should be completed by early-autumn. After a checkout of performance, both systems will be put in service to gather data on normal driving activities.

TravTek Near-Miss Project

In a different approach to studying conditions associated with near-misses, NHTSA is studying near-misses that occurred during the TravTek operational test [7]. As part of this operational test, a camera car was used to perform controlled experiments with volunteer drivers. The data from these tests include a number of situations which were judged by the in-vehicle observer to be near-misses.

DEVELOPMENT OF DRIVING SITUATIONS, M

The dimension of the vector M is equal to the number of distinguishable driving situations that will be used for estimating effectiveness. This dimension establishes the number of elements that need to be developed for the other components of effectiveness. Thus, realistically, the dimension of M will be determined by the ability to obtain estimates for the other elements of the components of Equations 5 and 6 or 9 and 10. It should also be noted that there is no best single way to “slice the cake” and that the comprehensiveness of any approach may suffer due to the multitude of parameters. This section discusses projects that are currently underway to establish a set of distinguishable driving situations that can be used as the basis for establishing the dimension of M. An important consideration in selecting the dimension of M is the need for the pre-crash driving situations to be describable by appropriate differential equations and for them to be recognizable in the various crash data files.

Problem Definition Study

As the first step in the process of identifying and quantifying distinguishable driving situations, an extensive review of available collision data from the GES and the Crashworthiness Data System of the NASS was performed by the Volpe National Transportation Systems Center (VNTSC) with support from Battelle and Calspan Corp. This review has been published in a number of reports [8-21]. A summary of the first-level description of driving situations that were obtained during that study is presented in Figure 1. Note that this also provides estimate of elements of N,,.

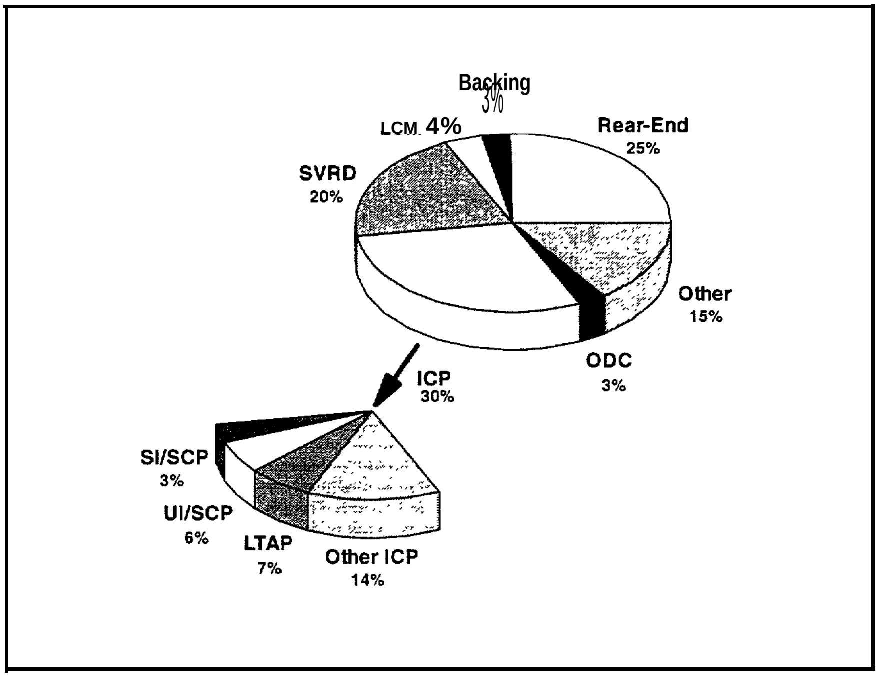


FIGURE l- DISTRIBUTION OF CRASH TYPES (1993 GES Data) [21]

This study also identified the key causal factors which contribute to collisions. Consideration of these causal factors is an important part of understanding the circumstances that surround pre-crash driving situations. A summary of the causal factors identified in this study are included in Table 1.

Table l- Summary of Causal Factors Percent [21]

Crash Type	**Rec.** Error	Dec. Error	Err. Action	Psy. State	Veh. Defect	Rd. Surface	Atm. Visibil	Total
RE	57	27	1	12	1	2	0	100
BK	61	26	2	5	6	0	0	100
LCM	65	32	3	0	0	0	0	100
SVRD	16	18	16	25	5	20	0	100
SI/SCP	41	16	29	12	2	0	0	100
UI/SCP	74	12	3	3	0	7	1	100
LTAP	49	41	9	1	0	0	0	100
OD	18	7	20	33	4	18	0	100
Overall	44	23	8	14	3	8	0	100

Nomenclature

Crash Type

RE-----Rearend

BK-----Backing

LCM---Lane change/merge

SVRD--Single Vehicle Road Departure

SI/SCP-Signalized Intersection, Straight Crossing Path

UI/SCP--Unsignalized Intersection, Straight Crossing Path

LTAP--Left Turn Across Path

OD-----Opposite Direction

Causal Factor

Rec. Error----Recognition Error

Dec. Error----Decision Error

Err. Act.----Erratic Action

Psy. State-----Physiological State

Veh. Defect-Vehicle Defect

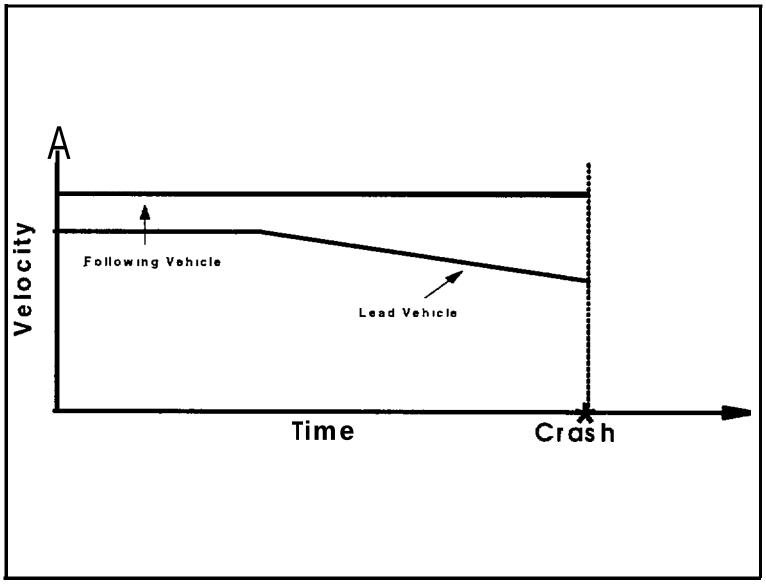
Rd. Surface---Road Surface

Atm. Visibil--Atmospheric Visibility

Performance Guidelines Projects

The VNTSC initial review of the collision data files has been followed by a series of projects to develop a more detailed understanding of the pre-crash circumstances which surround various types of collision. This work is being done in projects that are developing performance guidelines for four different collision modes [22-25]. These reviews are seeking to characterize each subelement of the collision by the time and space relationships that preceded each type of collision.

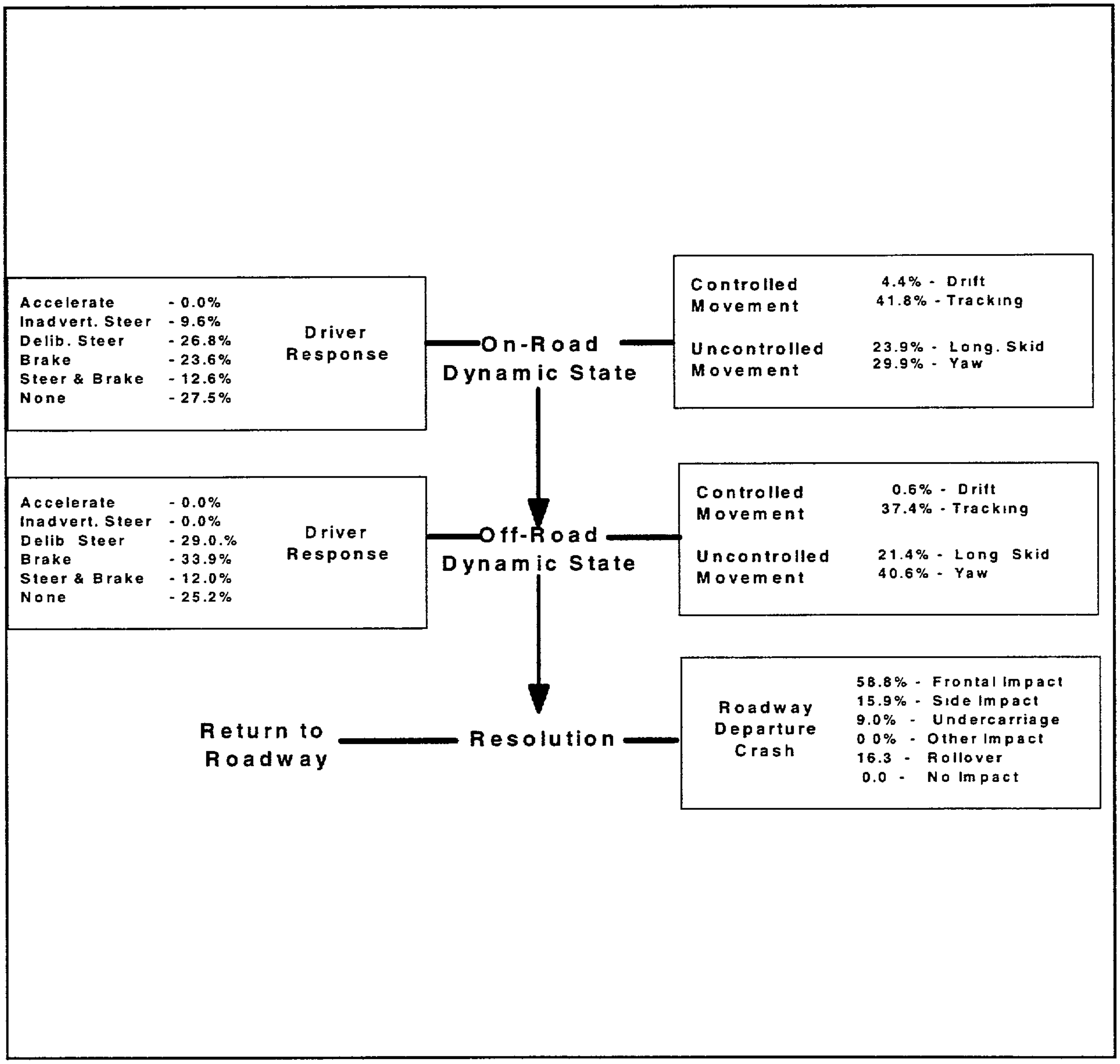
FIGURE 2 - VELOCITY PROFILES FOR REAREND CRASH EXAMPLE [22]



One approach is to identify the full spectrum of time-space relationships that can precede a particular type of crash. For rearend crashes, it is insightful to portray the velocity of each vehicle on a common diagram. Figure 2 diagrammatically shows the velocity-time relationships for rearend crashes where the lead vehicle slows to a stop and the following vehicle continues at an undiminished speed [22]. This is a common type of collision in stop-and-go traffic. An advantage of this type of presentation is that qualitative information about both acceleration (the slope of the curves) and distance (the area under the curves) can be derived from the diagram.

A second approach is to subdivide vehicle motions by categories that are available from crash data files. An example of this approach is shown in Figure 3 which describes the conditions that precede a road departure due to excessive speed [24].

FIGURE 3-CHARACTERIZATION OF CRASH PROFILE FOR ROAD DEPARTURE EXAMPLE [24]



Consolidation Project

The third stage of specificity in the development is to consolidate the work done during the first two stages described above. This project will consolidate the work by the current contractors into a common performance specification framework. The approach will consist of identifying the major dynamic subtypes of collision for each type of collision (rearend, intersection, lane change/merge, backing, and road departure) and will focus on vehicle and roadway conditions rather than driver or environmental conditions. The "pre-crash cluster" from the crash data files (Summarized in Table 2) will be used as the basis for these subdivisions. Each subtype will have a dynamic description that is unique from the other subtypes and should be amenable to description by a differential equation, with initial conditions and control inputs. The outcome of this step should be a list of driving situations that are described by a differential equation and an accompanying diagram of the pre-crash conditions. This approach is similar to the approach used in other projects, for example the DRIVEM model in the late 1970's [26]. This work is being done at VNTSC.

Table 2-Pre-Crash Variables [31]

Pre-Event Movement (Prior to Re-cognition of Critical Event Including:	**Critical Precrash Event Including:**	**Attempted Avoid-ance Maneuver Including:**	**Precrash Stability Including:**	**Pre-Impact Location including:**
Going straight	Vehicle loss of control	No avoidance maneuver	Tracking	Vehicle stayed in travel lane
Stopped in traffic lane	This vehicle traveling off the edge of the road on the right side	Braking	Skidding longitudinally	Vehicle stayed on roadway but left travel lane
Turning Left	Other motor vehicle in lane traveling in same direction with lower steady speed	Steering left	Skidding laterally	Vehicle departed roadway
	Other motor vehicle encroaching into lane from adjacent lane (same direction)	Steering right		
		Braking and steering		

RELATIONSHIP BETWEEN SYSTEM EFFICACY, FALSE ALARMS, AND EFFECTIVENESS; (P-R)

The heart of any study of safety improvements due to introduction of collision avoidance systems is the relative probability of having a collision. Each of the subelements of the two vectors P and R is the probability of a collision under specific circumstances and hence the range of values for each subelement is from zero to one. A value of zero for any subelement means that there is no likelihood of a collision for the specific conditions. Likewise, a value of one means that a collision occurs every time the specific circumstances occur. In most cases, the value of each subelement of either vector is going to be small. However, rather than discussing the absolute value for the subelements, the primary question is the relative size of the probability when a new system is introduced compared to the collision probability under normal driving conditions with no augmentation from a collision avoidance system. If the difference between corresponding elements of P and R is positive, the system is effective in reducing collisions for the corresponding conditions; but if the difference is negative, then the collision avoidance system would produce more collisions than the baseline. If the difference is zero, the collision avoidance system has no effect on the likelihood of collision.

The challenge for experiment designers and data collectors is to provide a sound basis for making estimates of the relative collision probability associated with a new concept or system. This section discusses the impact on system effectiveness of the opposing features of system efficacy rate and false alarm rate.

For purposes of this discussion, efficacy rate and false alarm rate are defined in terms of the four system performance alternatives shown in the following table.

Conceptual System Performance

System Response	**Situations Requiring a Signal**	**Situations in Which a Signal not Required**
Signal	True Positive	False Positive
No Signal	False Negative	True Negative

Based on this table, the ratio of number of times that the system gives a false positive to the total number of times it gives a signal is the false alarm rate (FAR). Similarly, the ratio of number of times the system provides a true positive to the number of times that a signal is required is the efficacy rate (ER). Efficacy rate is also known as the “hit” rate and the complement is known as the “miss” rate.

The relationship between these terms and effectiveness of the system is most easily seen if a single driving situation is used. For this explanation, the effectiveness of the system in preventing collisions associated with the driving situation is given by:

$$E_i = (P_i - r_i) * m_i / n_{wo/i} \qquad (11)$$

where p_i, r_i and the other terms correspond to the specific driving situation of the corresponding vector terms in Equation (6).

The basic relationship between p, and r_i is given by the following equation.

$$r_i = p, \ (1 - ER_i) \qquad (12)$$

This equation is only valid if the driver reacts perfectly to the signal. Under this hypothetical condition, it can be shown that the effectiveness equals the efficacy rate. If however. the driver's reaction is not perfect, then the expression for r_i needs to be modified through introduction of a function of the driver's performance, f_i as shown below.

$$r_i = p, \ (1 - ER_i * f_1) \qquad (13)$$

The function f_i describes the "goodness" or quality of action elicited by the signal. It typically will have a range from zero to one. The "goodness" of a driver's response is related to the occurrence of a driver response, the correctness of the driver's response and the time delay in making the response. The goal of any collision avoidance system is to have the driver react properly and in a timely manner each time a signal is activated. If, however, the driver reacts in a inappropriate manner, it is possible for the collision rate with the system to be higher than without; a circumstance that is clearly to be avoided. Under these conditions. the value of f_i will be negative and the corresponding value of r_i will be greater than p, . This corresponds to a negative value of effectiveness. The possibility of eliciting inappropriate action is especially possible for Category 1 systems (see description of system categories in Table 3) which provide signals to make a driver aware of a hazardous situation but to not necessarily elicit immediate collision avoidance action.

Note that the paper at this workshop by Dr. Dingus on the relationship between Measures of Performance and Measures of Effectiveness contributes to identification of methodologies for development of the functional description of "goodness" [27].

A second modifier of the basic equation is a function based on a driver's experience with a system. This function, denoted as g,, represents the effect of the false alarm rate, It is a function which can have a value between zero and one. The functional relationship between driver performance and false alarms is not straightforward; however, it is generally accepted that false alarms do not improve the effectiveness of a system and hence g, is presumed to increase as false alarm rate increases. The inclusion of this functional relationship in the expression for r_1 yields:

$$r_1 = p_1 (1 - ER_1 * f_1 * (1 - g_1)) \qquad (14)$$

Thus. the effect of false alarms would be to increase the value of η in the above equation. If the false alarm rate exceeds the acceptance level for the individual driver, the driver will disconnect the system. In this case, g, will equal one and the value of η equals p, since the system is no longer functioning. The tolerance threshhold will depend on a number of factors. Two of these factors are the category of system (See Table 3) and the type of signal that is presented to the driver. It has been suggested that the type of signal should match the category of the system. For example, it is suggested that the signal for a Category 1 system should be either visual or audible, but not both and that it should not be overly alarming. However, for Category 2 systems it is suggested that the signal contain two modes, visual plus either audible or tactile. [28]

In addition to the possibility of causing a system to be disconnected, false alarms may cause the driver to divert their attention from the driving task to take, or at least begin to take, the indicated action. This diversion from the immediate driving task can be the cause of a collision. A second experiential factor is the effect of nuisance alarms. Nuisance alarms have been defined as:

"Alarm activations occurring when a system functions as designed but when the situation does not constitute a true crash threat for the driver in question" [8].

Thus, nuisance alarms represent a difference of opinion between the system designer and an individual driver of the situations where a signal is necessary. A high rate of nuisance alarms can have the same impact on driver reaction as false alarms, and for purposes of this discussion are included in the function g, Although the causes and remedies for these two experience-related factors (false alarms and nuisance alarms) are different, the effect of both is a degradation of driver utilization of the signal from the collision avoidance system.

Table 3-Description of System Categories [32]

	Feature	
	Significance of Vehicle Posture	**Action Needed**
Category 1	Potential for collision exists - vehicle(s) not on a collision course	Caution needed but no immediate collision avoidance action is necessary
Category 2	Collision is imminent - vehicle(s) on a collision course	Immediate collision avoidance action by the driver is needed
Category 3	Collision is imminent - vehicle(s) on a collision course	Immediate collision avoidance action will provided by an automatic control system

Performance Guidelines Projects

The four projects underway referred to earlier have the goal of developing performance guidelines for advanced collision avoidance systems. Each project is addressing a specific type of collision. These projects include experiments in which drivers experience situations where collision avoidance action is necessary. The experiments include exposure to these situations with and without the aid of collision avoidance systems. Thus, the data from these experiments will be a source of the relative probability of collision (P- R) or near-miss (V - W).

Human Factors Research

Drivers' response times to warnings will be influenced by how quickly they can detect and understand warning signals and decide on appropriate actions. The actions are affected by the design of the driver/warning system display interfaces. The agency has initiated several human factors studies to investigate how warning system interfaces need to be configured to provide optimized driver response, leading to a more effective driver/hardware system. In one program, various laboratory, test track, and simulator studies will be conducted to determine the requirements for optimization and standardization of design parameters of lane change/merge system interfaces [29]. Another parallel study will investigate human factors issues related to rear object detection systems [30]. It will also be possible to develop estimates of (P-R) through experiments which utilize DASCAR.

False Alarm Study

The agency also has a separate study of the effect of false alarms from systems which have been installed in the private vehicles of a set of drivers. Drivers will be presented with acoustic signals. typical of likely crash avoidance warning sounds, while they are driving. The warning signal will require the driver to then search for an external event (a light), just as an actual crash avoidance warning would require external search and confirmation. Some warning signals will be valid, that is, will indicate that a light is on. However, the manipulation of most interest will be in the occurrence of false alarms, that is, acoustic warnings that are not related to the occurrence of the light. In this way, drivers under normal driving conditions over extended periods will be subjected to nuisance warnings in a similar manner that owners of crash avoidance warning devices would be. This work is being done as part of a contract with COMSIS. [30]

3.0 SUMMARY

This paper has developed a conceptual framework for showing the relationship between system effectiveness and measurements. The framework includes the basic expressions for relating system effectiveness to the size of reduction in number of crashes. It also includes consideration of the relationship between near-misses and crashes: and incorporation of the effect of system performance and driver experience. The paper also describes current

NHTSA projects that are associated with each element of the framework for evaluation of safety system.

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For Meaningful Evaluation of The Safety Impacts of ITS Products

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1. INTRODUCTION

This paper serves as a discussion of four individual presentations made in the morning session of a Workshop on ITS Safety Evaluations, May 1 & 2, 1995, in Reston, VA. The original papers were as follows:

- "Overview and Methodologies of the ITS Safety Evaluation Process" by Alison Smiley,
- "Moving From Measures of Performance to Measures of Effectiveness in the Safety Evaluation of ITS Products or Demonstrations" by Thomas Dingus
- "Systematic Evaluation of ITS/IVHS Safety Impacts" by Michael Van Aerde
- "DOT's Approach to ITS Safety Evaluations" by August Burgett

This discussion is in two parts. Firstly, an overall view of the process of ITS safety assessment is presented, synthesizing various aspects of the original papers into a global sketch. The contributions of each of the above authors to portions of this global view are cited in the discussion. In the second part, each of the four papers is briefly discussed in a manner that both summarizes prominent points of the original author and includes my comments, as well.

Part I - A Macro View of the Subject Matter (viz., anticipating the safety record of motor vehicle traffic in the future, when identified ITS products may be in broad usage.)

The four authors, together, have afforded us a broad scope of coverage of "the future safety" subject. The central problem is, how do we go from empirically-measurable data showing how individuals drive with and without ITS equipment to the safety impact of such technology at some remote date in the future. Clearly, the authors all concur that the challenge of this prediction task is formidable; perhaps like long-range forecasting of the weather or the consumer price index, given a single definable disturbance.

One means of tying together the multiple points of view on this problem can be fashioned by expanding on a picture analogy made in the paper by Tom Dingus. He imagined that future safety is like a hard-to-access island lying offshore from the terra firma upon which empirical knowledge can be generated. Tom proposed that the effort of safety evaluation must, ultimately, bridge the intervening sea, perhaps with heavy reliance upon near-misses as an empirically-observable means of spanning the abyss. This suggestion also aligns remarkably with material presented by August Burgett. An expanded and hopefully integrative picture of these concepts will be offered below.

The Smiley, Dingus, and Van Aerde papers all dwelt heavily upon the tasks of empirical measurement and the means of their extrapolation to safety. Dingus noted that the best empirical studies must still be adjoined to a bridging structure in order to connect our knowledge of "the measurable" to that which is ultimately important the Future Safety Record, FSR,(my term, not Tom's) that will prevail some years hence, when the subject ITS technology becomes a popular part of the American driving experience. Although Tom's presentation seemed to imply that we need to bridge from mainland empiricism directly to the outlying island, FSR, he does acknowledge that empirically-derived knowledge is "several theoretical steps and a complex relationship away from a direct safety relationship". The implication is that multiple bridging steps are probably needed.

By miraculous coincidence. August Burgett proposes his own bridging concept that appears to take us in multiple steps from empirical knowledge to the Present Safety Record (PSR) a practicable way point on the path to the FSR. Some subtle distinctions are important, though. Augie discusses the use of present safety data to fashion a quantitative model of each type of crash as it is experienced today. The model is ultimately stochastic since it derives from information that is probabilistically distributed, yet is deterministic in the kinematic makeup of the final seconds before each crash. But the "specifications" characterizing each crash type are based upon the accidents that we see, today accidents occurring from causal mechanisms reflecting today's driver, vehicle. and highway elements. Showing how a new technology might interact with. and perhaps mitigate these mechanisms, seems a highly valuable step toward the ultimate concern for the future state in which driver, vehicle, and highway (esp., traffic) elements have adapted to and perhaps somewhat compensated for the new ITS technology.

Figure 1 shows a sketch depicting the overall process by which we may anticipate the safety impacts of new products that are intended to assist in the driving process. The figure primarily shows paths of knowledge, or discovery, from which safety impact is predicted. Seven quite dissimilar elements are illustrated, as follows:

1. At the lower right is Dingus' island that I have labeled, the Future Safety Record. This element represents the actual national crash experience that will prevail many years from now, when one or more ITS technologies have found market success and have arrived at mature levels of penetration into the vehicle population. The island is sketched as a wilderness place, from our current vantage point, because it does not lie in the currently-known world; it exists only in the murky future. The object of all of our safety-related studies in ITS is to properly illuminate this future state, however. such that we can guide safety-effective commercialization of ITS products in the present. Thus, the two big searchlights that are operated more or less from the mainland. The methodological question is, from whence do we get this needed illumination?

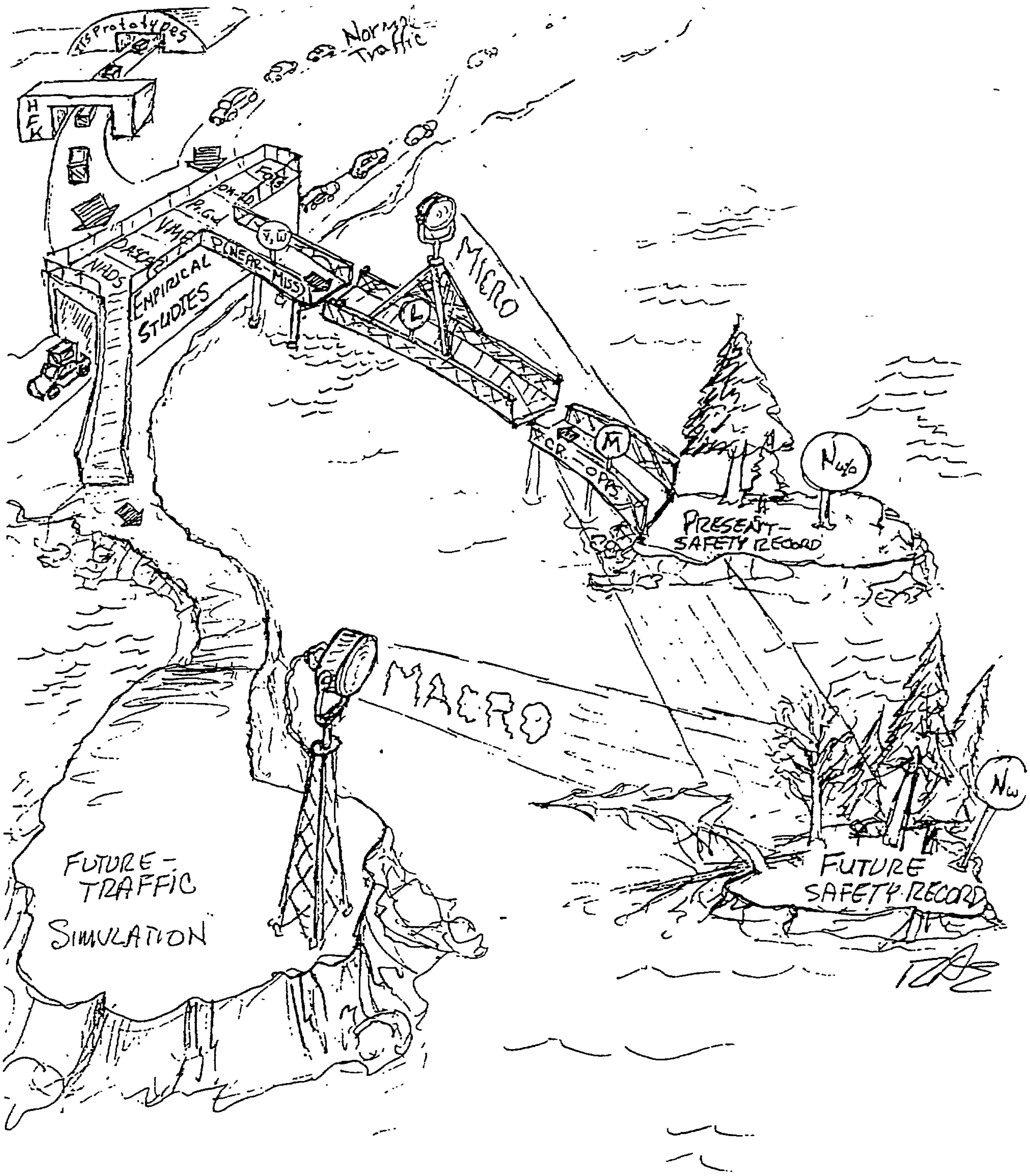

Figure 1. Predicting Safety Impacts: Conceptualized Paths of Knowledge and Discovery.

2. At the upper left, new ITS technology is conceived, implemented as working prototypes, and subjected to iterative stages of improvement with the aid of the existing knowledge base on human factors and the control of the motor vehicle. A major point of Smiley's paper is that the likelihood of safety-effective ITS products will rise if the development process directly addresses the human constraints on the application, from the outset. Hopefully the functional prototypes brought forward for experimentation and field testing will have already been made reasonably usable and reliable so that the safety prediction process is focused on truly worthy candidates.

3. To the right of the ITS prototyping facility lies the regime of "normal traffic". Insofar as normal traffic exhibits the full array of driving behaviors and crash risks posed with conventionally-equipped vehicles, it constitutes the authoritative manifestation of all factors influencing the current safety record. Normal traffic must be studied both for the sake of characterizing the reference, or control set, of driving behaviors and for creating an archive of electronic data upon which ITS functionality can be modeled.

4. The upper left structure labeled " empirical studies" represents the total set of tools and methods by which to directly observe and characterize driving behavior. The purpose of empirical studies will be to establish the mechanism and probability of <u>observable</u> threats to safe driving. both with and without ITS. In an operational sense. the measures that speak to the "threat" issue have a certain hierarchy. At the "softest". or least authoritative end of this hierarchy lie many of the "measures of performance" mentioned in Tom Dingus' paper, including glance duration. steering wheel reversal frequency, etc. In the middle lie measures including some that Dingus identified as having face validity for use as "measures of effectiveness" such as lane exceedance. braking level, and the like. At the top of the empirically-observable hierarchy lie near-misses the driving experiences that are expected to occur on the order of hundreds to thousands of times more frequently than crashes. An implicit hypothesis. here, is that near-misses are truly "crashes in the making" except for fortuitous, last-second corrections of the threat.

   As for tools, the empirical studies are shown to derive from:

   - The National Advanced Driving Simulator (NADS) and other driving simulator facilities and methods;
   - The Data Acquisition System for Crash Avoidance Research (DASCAR) which enables detailed study of individual vehicles as they are driven in traffic
   - The apparatus and software by which the Vehicle Motion Environment (VME) is characterized through direct observation of traffic passing by instrumented sites:

Proving grounds tests;

- On-road tests (accompanied by a research professional);
- Field operational tests (which are generally unaccompanied);

The fruit of all such empirical studies is depicted as leading in two directions: namely. a) toward an analytic process for illuminating the FSR in light of the apparent “micro-structure” of the future driving environment, and b) toward an illumination of the FSR in light of the apparent “macro structure” of the future driving environment. (Of course. new empirical knowledge also feeds back to guide new product development, itself, although not shown on the diagram) The prominent path for utilizing near-miss observations is shown as constituting a platform, or bridge approach element, labeled with Burgett’s symbols for the probability vectors of near miss events, v and w.

5) At the right-center of the sketch, the Present Safety Record is shown as an island, also, lying not too distant from the Future Safety Record, but still separate from it. The PSR island is labeled with Burgett’s term, Nw/o i.e., the number of crashes occurring annually in the present, without ITS products in service. A recent stream of NHTSA studies cited by Burgett have scrutinized hard copies of PSR data in order to yield stereotypical models of individual crash types. Because the work is crash-type-specific, it is seen as leading towards a predictive capability that addresses the “micro-structure” of the total safety experience in the future. Accordingly, another platform. or bridge approach, is shown originating from the PSR island and is labeled with Burgett’s symbol, M, representing the probability vector of “crash opportunities”. This vector has operative variables which are intended to align, one-for-one. with the respective variables of the probability vectors for near-misses, v and w. Thus, the approach on the right is shown directly in line with the one coming out of empirical studies on the left, although completion with an intermediate bridging piece is also required. The implication is that the “micro structure” of the driving environment includes a set of near-miss sequences that are matched, one-for-one, with corresponding crash types. The relationships which establish this correspondence. and which render one set predictable given the other, depend upon both empirical discovery and new forms of stochastic modeling as indicated, below.

6) In the center of the span between near-miss vectors and crash opportunity vectors is the “Analytical Framework” element L. This feature provides the means for extrapolating from the empirically-measurable near-misses to the rare but crudely-characterizeable crash types. Nevertheless, the extrapolation is in a probabilistic dimension. The L matrix basically says, “if you anticipate v and w vectors as near-miss probabilities of a certain type, you should expect (the computed) number and severity of crashes of the same type. The computation in question requires the formulation of L. (Current research at UMTRI is showing that a variety of analytic forms are attractive candidates for the L relationships. The forms have been used in other situations where exceedingly rare events are being predicted from more numerous empirical data; e.g. prediction of 100-year floods, Richter-8 earthquakes, etc. It should also be possible to validate the L formulations since VME data will characterize near-miss behavior based upon observations of normal traffic yielding a data set that should be test-able against the same M vector that NHTSA is constructing from current crash data.)

7) At the lower left is a "mainland" feature involving macro-level simulations of the traffic environment, based upon the findings from empirical studies. This capability was presented briefly in Van Aerde's paper and was used extensively in the safety evaluation for TravTek. Such simulations address traffic flow over extensive networks of streets and highways, assigning crash risks to differing road types and traffic patterns in a manner that reflects the respective threats posed by all the differing factors in the model. Crash-risk factors posed by ITS products are also included, as Van Aerde has mentioned. Since the model is able to represent differing levels of penetration of ITS products into the vehicle population, and to simulate their influences on routing and traffic flow, this predictive method addresses future states that are impractical to study, empirically. Necessarily, such simulation deals with crash risks at the aggregate, or macro level. It is not currently possible to simulate a large network of many thousands of vehicles in a manner that captures the local, intervehicular, movements and the human-like steering and braking reactions to nearby vehicles i.e., the domain within which specific crash types emerge. Thus, computations of future safety impact address crashes, generically, yielding total accident counts without further breakdown as to crash type.

Part II - Consideration of each of the Four Papers

"Overview and Methodologies of the ITS Safety Evaluation Process" by Alison Smiley,

Smiley's thesis is basically that the driver is not only exceedingly complex in terms of baseline behavior, but is also highly adaptable to changes in the driving environment.

Methods for determining the a priori safety impact of ITS products are thus saddled with the need to capture and characterize performance, assess the factors that are plausibly safety-related, and detect adaptive trends that may sooner or later pose safety degradations. In the end, much of the assessment of safety impact will be on a relative basis (e.g., comparing safety-relevant performances that prevail with and without ITS). Smiley takes the view that certain generic goals for ITS functions can be stated up front insofar as traffic safety for the individual user is concerned, for example:

> from a hardware point of view, sensor systems must be able to detect and reliably act upon all forms of vehicular objects found on roadways...(although this author's experience with current sensor prototypes suggest that some probability of mis-read "targets" will virtually always prevail.)
> from the viewpoint of driving behavior, the driver's response to an ITS system must not show a troubling alteration in visual search activity, patterns of mirror usage, propensity to change lanes, etc...

As a preventive against foreseeable blunders in system design, good human factors guidance in the design process should go a long way to ensure "useability". And since usable systems are typically safer than difficult-to-use systems, this initial evaluation and synthesis step should benefit long-term safety goals. A powerful element in this early stage will be a systems approach to design, especially when classical principles of good human factors design are incorporated as system requirements.

In subsequent stages of safety assessment, “naturalistic” features of any test are improved at the almost-inevitable expense of experimental control. Low on the naturalism scale, but still very valuable for advancing system development, experts can operate the system to judge safety acceptability using their own estimates of the demands, tolerances, and vulnerabilities that will be exhibited by the general driving population. The methodological sequence graduates from simulators to test tracks to accompanied operation on public roads to, finally, unaccompanied use of equipped vehicles by individuals engaged in their normal trip-taking activities. It is recognized that the ultimate realism, attained when the penetration of the ITS system causes the very traffic environment, itself, to change, will not be fully addressable until it materializes in practice.

This paper presents a great summary of the human factors regimen that can be applied to guide the development and assessment of ITS systems. Indeed, much of Smiley’s tutorial covers principles that appear warranted in the typical ITS safety assessment. Some of the concerns such as the retention of normal vigilance with ITS systems seem to have face validity although questions of judgment will abound. In the case of visual search behavior with and without Intelligent Cruise Control, for example, it seems very likely that the drivers will inevitably relax their attentiveness to the vehicle ahead, especially when the system incorporates an “intervention-prompt” feature. Judgments will be needed for weighing the extent of attentiveness reduction against the reliability of the mechanized-prompt and human-response process.

Speaking as one trained in mechanical engineering, it is both bitter and sweet to hear all this talk about the adaptive nature of the human controller. On the one hand, every ITS innovation will require that the driver accept and learn to utilize the new feature. Adaptation to some degree is simply required, in every case. On the other hand. we have the prospect that the driver may modify other aspects of control behavior, quite apart from those that may be needed merely for “operating” the system, as the functionality of the system is learned through observation. Since the driver’s adaptation process will require repetitive observations, these “other aspects of control behavior” may manifest themselves over time periods ranging from seconds to years, depending upon the frequency of the observable responses of the system.

With Active Safety Technologies (AST), we will expect that the frequency of observation of the system function by an individual driver will depend upon such factors as:

driving style
trip-taking activity
traffic environment

properties of the AST system and vehicle platform
highway topography and climatic environment

Each of these subcategories involves its own probability distribution. If certain system attributes are manifest every minute while others are only provoked by circumstances occurring every month, we may expect a more pronounced adaptation of driver behavior to some attributes than to others. If the system is only apparent, at all, on a rare basis (such as in the case of a collision intervention system) one would tend to assume that adaptation is not the issue.

We observe that with any of the ITS innovations to the motor vehicle, the driver is being given a “new reality”. Since formal attempts at familiarizing the driver with this reality by means of the owner’s manual, video tapes, dealer comments, etc. will be only partly instructive at best and simply passed over, at worst, each new operator of a given system will be more or less in the dark about the new reality. What is actually real will be discovered only incrementally, by observation, and imperfectly with each iteration. Overlaid on this groping process will be the driver’s tendency to adapt behavior in a way that optimizes on certain preferences that are highly personalized, even if subconscious (viz., I like to watch the scenery, I like to get there quickly, I avoid stops and left-hand turns, I adjust vigilance according to perceived risk, and so on.) Thus. depending upon the degree of error in the driver’s perception of system functionality and the personalizing preferences, one’s adaptation to a new ITS functionality could yield odd driving behaviors in the beginning until things get sorted out.

The crucial evaluation questions that spring from this issue are twofold, namely, 1) for how long must we expose drivers to a given system before we can assume that the observation-and-adaptation transient has settled to a reasonable equilibrium? and 2) how do we develop an efficient process for identifying the likely adaptation modalities. measuring them experimentally, and assessing their crash-risk potential?

Smiley further cited the cases of Center-High-Mounted-Stop-Lamps (CHMSL’s) and Antilock Braking Systems (ABS). as examples in which behavioral adaptation by drivers may have caused a lower-than-expected safety effectiveness. I tend to agree with the argument in the case of CHMSL’s and to disagree relative to the antilock example. In the CHMSL case, drivers have the benefit of observing the functionality every time they see an equipped vehicle braking ahead. Thus it is plausible that, as the equipped population grew, drivers indeed could have become inured to the device. thereupon adopting a tighter-headway stratagem in dense traffic with the aid of the lead time provided by CHMSL’s that are visible on vehicles ahead of the preceding vehicle. This seems like a classic demonstration of Smiley’s fundamental point on the matter of risk compensation. given that behavioral adaptation would be supported by thousands of observable events in the life of each typical driver, per year.

With ABS, however, a probability analysis by Ervin & Winkler (1987) indicates that only approximately one wheel-lockup event (and thus an ABS activation sequence) will occur on wet or dry (but discounting icy) conditions with a typical passenger car each year. Thus, one must question whether the driver's perception of ABS, supportable by direct observation only once per year or so is anywhere near sufficient to stimulate a significant process of adaptation, or risk compensation. Further, since ABS will not substantially shorten stopping distances under wet or dry friction conditions, it is not likely that the driver would even perceive a reduction in crash risk when the ABS does activate. so as to then adapt toward higher-speed, riskier, driving. (Note that the primary purpose of ABS is to secure directional controllability during friction-limited braking, rather than to elevate deceleration capability, per se.)

Moving From Measures of Performance to Measures of Effectiveness in the Safety Evaluation of ITS Products or Demonstrations by Thomas Dingus

Dingus calls for the orderly framing of a quasi-scientific empirical method when organizing studies of safety effectiveness for ITS products. The method entails statement of an hypothesis (although I found the example hypotheses to be rather thin, apparently lacking in substantiating principles) upon which distinctly measurable phenomena can be identified and captured through an experimental method. When the hypothesis is targeted at an abstract quality such as "safety", for example, this quality must be "operationalized" such that the measurement plan can be formed. But operationalizing the safety goal for driving performance means that we unavoidably face the fantastic level of complexity that attends crash causation.

Dingus gives the example case of the TravTek Camera Car Study which sought to assess the relative safety of alternative navigation systems as evidenced by differences in driver workload and other measures indicating the quality of the driver's control activity. One measure that was thought to be indicative of workload was the mean speed over a defined trip a lower value of this speed measure would imply that navigation workload was causing the driver to slow down. And yet other independent measures of driving control errors indicated that the navigation aid resulting in the lowest speeds of all (i.e.. a paper map) was also being driven with the least safety-related errors. Clearly, one would conclude that some form of compensatory behavior by the driver was adapting to the overloaded condition such that a net safety benefit was accruing with the paper map. Thus, the utility of workload measures, by themselves, may be insufficient for assessing the safety impact of systems in the hands of the continually-adapting driver.

Dingus presents two additional cases in which "measures of performance" were significantly influence by not only the expected behavioral response to a new ITS technology but also by what might be called "condition variables". An example is given in which lane boundary deviation is heavily influenced by the prevailing traffic density. in addition to whatever smaller variations derived from use of a navigator. The overwhelming influence of the condition variable traffic density rendered the primary measure of performance of little value (since a precise measurement of nearby traffic density could not be conveniently obtained throughout the experiment.) In a second example, the eye-scanning behavior of subjects was targeted as a primary measure of performance, but was later found to have been significantly influenced by the degree of area familiarity of the drivers. While this confounding influence did perhaps serve to handicap the experiment's measurement sensitivity, I found it much more troubling that the glance-frequency data went in the opposite direction of "face-validity" measures of safety-related control such as lane deviations. This anomaly was not commented upon in the paper.

Discussion of multiple experiments is presented, but each is burdened by the lack of even an approximately useful model of the human actor, given the myriad of stimuli appearing in the highway driving context. Thus, it has been necessary to assess the potential safety impact directly from "face validity" measures that seem rather compelling like lane deviations and the number of high-level excursions in longitudinal and lateral accelerations, and from measures for inferring workload like glance-taking and steering wheel variance etc.

But the problem with using any of these human performance measures for assessing potential safety impact is that they rest on principles that are "several theoretical steps and a complex relationship away from a direct safety relationship", per Dingus. Examples are given of measures that may be arguably closer to direct safety (i.e., crash-potential) relationships including observations of skid marks, glances whose duration is long relative to driver reaction time delays, evasive maneuvers near the limits of control, path and speed-keeping anomalies that align with near-miss phenomena, or traffic conflicts, and factors that have been already shown to correlate strongly with crash frequency such as the speed variance of vehicles in a traffic stream.

What matters most is that 1) the measurements accord with the terms (the theoretical construct) of the hypothesis and that 2) the measurements are sufficient for covering the influential variables. But the notion of "necessary and sufficient" empiricism is a dream in the face of a totally uncharacterized system (viz., driver, vehicle, and roadway.)

Half of Dingus's paper deals with experiences and examples of Measures of Performance that, in various ways, I found to be very close cousins to the stated Measures of Effectiveness. A number of anomalies were cited. showing that the human driving system is tremendously complex and (as per Smiley's theme) is demonstrably adaptive in many ways. The examples demonstrate the difficulty of ensuring that the empirical measurements simply account for the exhibited behaviors, let alone ensuring that safety-relatedness has been achieved. While a great deal of experience will be needed to feel confident that the necessary and sufficient variables are being measured in ITS experiments, the greater long-term drama seems to fall on the question of safety relevance of these measurements.

Dingus portrays this concern in a pictorial image of safety as an island lying offshore from coastal towns which are accessed from more remote areas via a highway network. The outer network of highways represents the Measures of Performance the means of progressing “closer” to the goal, safety. But, MOP’s are only able to lead us to the local street systems of the coastal towns, representing the Measures of Effectiveness (MOE’s). Even if the MOE’s have a certain scientific pedigree deriving from good demonstrations of crash-relatedness in some relevant (but presumably, differing) context, a lot of water must be crossed to get to the island. Dingus argues that we need a “ferry” or perhaps a “bridge” of various kinds to cross the water of ignorance that separates MOP’s and MOE’s, as here defined, from true measures of safety impact.

The problem, of course, is that the island, Safety, lies in a different dimension called, “the Future”. And even if the human species were as stable as Gibraltar, behaviorally in all its adaptability, personal preferences, multi-sensitivities, etc. we would still have the problem of a massive extrapolation from what is known through measurement in a present experiment to the future state when driver response to all the “influential variables” comes to full bloom. And the “bloom” will be full when a real ITS product reaches its high-penetration implementation and prevails there for multiple years.

Some might suggest that this problem is analogous to that of long-range, location-specific, weather prediction; but in the weather case, there is a running integral of physical conditions over time (which makes it an unfair analogy because of the tremendous importance of initial conditions and integration errors that grow with time.) Perhaps a better analogy is the long term prediction of, say, the standard of living of the U.S. population over the next twenty years given the current mechanisms of monetary control, but barring global catastrophe, insurrection, and so on. In other words, even if a time integral is not involved, in a strict sense, there is a profound “unknowable-ness” to such futurisms.

Nevertheless, a ferry or bridge of some kind is needed to take us closer to this imagined destination. Dingus expresses the belief (a view that aligns with current research at UMTRI, coincidentally) that the bridge consists in the analysis of near collisions and/or traffic conflicts.

The same view is expressed in the paper by August Burgett, discussed below. It has been noted that a large technical community, mostly in Europe, has shown compelling evidence linking observed traffic conflicts to crash rates at many specific intersection sites. The potential of mechanizing traffic conflict observations using modem technology (such as in the Vehicle Motion Environment project being funded by NHTSA) offers the possibility of a wholesale upgrade in the quality and volume of data that may stereotype near-crash scenarios and condition variables in quantitative terms, for the first time. The advantage of this approach is that near-crash conditions have been seen to occur at frequencies which are hundreds to thousands of times higher than those of crashes, themselves.

Thus, a cataloguing of near-crash attributes would provide a very high level of “face validity”, and most importantly, the potential for extrapolating to crash rate predictions, given a crucial caveat i.e., all things in the future must remain equal to the conditions that were experienced by our test subjects during the simulator episode, proving grounds test, on-road experiment, or field operational test in which we studied near-miss phenomena. We may be able to make reasonable assessments of the safety-relevant behaviors observed under the conditions that we managed to cultivate, empirically, but we should not claim an inordinate level of confidence that we know a) how those conditions will change in the "real case" nor, b) how drivers will respond to or compensate for those conditions when they prevail.

Systematic Evaluation of ITS/IVHS Safety Impacts

by Michael Van Aerde

Analysis of the safety impact of route guidance devices includes two parts. namely, 1) a facility-related component by which safety risk varies according to the routing that actually prevails over a given road network, and 2) a so-called "gadget factor" component associated with changes in the driver's control quality due to the task of interacting with an ITS display device. Van Aerde's presentation differs from those of the two preceding papers in its inclusion of item (1). The second item has been addressed by all three of the papers reviewed to this point.

Van Aerde mentions certain "surrogate measures" of accident risk which align with Dingus' category called "Measures of Performance". Van Aerde acknowledges. in line with Dingus' main theme, that there is a "real challenge in determining the nature of the functional relationship between the safety surrogates and...accident risk."

Referring to safety assessments conducted in the TravTek field test. no new ground was broken to deal with the key "functional relationship" mentioned above. but a large number of surrogate measures were collected and fused into a dimensionless form of safety index. That is, various surrogate measures had been collected on the proposition that each had at least an intuitively-appealing and in some case, demonstrated relevance to safety. They were ultimately fused together using an approach for weighting the highly dissimilar measures. At the bottom line, the changes in vehicle routes through the network presented the dominant safety effects while the more or less ergonomic effects of human interaction with the on-board devices were secondary. Because TravTek-guided vehicles were occasionally diverted from low-risk freeway segments onto higher-risk surface streets, these vehicles tended to show a net increase in crash risk over vehicles that were unequipped and that stayed on freeways in the face of congestion incidents rather than diverting to a quicker alternative route.

The INTEGRATION computer model is cited as a tool which afforded a macro accounting of each trip according to the road links used and the traffic conditions prevailing continuously on each link. The model also permitted extrapolation of results to cases of high penetration of TravTek equipment into the vehicle fleet. Since the model is only able to distribute vehicles according to defined routing rules, it does not attempt to explicitly represent the micro-aspects of human interaction with ITS equipment.

Nevertheless, the macro safety analysis (at higher penetrations, for example) can include the ergonomically-driven risks seen through empirical results by adjusting the exposure risks that equipped vs. unequipped vehicles would bear as they travel along their respective routes.

The matter of penetration level poses a profound issue for all ITS safety prognostications. Van Aerde's work with his INTEGRATION tool provides a great construct for beginning to think about the implications of penetration. At the first level, there is a direct overlay of the "new rules" of routing and traffic movement such as fall out in a rather tidy manner from route selection algorithms such as those embodied in TravTek vehicles. INTEGRATION is configured specifically to enfold such changes in the routing activity of simulated vehicles. As the population of equipped vehicles is simulated to rise, the aggregate effect on community-wide traffic flow and route-taking is observed. Of course, modeling at only the level of the routing algorithms and some %-compliance factor assumes that sociological phenomena will not also get underway, as penetration rises, to affect the routing behavior (esp. the readiness to divert) of either the equipped or unequipped populations.

It is also interesting to at least briefly consider whether traffic flow models may be useful for addressing the traffic flow impacts that attend the growth of control-enhancing systems. In such cases, the "new rules" for routing and flow are fundamentally unknown. In particular, the rules do not emerge explicitly from the design of the products as they nominally do in the case of route-guidance systems. Rather. changes in traffic that may be induced by the penetration of certain control aids will occur in an indirect manner based upon the perceptions and performance of the equipped drivers, as well as the perceptions and reactions of others who, whether they are equipped or not, increasingly encounter the system's use in vehicles nearby. In this class of systems. Intelligent Cruise Control seems conspicuous for its potential alteration of traffic flow dynamics. for better or for worse. If modeling tools such as INTEGRATION are to be employed in projecting the safety benefits of systems like ICC, new empirical data will be needed to guide both the meaningful definition of the inter-vehicle dynamics that govern car-following as well as the risk-weighting that should attach to each user in the traffic stream. And, indeed, it could well turn out that the structure of traffic modeling tools like INTEGRATION are simply unsuited to any analysis of the safety impacts of control-enhancing systems. Nevertheless, we will need an analytic or simulation context in which to extrapolate our limited empirical findings to large-scale penetrations.

DOT's Approach to ITS Safety Evaluations

by August Burgett

The paper addresses the concepts and methods for determining whether drivers operate vehicles more or less safely with an ITS system and, correspondingly, whether a fully equipped population of vehicles would have greater or fewer crash-related losses. The concept of a "bridging analysis" is presented in essentially the same context as that posited by Dingus. That is, the need exists for a framework that bridges from the empirically-measurable domain of "near-misses" to the ultimately-meaningful domain of the national crash experience. Again, the attractiveness of near-miss research is that it offers a probability target that is tractable for empirical work, being orders of magnitude larger in size that the probability of crashes, themselves. Because this target is large enough to address through empirical work, it is becoming the object of new technology-assisted measurements in the field. In order for such measurements to help in predicting the safety impact of future ITS products, however, certain analytic tools are needed for examining the ITS functionalities in light of crash. or at least near-miss, mechanisms that have been quantified.

Burgett's paper provides an abstracted formulation for expressing the net accrual of safety impacts. based upon findings from empirical research on near-misses and national populations of crash data. The NHTSA program in crash avoidance research is mapped onto this analytic form, showing how different terms of the calculation are being addressed in differing projects. In my reflection, below, comments are made on certain aspects of the NHTSA program, in light of the analytic construct.

Burgett's expression is as follows:

$$E = L(v - w) \quad M/N$$

where:

E is the estimated effectiveness of a given crash countermeasure (and presumably of any other ITS product that appears to alter driving performance in a safety-relevant way)

L is the "mapping matrix" relating near-miss probabilities to collision probabilities

v is the probability vector for near misses w/o the ITS system

w is the probability vector for near misses with the ITS system

M is the probability vector for collision opportunities

N is the baseline number of collisions occurring in recent years w/o the system in place

The "Analytical Framework Project" is essentially undertaking to develop mathematical approaches for expressing the relationships that are included under the matrix. L. The so-called bridging analysis intends to extrapolate the "tails" of the statistical functions in which kinematic conflicts of near-miss events turn into crashes. The distribution of empirical data, such as from a VME data archive, is illustrated in conceptualized form in Figure 2, showing that only a relatively poor level of confidence may be supported down at very low (and thus very infrequently observed) levels of "crash margin" i.e., the ratio of the instantaneous clearance, C, between two vehicles divided by the rate of closure, R, of that clearance. It is this low probability tail of the distribution that must be bridged all the way to zero values at which crashes occur. Bridging toward the Zero-Margin end of the scale will require a modeling effort which combines empirical knowledge defining the process of near-miss driving in operational terms with a theoretically-solid treatment of the statistics of rare events. Thus, the bridging is a stochastic modeling exercise, integrating certain fundamental kinematic constraints and human response rules which observably accompany specific types of near-misses that are 1) arguably related to corresponding crash modes and 2) probable according to the probability density function within which each type of near-miss was observed.

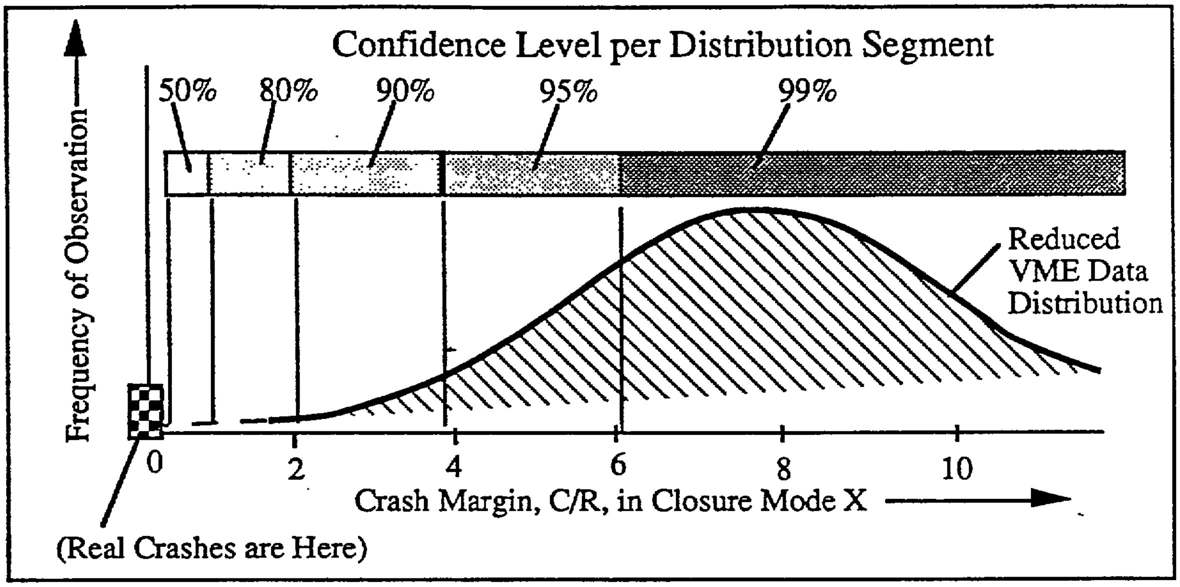

Figure 2. Distribution of Empirical Data.

A variety of approaches are being studied for the bridging analysis in a study now underway at UMTRI. All of the candidate approaches make the assumption that the phenomena actually present in near-miss driving episodes are also present and ordered the same in pre-crash phase of true crash-producing episodes. Potential challenges to this approach will prevail when any aspect of the physical system that influences near-miss control phenomena (be it from the driver, vehicle, or roadway elements) both: 1) is not exercised in the same domain as in crash-producing episodes, such that the empirical measurements of near-misses still leave a knowledge gap relative to full "pre-crash reality” and 2) contains a discontinuity or other severe nonlinearity that could render this gap crucial.

A classic example of this type of issue lies in the high-level (panic) braking that appears in the final segment of many crash-bound events, although it is likely to be substantially less represented in data from near-misses. Thus, if we observe lots of near-misses that lack panic braking and then proceed to use these data in evaluating, say, an automatic braking ITS package for its crash-reduction potential, we might mis-align the results relative to the true safety impact because a near-miss that was avoided by automatic braking may have entailed a distinctly differing level of “need” for kinematic intervention than the crash-bound cases. Although Kalman filters and system identification techniques should be useful for maximizing the knowledge gained from measuring the mechanics of near-misses, human behavior phenomena that differentiate near misses from completed crashes may be much tougher to ferret out. Nevertheless, as the near-miss incident gets closer and closer to a completed crash, the remaining time-to-collision may get so short that the missing phenomena become moot.

The measurement system for quantifying the Vehicle Motion Environment (VME) will yield data that directly and explicitly characterize the vector of near-miss probabilities for non-equipped vehicles, v in Burgett’s formulation. That is. all early use of the VME system will involve data-taking on contemporary traffic, wherein all the vehicles are conventional and unequipped with ITS packages. Once these data have been archived, however, they offer a modeling context in which to overlay crash-avoidance, or AST-type, functionality. Very large volumes of near-miss measurements taken from many real road sites would enable a simulation of candidate AST systems, modeled as an overlay on VME data, rendering the basis for Burgett’s probability vector, w, for near-misses with AST-equipped vehicles. The crucial issue with “very large volumes of data” is that of capturing a large population of not only the near-misses, but also the important crash “opportunities” that are implicit within the probability vector, M. Clearly. these opportunities exist in as many modalities as there are crash types. And since the VME concept involves collection of data at one road site at a time, it will be imperative that the data-taking period at each site stretches long enough to satisfy the need for near-miss volume across a reasonable spectrum of crash opportunities.

The portable Data Acquisition System for Crash Avoidance Research, DASCAR, offers yet another methodology for studying both the “with” vector, w and the “without” vector. v of Burgett’s general expression for safety effectiveness. In this case, the motions of an individual instrumented vehicle are recorded. with a much higher level of definition of the driver’s actions and characteristics than through VME measurements, but probably with a good deal less definition of the proximal traffic environment within which the vehicle is moving. In the DASCAR case, a candidate ITS system can be installed, physically, allowing its direct assessment in proving grounds and public highway experiments. Compared to the “simulated overlay” of ITS system functions onto VME data, this approach is more compellingly naturalistic, except for the alerting nature of the test on the subject driver one of the concerns expressed in Smiley’s paper. This approach also proceeds serially in real time, however, and is thus much less productive of near-miss opportunities that is afforded through the VME. (Ervin, 1994).

The Burgett paper also delineates portions of the NHTSA research program that address the "opportunity vector", M, within which pre-crash driving situations are given objective definitions that align with specific crash types. Much of this work begins with detailed scrutiny of crash data files. Causal factors are identified and characteristic kinematic signatures of the pre-crash phase of individual types of crashes are determined. This work is especially important for the ultimate connection of the empirically-derived knowledge to the factual mechanics of real crashes. One could say that it serves to characterize, in analytic terms, the pre-crash processes which, if avoided, will serve to eliminate the crashes themselves. Thus, an AST system can be targeted at one or more of these pre-crash processes and, indeed, effectiveness can be assessed on the basis of the system's ability to "avoid them".

References

Ervin, R.D. and Winkler, C.B, "The Influence of Braking Efficiency on the Probability of Wheel Lockup", SAE Paper 870334, February, 1987

Ervin, R.D., "Evaluating Active Safety Technology for the Motor Vehicle", Commissioned Paper presented to the Workshop on Collision Avoidance Systems, organized by IVHS America, Reston, March, 1994.

Section III

Case Studies

Section III consists of a series of safety evaluation case studies of interest to those studying the safety of ITS and other automotive safety systems. These papers are listed below.

The paper by Perez describes the process of conducting the safety evaluation of the Travtek Advanced Traveler Information System (ATIS). This was the first major operational test of an ATIS system and, as such, faced a number of logistical as well as conceptual challenges in the area of safety evaluation. The paper describes the scope of the safety evaluation; methods applied; data reduction and analysis, and recommendations for conducting enhanced ITS safety evaluations in the future. Of particular interest are the descriptions of how the fusion of driver performance data was accomplished for safety modeling. This paper clearly indicates the need for new and innovative approaches to the evaluation of ITS products and services.

The European perspective on collision avoidance systems was presented by Crompton of the U.K. Department of Transport. The paper discusses issues of legal liability in the European Union, including distinctions between contract, negligence, and product liability; the driver's role in terms of contributory negligence; ways of reducing liability by means of adherence to standards; contractual allocation of responsibility among CAS suppliers and manufacturers; and the impact of advertising on liability. Categories of controllability for hazards and their role in assessment of CAS integrity are discussed. The paper concludes with a review of requirements specification approaches, design, and testing of CAS software.

Case Study: The Safety Evaluation of Trav-Tek
William A. Perez, Science Applications International Corporation

Case Study: Safety Evaluations of Collision Avoidance Systems: Technical and Political. Aspects from a European Perspective.
Michael J. Crompton, Department of Transport, London.

Case Study: Evaluating the Safety of Air Bags -- Lessons Learned for ITS
Joe Marsh, Ford Motor Co.

Case Study: Precursor System Safety Analysis of the Automated Highway System.
Dick Leis, Consultant

Discussant Rebecca N. Fleischman, General Motors Research and Development Center

The Case Study of Air Bags, by Marsh, provides a rich description of lessons learned in the evaluation of air bags that have applicability to ITS safety evaluations. The author offers a number of “lessons learned” for safety evaluators including: Beware of early success stories: in-depth analyses of collisions can be used to gain early insights into a new system: very minor and unexpected factors can ultimately have major system impacts; and surrogate measures for crashes can be used with care.

The final case study, by Leis, describes a precursor safety analysis of an Automated Highway System (AHS). This case study is an example of a classic safety engineering approach to an ITS system that has yet to be built. This analysis focused on a very narrow subset of safety issues that must be addressed in an AHS. Classic fault tree methods are used to identify threats, and threat agents such as fixed objects, rogue vehicles, and other AHS vehicles. The analysis is structured around various assumptions of AHS operation. Throughout. various formalisms are presented and recommendations are made on the AHS design. Leis concludes that classic safety engineering principles of authority, fail-safe operation, and privilege/burden relationships appear applicable to AHS operation. An interesting aspect of this paper is the complexity associated with safety evaluation for even a very tightly defined subset of all safety issues associated with an AHS.

Fleischman, the discussant, draws broad conclusions from these papers. In general, safety analyses should be pro-active. It should begin with evaluative thinking and continue through design, testing, and deployment of a technology. Safety evaluations must address liability concerns and accept design guidelines that promote safety Real-world field studies are particularly valuable and institutional cooperation are critical to improving safety data acquisition. Increasing knowledge of driver/system interactions, behavioral safety correlates, and societal implications are important.

THE SAFETY EVALUATION OF TRAVTEK

William A. Perez
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ABSTRACT

TravTek represents the first major operational test of an Advanced Traveler Information System (ATIS). The operational test was designed to answer a wide range of questions regarding the deployment and use of Intelligent Transportation Systems (ITS) technologies and services. The TravTek system represents a distributed architecture where the ATIS vehicles planned routes based on real-time traffic information provided by a Traffic Management Center (TMC). The in-vehicle system provided drivers a wealth of travel related information that included a computerized yellow pages linked to the navigation system, navigation information, route guidance information, and incident and congestion information. The TravTek system provided drivers the information in various formats (e.g., map-like display versus simplified turn-by-turn display) and modalities (visual versus auditory). The system with respect to the driver interface and data collection capability was truly designed for conducting field research. One of the major evaluation goals for TravTek, was the examination of the safety impact of the deployed system as well as extrapolation of the safety impact for a fully matured system. This paper focuses on the methodology and lessons learned from the TravTek safety evaluation. Results of the evaluation are presented to illustrate methodological and analytical issues.

1. INTRODUCTION

Advanced Traveler Information Systems (ATIS) present the capability to make travel more efficient and safe. Efficiency would be derived through the employment of navigation. route planning, route following, and real-time traffic information. Drivers will be less likely to get lost, will plan more efficient trips, and will avoid incidents and congestion. Furthermore, depending on the system architecture, network-wide benefits will be realized in terms of efficient traffic flows that will benefit ATIS as well as non-ATIS equipped vehicles.

ATIS also present the capability of making travel safer. ATIS is envisioned to have multiple components that will be interrelated (Perez & Mast, 1992):

- In-Vehicle Routing and Navigation Systems
- In-Vehicle Motorist Services Information Systems
- In-Vehicle Signing Information Systems
- In-Vehicle Safety Advisory and Warning Systems

Some of the components envisioned for ATIS will have a direct impact on driving safety. For example, In-Vehicle Safety Advisory and Warning Systems will provide drivers early warning of roadway hazards such that drivers will be better prepared to respond in a safe manner. On the other hand, In-Vehicle Routing and Navigation Systems will provide drivers with navigation and route guidance information, perhaps supplemented with real-time traffic information. These capabilities can increase safety by allowing drivers to concentrate their resources on driving tasks, especially when driving on unfamiliar routes. Rather than employing paper maps or written directions which may result in long and frequent glances away from the roadway, a well designed In-Vehicle Routing and Navigation Systems will provide drivers with the required information in a safe and easy to use manner.

ATIS also present the potential of negatively impacting driving safety. ATIS presents drivers information that they need in different ways than is currently presented. There are a wide range of options for developing and designing specific ATIS interfaces. The driver-ATIS interface will be critical in defining the degree to which driving safety will be maintained or enhanced. A poorly designed ATIS interface that overloads the driver with information. promotes long and frequent glances away from the roadway, and requires extensive driver intervention while the vehicle is in motion may serve to increase risk (Walker et al, 1990).

The TravTek Operational Test was designed to evaluate the safety impact of a given ATIS design. Also. experiments were performed to explore the safety and ease of use of subcomponents of the system. TravTek presents a subset of the elements envisioned for a full-up ATIS. The system provided navigation, route guidance, real-time traffic information, and area wide information database. These elements were integrated in the vehicle such that route selection employed real-time traffic information (Riilings & Lewis, 199 1).

2. SCOPE OF THE SAFETY EVALUATION

The objectives of the safety analysis for TravTek were to determine (Burgett, 1991):

a. If the users of the TravTek system as deployed in Orlando experienced a different level of safety than drivers of comparable vehicles without the TravTek system;
b. How the different TravTek configurations affected the safety experience of the drivers;
c. How the safety experience as observed in Orlando for the 100 vehicle deployed in the operational field test would change as a function of the level of market penetration as the system becomes more widely deployed.

Part of the challenge of the TravTek Safety Evaluation was defining how one would objectively and empirically evaluate “level of safety.” Safety is frequently evaluated by examining the accident experience associated with a given design in comparison to an appropriate baseline condition, Accidents are a result of a complex set of variables where it is frequently difficult to establish a causal relationship between a set of subject (e.g.. driver characteristics), system (e.g., ATIS, vehicle design), roadway design characteristics, and environmental variables and the accident outcome.

Use of accident data for safety evaluations requires relatively large volumes of data to be collected with respect to exposure (e.g., number of vehicle miles driven). Accidents are a relatively rare event. For example, for Urban areas one would expect approximately 1.96 vehicle crash involvement's per million vehicle miles (Perez et al, 1995). This rate is based on national statistics from the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA). This accident rate is not specific for renters driving as tourists in an ATIS-equipped vehicle.

Performance based measures related to safety have been identified for quite some time. For example, Council et al (1980) discuss such measures as speed variance and vehicle following distance as "proxy measures" for accidents. However, criteria with respect to what represents safe or unsafe performance measures are not available. These "proxy measures" are generally employed in experiments where relative comparisons are made between conditions. For example, a given roadway design is shown to lead to longer following distances relative to what was observed before the application of the highway treatment. In the absence of actual accident statistics, this result could be used to suggest that the highway treatment increased safety.

For the TravTek operational test, there was also the requirement to employ the test results in analyses that could extrapolate to conditions of greater market penetration. The operational test included only 100 vehicles, of which only a subset was equipped with ATIS capabilities and on the road at any given time. Therefore, the system as implemented for the operational test was not at all likely to result in measurable network-wide effects. Existing traffic models such as CORFLOW present simplistic models of the driver with respect to such variables as following distance. Furthermore, at the start of the TravTek evaluation no models existed that contained a safety module or routine that could estimate the network safety impact of the implementation of such a system as TravTek. An additional challenge for the TravTek safety evaluation, was to develop a safety sub-model and to integrate relevant system and driver performance variables into the model.

3. METHOD

Figure 1 presents an overview of the methodology employed to conduct the TravTek safety evaluation. There were four major analytical steps that included:

1. **Evaluation of TravTek operational test incidents and accidents.** For all of the studies, each incident and accident was examined. For accidents, statistical comparisons were made if possible. There were few accidents in TravTek, and this finding along with the fact that there were relatively few miles of travel (e.g., less that 1.5 MVM for experimental drivers), makes the statistical analyses of accidents less than conclusive. Detailed discussion of the limitations and additional requirements for use accident data for operational tests is discussed in more detail later in this paper where representative results are discussed.

2. **Evaluation of the safety impact of TravTek in-vehicle devices.** In the TravTek study, experiments were designed to evaluate the impact of different system and control and display configurations on driver behavior and such potential ATIS benefits as time savings and congestion avoidance. For the experimental studies, it was anticipated that no crashes would be observed. Therefore, safety related measures such as close calls, driver subjective impressions of safety, and driver performance measures were collected. The Data Reduction and Analysis section of this paper presents a discussion of selected measures and how they were employed to assess safety risk.

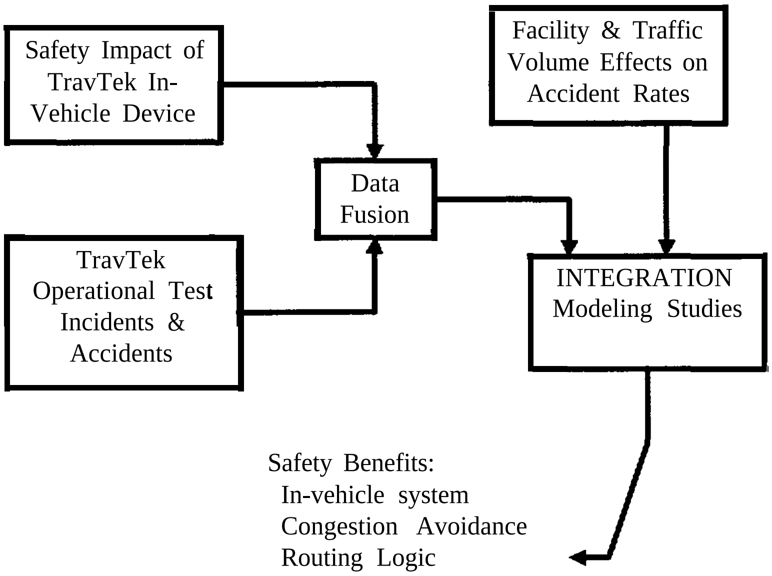

Figure 1. Overview of the TravTek Safety Evaluation Approach

3. **Estimation of facility and traffic volume effects on accident rates.** In order to support the modeling studies of safety, relationships between accident rates and facility type and traffic volume needed to be established. The TravTek system was designed to route drivers from their origin to destination (O/D) in the shortest amount of time. The system tended to create routes that placed drivers on higher class roads (e.g., freeways if possible). In addition, when real-time traffic information was available, the system would route drivers as to avoid congestion causing incidents. The approach entailed examination of literature findings with respect to these relationships and calibration of the obtained relationships with Orlando specific data.

4. **INTEGRATION modeling studies.** In order to conduct the INTEGRATION (VanAerde et al, 1995) modeling studies, findings from the above empirical and analytical efforts needed to be quantified such that they could be applied in a modeling effort. Subsequent sections of this paper describe a data fusion methodology that was used to integrate the results of the TravTek empirical studies for use in the modeling studies. The INTEGRATION modeling studies also employed performance data with respect to such observed performance measures as

number of wrong turns with and without a TravTek device present in the vehicle. The modeling studies allowed the examination of interactions between the impact of the in-vehicle device on driver performance and safety effects associated with the routing logic of the system.

TravTek Experimental Configurations

The TravTek system was designed to fully support the conduct of field research. Unlike an ATIS product-level system, the TravTek system provided capabilities for logging driver/system performance data in addition to providing the services described earlier (e.g., route guidance, navigation). The system was also designed to support the configuration of alternative systems presenting varying levels of capabilities to the drivers. The following were the three main alternative configurations used in the operational test:

Services (S) Configuration: This was an experimental control, or baseline condition for evaluating navigation and route guidance provided by the other configurations. Accordingly, it provided neither navigation nor route guidance information. This configuration only provided In-Vehicle Motorist Services Information Systems capabilities to the drivers that could be used while the vehicle was parked.

Navigation (N) Configuration: This configuration provided all of the features in the S configuration as well as navigation and routing options based on in-vehicle storage of nominal travel times.

Navigation Plus (N+) Configuration: This configuration provided all of the features of the N configuration plus the addition of real-time traffic information which was employed in the routing algorithm.

TravTek Empirical Studies

The TravTek Operational Test included the conduct of five separate empirical tests. The following presents a brief overview of each of these empirical studies. Detailed descriptions of the methods, procedures, and results of these studies are presented in separate study reports.

Rental User Study: This included the participation of visitors to the Orlando, Florida area. The drivers were recruited by AAA from their club membership. The study employed the S. N, and N+ configurations described above. Safety data from this study included incidents and crashes. and driver subjective impressions about the impact of TravTek on safety.

Local User Study: This study included the participation of Orlando residents that were high mileage drivers. The drivers in this study drove N and N+ equipped vehicles for approximately 2 months. In addition, a subset of the drivers in this study participated in the Camera Car Study. Safety data from this study included driver subjective impressions about the impact of TravTek on safety.

Yoked Driving Study: This study included the participation of visitors to the Orlando, Florida area. The drivers were run in a controlled field experiment that included the S, N, and N+ configurations. The drivers were run in yoked triads over three selected Origin/Destination pairs to evaluate the impact of route guidance on navigation and real-time traffic information on congestion avoidance. The study included an in-vehicle observer. Safety data from this study included observer recorded close calls, subjective workload ratings, and driver subjective impressions about the impact of TravTek on safety.

Orlando Test Network Study (OTNS): This study included the participation of visitors to the Orlando, Florida area. The study employed the N configuration. However, six different display configurations were formed as follows: (a) Turn-by-Turn display with voice; (b) Turn-by-Turn display without voice: (c) Route Map display with Voice; (d) Route Map display without voice: (e) no visual electronic navigation display and paper map with Voice: and (f) no visual electronic navigation display and paper map without voice. The same O/D pairs used in the Yoked Driver Study were employed in this study. The study included an in-vehicle observer. Safety data from this study included observer recorded close calls, subjective workload ratings, and driver subjective impressions about the impact of TravTek on safety.

Camera Car Study: The Camera Car Study included two separate evaluations that employed different subject populations. The first study entailed the participation of visitors to Orlando that had not been previously exposed to TravTek. The second study employed drivers from the Local User Study. These drivers were tested during the beginning and end of their driving experience. The same O/D pairs used in the Yoked Driver Study and OTNS were employed in this study. The study included an in-vehicle observer. Safety data from this study included observer recorded close calls. subjective workload ratings, video recorded data, vehicle/driver performance data (e.g., steering deviation), and driver subjective impressions about the impact of TravTek on safety.

4. DATA REDUCTION AND ANALYSIS

This section presents a subset of the results of the TravTek safety evaluation to illustrate the methodology and lessons learned.

Facility and Traffic Volume Effects on Base Accident Rates

For these analyses, a base accident rate needed to be derived prior to overlaying the potential effects of facility type and accident rates. Originally, the plan was to obtain base accident rates for Avis rental vehicles in the Orlando area. Due to the way in which Avis stores and reports accidents, such analysis was not possible. Avis provided “incident” rates for Orlando and their National fleet of vehicles. Incidents were defined as events that result in vehicle damage excluding mechanical failure. Therefore, the incident rates would include such things as hail damage, vandalism, as well as crashes.

In order to derive a base rate for the Orlando area, information from the General Estimate System (GES) and the FHWA report of vehicle crashes was used. It should be recalled that GES presents statistics for police reported crashes. Research by Miller et al (1991) indicates that the police reported crashes underestimates the true crash rate by a factor of 2 to 4. Also, the FHWA reports detailed statistics for fatal accidents. No detailed statistics are provide for property damage crashes where exposure estimates are also provided. Details for the procedure employed are presented in Perez et al (1995). Estimation of the impact of congestion on accident rates was carried out by examining the literature. Results in the literature indicate that accident rates during congested conditions increased by a factor of 2.5 on freeways when congestion was present (Sullivan & Hsu, 1988). For arterials, congestion increased accident rates by a factor of 1.25 (Hall & de Hurtado, 1992). Data collected from the Orlando Freeway Management Center (FMC) verified the above congestion effect on accident rates for freeways; however, there was insufficient Orlando data to verify the congestion effect for arterials. These findings were subsequently used in the modeling effort to superimpose the congestion effect on the base accident rates by facility type.

Analysis of TravTek Crashes

The entire fleet of TravTek vehicles drove approximately 690,277 miles during the test phase of the program. These miles were for only those drivers that were subjects in the various empirical studies. There were a total of 3 accidents in the TravTek operational test. The accidents were property damage crashes where none of the TravTek drivers were cited by the police.

The crashes involved rental drivers that were assigned to N+ or N configured vehicles. Two crashes occurred on private property (parking facilities) where the TravTek vehicles were stopped in traffic when they were struck. The third crash occurred on a public road and it involved minor property damage.

The drivers did not indicate in their reports that the TravTek system was a factor in the crashes. Two of the crashes would appear to be unrelated to the TravTek system since the vehicles were stopped and were in an area where no further TravTek guidance directions were available to the drivers.

Qualitative analysis of the TravTek vehicle crashes suggests that the in-vehicle system was not related to the reported crashes. However, the critical question is, are 3 crashes. given the number of miles driven, statistically higher or lower than an expected value (a baseline accident rate)? In other words, can one determine the degree to which the TravTek in-vehicle system was associated with accidents and whether this relationship is higher or lower than would normally be expected? Out of the total mileage, the drivers drove approximately 107,529 miles in the control condition (no TravTek display present while the vehicle was not in Park). There were approximately 582,698 miles driven by subjects who had access to TravTek displays and functions while the vehicle was being driven.

The above statistics with respect to number of crashes and miles driven, present a vehicle crash involvement rate of 5.15 per million vehicle miles (MVM) for the TravTek vehicles in the N+ and N configurations. This rate is higher than the vehicle crash involvement rate of 1.93/MVM in urban areas. However, research by Miller et al (1991) indicates that there may actually be 2.5 times as many accidents as reported in the national statistical data base. In TravTek all crashes were reported. If we assume a correction factor of 2.5, then a value of 4.825/MVM would be estimated.

Based on the number of miles driven and an adjusted national rate of 4.825/MVM, the Poisson probability for observing 3 or more crashes is 0.53 for the TravTek conditions. For the control condition, the probability of zero crashes given the number of miles driven is 0.60. Though the vehicle crash involvement rates for the control condition (zero crashes) and the TravTek conditions (3 crashes) were different than the national adjusted rate, neither of these observations were statistically significant. Observing 3 or more crashes for the TravTek conditions and zero crashes for the control condition. are statistically likely events given the assumed national crash rate and the number of miles driven in each condition. These global results suggest that TravTek had a safety neutral effect.

As a point of illustration, Figure 2 presents Poisson probability distributions for number of crashes where two samples are drawn form the same population with a rate of 4.825/MVM. For one sample there is 0.5 MVM of exposure, and for the other 2.0 MVM. With lower levels of exposure we obviously expect to see fewer crashes. Furthermore, for low levels of exposure one would expect to see a positively skewed distribution. With 2.0 MVM of exposure the Poisson distribution appears more normal in shape. Use of this type of statistical procedure is principally likely to find negative results with respect to crash rates under low levels of exposure.

Analysis of Performance Data

Performance data were collected in the Orlando Traffic Network Study (OTNS). Yoked Driver Study, and the Camera Car Study. The following presents a brief overview of the types of data and analyses that were conducted. The reader is encouraged to read the final reports being produced for these efforts.

The OTNS and Yoked Driver Studies yielded close call data obtained by an in-vehicle observer. These study, specially the Yoked Driver Study, also provided data on benefits associated with time savings and congestion avoidance. Also, data on wrong turns (navigational errors) which resulted in longer driving times were provided. These data were used in the INTEGRATION modeling study, and though are not apparently related to safety, were shown to have predicted safety impacts under levels of greater market penetration.

The Camera Car Study provided the most detailed set of performance data in TravTek. The subject’s drive was videotaped for the Camera Car Study runs. This video tape provided a data base from which such measures as close call when a hazard was present was computed (Dingus et al, 1995). Table 1 presents summary results for this statistic as a function of in-vehicle display. The Paper Map condition resulted in the fewest number of close calls; however, in this condition the subjects made the greatest number of stops.

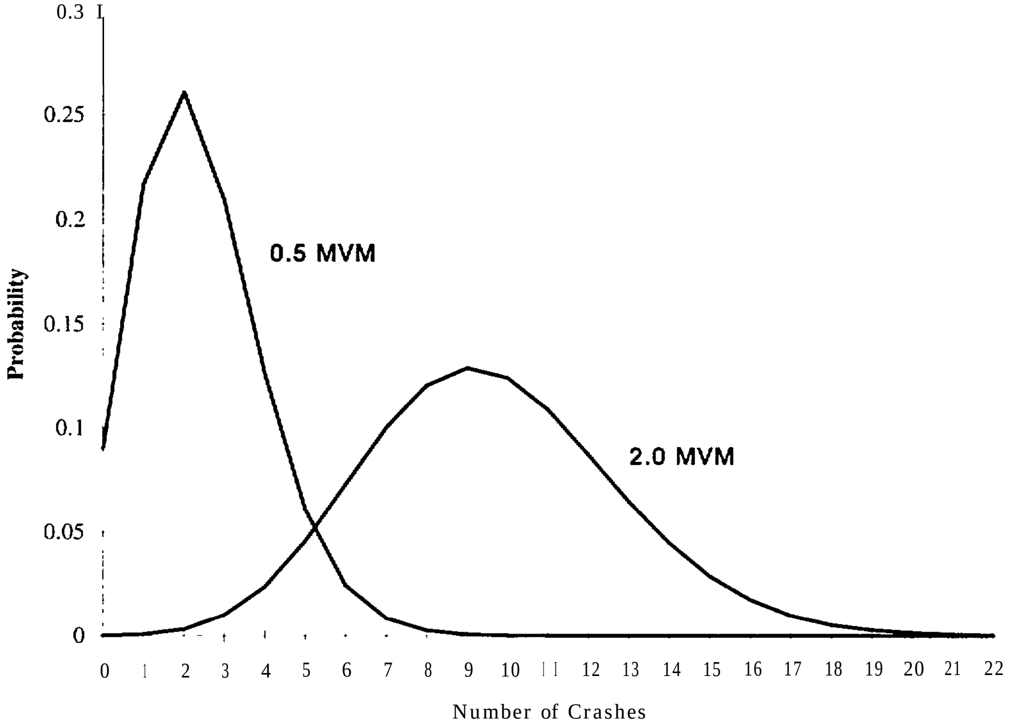

Figure 2. Relationship between level of exposure and expected number of crashes for samples drawn from a population with a crash rate of 4.825/MVM.

Table 1. Number of close calls when a hazard was present for alternative in-vehicle displays for the Camera Car Study.

Display Configuration	Number of Close Calls
Turn-by-Turn with Voice	30
Turn-by-Turn without Voice	52
Route Map with Voice	40
Route Map without Voice	102
Paper Map	19

The subjects in this condition stopped the vehicle when they needed route guidance information. The results indicate that the Turn-by-Turn display with voice has the fewest number of close calls for the TravTek conditions. Also, the voice presentation of route guidance information attenuated the number of observed close calls, and this is especially noticeable in the Route Map condition.

Additional performance metrics such as lane deviations, glance duration's in excess of 2.5 seconds, and abrupt longitudinal maneuvers were recorded in the Camera Car Study. Variables such as number of lane deviations, and number of abrupt longitudinal acceleration maneuvers showed better performance for the TravTek conditions relative to the Paper Map control with the exception of Route Map without voice.

Generally, the results of the Camera Car Study showed that the Turn-by-Turn display resulted in the lowest level of safety-related distractions which were at about the same level as experienced when driving with a memorized route. The other TravTek configurations. except for the Route Map Display without voice augmentation, appear to produce intermediate levels of safety related events, and the Route Map without voice augmentation appears to produce significantly more safety related errors and near-misses than any of the other configurations.

Fusion of Performance Data for Modeling

Figure 3 presents an overview of the overall method used to derive the final Integrated Risk Factors (IRF) for the TravTek study. The method entails four major steps: (1) Transformation of the selected Raw Risk Scores (RRS) into a common Transformed Risk Score (TRS); (2) Normalization of the Transformed Risk Scores into Normalized Risk Scores (NRS); (3) Computation of Component Risk Factors (CRF) for each individual factor from the Normalized Risk Scores: and (4) Computation of the combined Integrated Risk Factors (IRF) from the Component Risk Factors.

The first step in this process was the derivation of translation functions that converted the various safety related measures into a common metric. The approach employed subject matter experts to derive the functions. The subject matter experts were presented three data points for each performance metric which they rated with respect to risk. Figure 4 presents results for the lane deviation measure. The translation function for this measure is a quadratic function of the form shown in Equation 1. Quadratic functions were derived for all of the safety related measures described earlier.

Equation 1: $TRS=a+bxRRS+cxRRS2$

In addition to providing ratings of risk for the safety related measures. the subject matter experts provided weights for each measure. The weights represented the subject matter expert's opinions regarding the relationship between a given measure and safety. For example, weights were provided for close calls, lane deviations, workload ratings. subjective measures, etc.

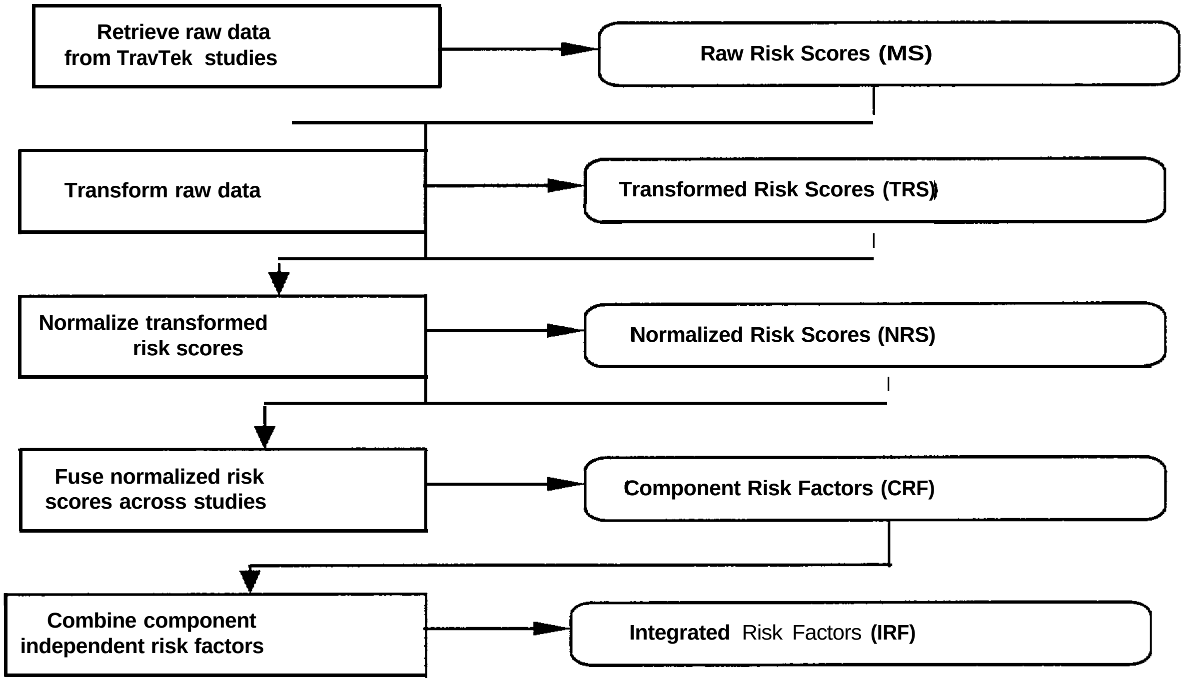

Figure 3. Methodology for Derivation of Integrated Risk Factors

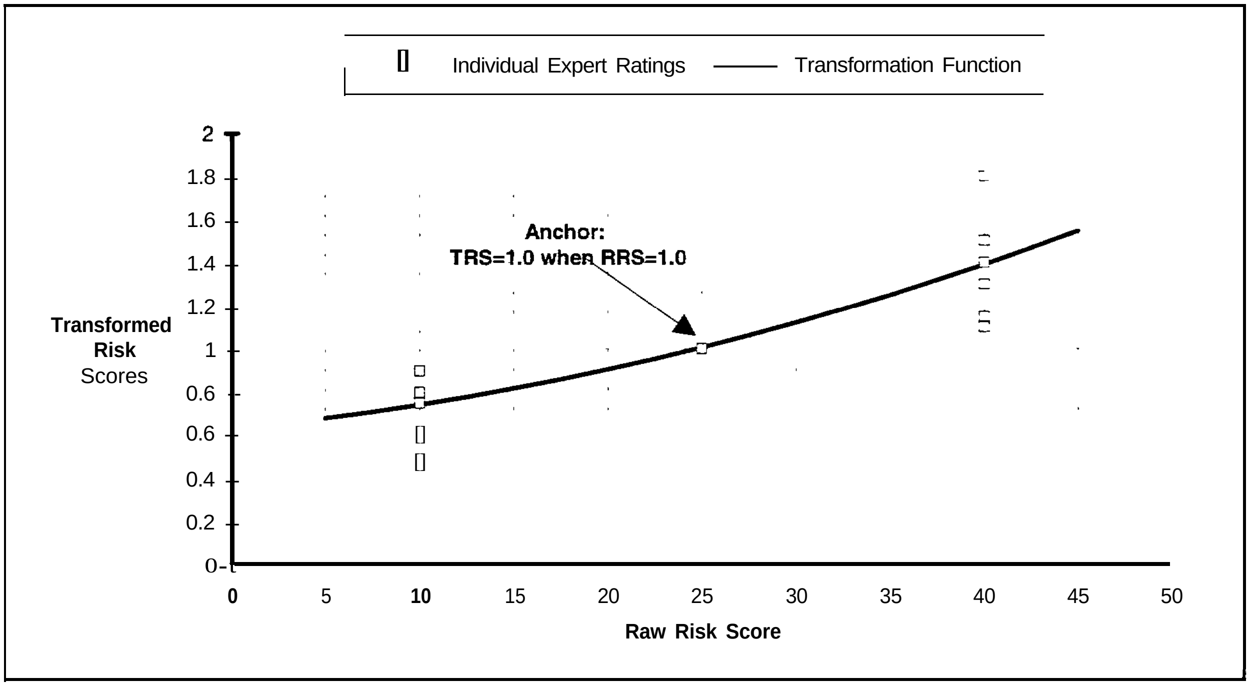

Figure 4. Illustration of Calibration of Transformation Function for Lane Deviations

In order to combine the diverse sources of data, Equation 2 was employed to establish weighted geometric or multiplicative averages.

Equation 2: $$CRF = \prod \left(NRS_i^{w_{NRS_i}} \right)$$

where: $$\sum \left(w_{NRS_i} \right) = 1.0$$

It should be noted that the TravTek operational test did not include all of the variables of interest in a factorial manner. In other words, none of the experiments included the crossing of all of the independent variables of interest (experience with system, local versus visitor, age, time of day, Route Map versus Turn-by-Turn, voice guidance on or off, and navigation versus navigation plus) included in this analysis. What were available were main effects and first order interactions. Also, safety related measures were not collected as a function of all interactions that were possible for the selected variables. The computation of the risk scores entailed a cross multiplication of available results where the variables were not assumed to significantly interact (beyond first order interactions).

The results of the data fusion process were in general agreement with the results of the separate analyses conducted for the empirical studies. However, additional subject matter expert ratings need to be collected if this method is to be employed in the future. There was a large variability in the ratings provided by the panel for the TravTek study.

The data fusion process was applied to the averages for the various independent variables (e.g., arithmetic means or sums from the separate studies). This technique needs to be applied at the subject level of analyses. That is, estimating level of risk for a given subject for a given dependent variable under different levels of the independent variables. This procedure can be carried out on an a priori basis for future operational tests. The procedures illustrated in this section can then be applied to the subject's individual data bases prior to statistical analyses. In addition, techniques that result in performance variables for such safety related measures as number of close calls that can be analyzed with parametric procedures need to derived. This may entail the use of more sensitive data coding techniques that results in a performance variable that meets assumptions underlying parametric tests. For the camera car study in TravTek, measures such as close call were not subjected to statistical tests.

INTEGRATION Modeling Studies

INTEGRATION modeling studies were conducted to estimate level of risk as a function of level of market penetration and traffic demand. The results from the previous analyses discussed in this report were input to the model. For example, a table of accident probability was developed for the baseline condition. Entries in this table were multiplied by factors associated with level of facility, level of congestion, and the results of the above data fusion process. The data fusion process resulted in a table of risk multipliers relative to the base condition.

The INTEGRATION model is described in detail by VanAerde et al (1995). Also, VanAerde et al describe the application of the model for estimating projected performance of a TravTek-like system with respect to such variables a travel time, number of stops, fuel consumption, and pollution. Figure 5 presents results with respect to projected risk for different levels of market penetration and traffic demand (e.g., congestion). The curves presented in Figure 5 are relative to 100% level of traffic demand which corresponds to the PM traffic peak in Orlando.

The results show that for low levels of market penetration (less than 30%) and high levels of traffic demand, one would predict greater risk for ATIS equipped vehicles relative to the background traffic. The reasons for these finding are related to the nature of the Orlando traffic network, the routing logic present in TravTek, and the fact that TravTek presents a distributed system. The Orlando traffic network does not present the opportunity for diversions from freeways to freeways in the case of congestion related diversions. Generally, when traveling in Orlando on a trip of 20 or more minutes, the TravTek system will route the traveler on to freeways. The systems' routing logic is biased for using the highest class roads available for a trip. Under conditions where no congestion exists, these tend to be the fastest and safest routes. When congestion is present, diversions tends to be from higher class roads to lower class roads, thus incurring a safety penalty for the diversion.

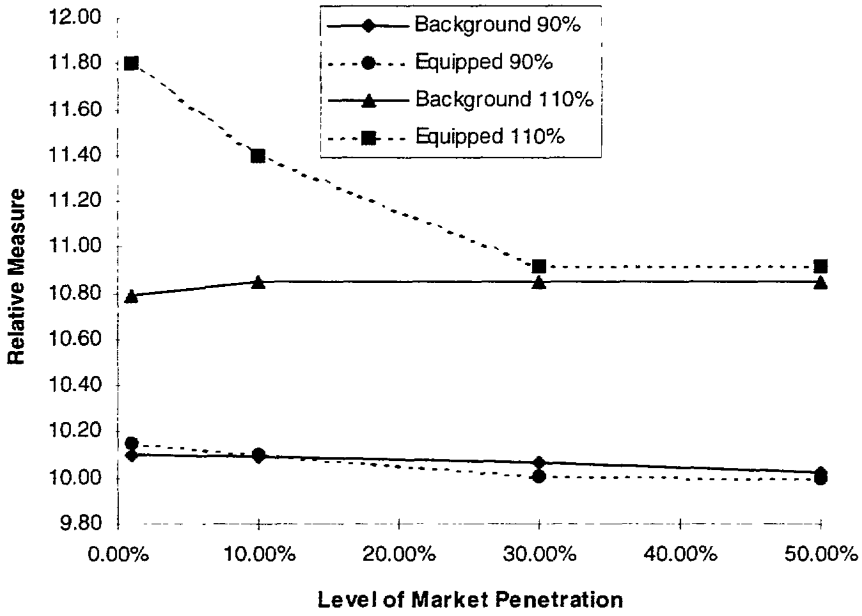

Figure 5: Orlando Network Level of Market Penetration Effects on Accident Risk.

The TravTek system presents a distributed system for generating of routes, each vehicle computes it's own best route. The TMC serves to collect, integrate, and transmit travel time information. The vehicles and the TMC are in a feedback loop with respect to travel times. That is, the vehicles transmit probe information to the TMC that include travel time on the links traversed. The probe data are used in the data fusion process in the TMC and subsequently transmitted to the TravTek vehicles. Under low levels of market penetration and diversion scenarios (congestion on the freeway that results in diversions), a greater proportion of TravTek vehicles divert relative to the background traffic. On the other hand, when more TravTek vehicles are present the feedback loop between the TMC and the vehicles results in a shrinkage of the proportion of TravTek vehicles that divert to the lower class roads. After a large number of TravTek vehicles have diverted, the diversion routes will become congested and more vehicles will remain on the freeway.

Additional analyses with 40% level of traffic demand, which corresponds to Orlando traffic at about 10:00 PM, suggest a safety benefit for TravTek equipped vehicles relative to the background traffic. The reason for this is that under a 40% level of traffic demand diversions due to congestion due not occur. The TravTek vehicles tend to use higher class roads more so than the background traffic, thus incurring an overall safety benefit.

5. SUMMARY

The safety evaluation of TravTek employed new methodology and procedure in this area of investigation. The results indicated that TravTek did not tend to impose a significant safety risk on the subject drivers. The Turn-by-Turn display with voice augmentation was shown to result in the best performance with respect to safety related measures relative to the rest of the TravTek display configurations. The Route Map display without voice as implemented in the study was shown to present the greatest amount of risk for route following tasks. However, there were relatively few near misses for all conditions and there were no accident in any of the experimental studies that examined alternative display configurations.

The modeling studies **predict** an increase in safety risk for ATIS equipped vehicles under low levels of market penetration and when congestion is present (congestion resulting in route diversions). The results are a function of the Orlando traffic network, the routing logic, and the nature of the TravTek system architecture as discussed earlier. Evaluation of a TravTek-like system in different traffic networks that allow for freeway-to-freeway, and arterial-to-arterial diversions would likely result in different safety predictions. Though some increased safety risk was predicted under a subset of conditions, under all conditions benefits with respect to fuel savings, pollution, and travel time were predicted for the TravTek system (Van Aerde et al, 1995).

6. RECOMMENDATIONS

The use of safety related performance measures appears to be the most promising method for assessing the safety risk of ATIS in operational tests. Safety data with respect to the number and characteristics of vehicle crashes should obviously be recorded. However, in order to conduct rigorous statistical analyses of crash data, large volumes of exposure data need to collected (in the order of 1 .5MVM per condition). This would be true for the ATIS equipped vehicles as well as the appropriate control conditions. The crash data analysis would be useful in identifying a system that presents a serious safety risk at best. Methods for conducting detailed crash analysis should be employed if feasible; however, these types of analyses should be conducted for both accidents occurring with and without an ATIS device on board the vehicle. Obtaining only detailed data on the crashes involving ATIS devices would tend to skew the analysis to only finding negative effects for the ATIS condition. In the TravTek operational test, Avis Vehicle Damage Reports, and in some cases police accident reports, were available. These reports did not provide sufficient details for clearly assessing the causal factors associated with the crashes. Problems with the use of existing accident reporting forms and procedures are not unique to the TravTek operational test but to all accident investigations that rely on existing reports (see Hughes et al, 1993).

Additional research for calibrating safety related measures needs to be conducted. For the TravTek study, a data fusion methodology was employed that used subject matter experts for translating raw performance variables to ratings of risk. This data fusion methodology can be expended to accommodate additional variables, alternative weighting schemes, and ratings from more subject matter experts.

The use of driving simulators and closed-course tracks for developing quantifiable relationships between driver/vehicle performance and the likelihood of crashes is another methodology that should be explored. A recent presentation at ITS America (Silberman, Poe, Young & Bachman, 1995) presented the results of analyses using traditional statistical procedures and artificial neural networks for analyzing data from alcohol impaired and non-impaired drivers. The techniques showed promise for correctly classifying drivers as impaired or not impaired based on a subset of driving performance measures. On-going research at Turner-Fairbank Highway Research Center employed the Highway Simulator (HYSIM) for investigating the relationship between sleep deprivation and safety. In the HYSIM multiple crashes were observed for sleep deprived subjects. The data from this experiment will be used to examine the relationship between driving performance variables and the occurrence of crashes. The HYSIM study allows for the examination of driving performance data under the same highway conditions for the same drivers where on the one hand a crash occurred and on the other a crash did not result.

One of the major issues with the use of driver simulation studies to develop relationships between performance measures and the likelihood of crashes is validation. That is, one would like to validate the established performance data/accident likelihood relationships under actual driving conditions. Validation in the strict sense of the word is not feasible. Extensive data would need to be collected where actual crashes occur or fail to occur where a set of independent variables are controlled (e.g., similar highway geometry).

For TravTek, the use of microscopic traffic simulation models for estimating safety risks as a function of market penetration was required. A lesson learned from this exercise is that the modeling study should be designed as early as possible. Knowing the data requirements for the modeling efforts serves to provide direction to the design of the empirical studies. In other words, if there is a desire to simulate the impact of different in-vehicle devices, under day/night conditions, with older and younger drivers, area familiar versus area unfamiliar drivers, etc. these conditions need to be adequately represented in the operational test. It is likely that all of the variables of interest will not be included in a factorial manner in the operational test. In other words, the operational test is not likely to have present 3-, 4-, or 5-way interactions among variables of interest. Careful consideration needs to be given to collecting data for what appear to be the most important independent variables, since in an operational test as in most behavioral research, it is not possible to measure performance under all conditions of interest. Inclusion of too many independent variables is likely to result in performance data with large variances where conclusive results can not be reached.

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SAFETY EVALUATIONS OF COLLISION AVOIDANCE SYSTEMS: TECHNICAL AND POLITICAL ASPECTS FROM A EUROPEAN PERSPECTIVE

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ABSTRACT

Collision avoidance system (CAS) is used here to refer to a system that can intervene as distinct from merely warn of an impending collision. Reliability is one factor in a critical area of the capability of such systems. This paper first considers the need for such systems to be demonstrably reliable and capable if they are to meet inevitable and potentially stringent liability requirements on designers and manufacturers. It explains what liability requirements exist in Europe now and how they might bear on the particular nature of CASs. It identifies the importance of controllability in apportioning liability between the system designer and manufacturer and the driver. After looking at CASs as part of a progression of automotive developments that aim to interpret and give effect to driver intention, the paper focuses on one representative aspect, namely the particular difficulty of ensuring reliability of the software. The paper describes one possible approach which embodies the concept of controllability, to show how confidence in the reliability of CASs might be achievable in practice by a progressive approach.

1. INTRODUCTION

Europe and the USA have traditionally had different approaches to vehicle standards, with a more formal type approval approach in place for existing vehicle systems in Europe. But what is the most appropriate approach as technical capabilities evolve? Both US and Europe face the same challenge of balancing safety and freedom of technical development.

Safety - related automotive systems can be broadly grouped as follows:

systems which advance safety - to be encouraged or freely permitted with guidelines or standards if required for safe or feasible delivery to the market place.

market driven comfort/convenience systems some of which may have safety related aspects - consumer demand will deliver systems to market if realistically priced and safety elements may need addressed.

systems which have traffic flow or capacity advantages - these will be delivered by market driven on-vehicle systems or by a mix of infrastructure and vehicle systems. Some of these may have safety elements which require examination and possibly some control/regulation before implementation.

systems where direct control of the vehicle by the driver is largely or wholly devolved. This covers systems where the shift is from the driver to the vehicle and, in the longer term, to systems that are vehicle/infrastructure combinations (ie both gradual evolution and step change).

systems which improve enforcement of safe driver behaviour eg speed limit control. Such systems are unlikely to appear unless mandatory and may include measures for higher risk drivers.

interaction ie. between a *range of systems* in terms of priorities and driver loading.

In some ways collision avoidance systems (CASs) may be represented in any and all of these groups.

The development of CASs in Europe is taking place in the following broad key statistical context: there are 160 million vehicles on European roads; an increase of 20 - 30% is forecast by 2010. There are currently 42,000 fatalities and 1.4 million injuries on European roads each year (AECA figures).

European interest specifically in CASs goes back to when the first radar patents for road traffic were taken out just after World War II. Since then it has largely developed in PROMETHEUS - Programme for European Traffic with Highest Efficiency and Unprecedented Safety - which ran from 1988 to 1994. This programme was led by industry, and produced a basic technical demonstration that CA is feasible. Several papers on this Programme were presented at the First World Congress on Intelligent Transport Systems in Paris last year [1]. The technology has tended to move well ahead of consideration of the vital acceptability issues.

Work to refine and validate this CA technology is now underway under a successor programme called PROMOTE. It is hoped to carry out some of this work under the third phase of the DRIVE programme - Dedicated Road Infrastructure for Vehicle Safety in Europe - which began in 1989. This programme is led by the European Union. But if CASs are to come into widespread commercial use their societal, legal and financial implications have first to be properly addressed: there is still a great deal to do.

Safety evaluation work in Europe so far has been carried out by PRO-GEN, a sub-Group in the PROMETHEUS programme. They produced some initial safety documentation and guidelines [2] as well as a report on their work throughout the programme [3]. In particular the PRO-GEN Safety Group developed methods of estimating the safety effects theoretically for comparison with on-road measurements in due course.

Their assessment was carried out in two stages:

I. estimating the 'maximum' likely reduction in accidents, assuming that the equipment and drivers operate as intended by the designer;

II. assessing qualitatively the degree to which drivers' responses to the new equipment might cause the estimate from stage I to be adjusted, giving an 'expected' reduction.

The results of the assessment applied to collision avoidance showed;

Theoretical maximum reduction (%)	Expected measured reduction (%)
30 to **40**	**25**

The Group concluded that the maximum figure will only be achieved if four conditions are met:

a) all equipment always works as intended, and equipment failure never causes an accident,

b) drivers always react instantly and as intended,

c) driver behaviour will be unaffected by the new equipment: for example, no driver will drive less cautiously than at present because of a greater sense of security,

d) all vehicles which can be equipped will be equipped.

Although **all** these conditions are important - on (c) for example, the Group's work has shown that behaviour modification must be taken seriously [4] - this paper concentrates on aspects related to the first of these. Condition (a) requires all system safety problems to have been anticipated and solved, so that system malfunctions will never cause accidents. Fulfilling that condition in an absolute sense is probably impossible. But the question is: can an adequate level be reached? 'Adequate' covers both

- **system definition** that is, sufficient for the envelope of road conditions in which it is expected to operate; and

- **high level of reliability including sufficient warning of failure**

There is a separate question of what is ‘adequate’ politically where perceived dangers can generate considerable public pressures.

The main requirement for a CAS is the ability to predict accurately the likelihood of an immanent collision and respond so as to reduce the threat. The response could involve the automatic control of the vehicle or an appropriate warning to the driver. The European demonstrator of CAS. developed in the PROMETHEUS programme, is essentially a warning only system. In either case the major issue is system reliability. It is crucial to safety. To liability. And hence to the economic viability of CASs.

Drivers deal with many potential hazards per mile/kilometre. Key questions are: can automatic systems *reliably* detect collision hazards; *reliably* judge whether the driver is responding appropriately to them: and. if not, *reliably* identify and implement a response strategy that is and **remains** optimal **throughout** the unfolding incident? Will the driver *perceive* it as the best strategy? **How** do we define *‘reliable’?* And what are the implications for other drivers some without CASs? Our knowledge and technical capability is not yet equal to answering all these questions fully. CASs may have to be limited, at least initially, to narrowly defined operational envelopes. A flexible gradual evolution and use of niche openings rather than major step change seem the most likely development scenario for CASs from a European view. This, combined with the fact that CASs (unlike, say, seat belts) potentially have different levels of capability and sophistication, suggests that flexible guidelines linked to safety principles and a good knowledge base, rather than rigid regulation by standards, is likely to be the preferred European approach to their control.

In deciding what approach to adopt in the case of CASs, Europe could choose from four broad options:

1. Do nothing

   - it has opted for this in the case of the progressive use of electronics for driver support - such as traction control.

2. Place a simple requirement on safety in general or on a specific area of safety

   - this approach works well in relatively simple situations especially as a transitional or fallback option.

3. Guidelines or codes of practice on the system development process and/or the system performance.

   - this approach is light, flexible and easy to update; but there **must** be a very strong commitment from industry to work with government and researchers where appropriate. The work of the Motor Industry

Software Reliability Association (MISRA), referred to later, is an excellent example.

4. International standards and EC Directives

   - this approach involves the longest timescales and the least flexibility but clearly may be appropriate depending on the circumstances. European agreement would be necessary as such an approach would be mandatory. And agreement is easier for some countries than others.

What approach to regulating the introduction of CASs the European Union will adopt remains to be seen. They are likely to wait and see what happens in practice rather than anticipate it. ‘Wait and see’ is a well precedented approach that is particularly suitable when, as is the case here, the situation is uncertain and/or complex; when to legislate could be counterproductive eg if it could inhibit or prevent worthwhile innovation; and when there are existing legal provisions in the Union and its Member States that would be relevant and could be sufficient.

2. LEGAL LIABILITY [5]

The principles of liability are already well established in law: for example, liability in contract with its principles of ‘fitness for purpose’ and ‘satisfactory quality’; and liability through negligence with its principle of ‘duty of care’. Unless and until a convincing case can be made to change the law, it is very much a case of seeing whether established principles apply to new situation. Manufacturers of automotive products already accept wide ranging legal liabilities for their products. And these products have become increasingly sophisticated over the years. The questions are whether the nature or extent of that liability is different in respect of products like CASs and, if so how. and what can and should be done about it.

Product Liability

There are generic European requirements on product liability which member states implement via their own domestic legislation. Some member states have legislated for these requirements in broad terms while others, like UK. have been more specific. **Product liability** was introduced as a legal concept in UK in 1987 by the Consumer Protection Act. This Act imposes **strict liability** on manufacturers of products that are for the benefit of private individuals (not businesses) if defects cause death, personal injury or loss or damage to property. The liability falls jointly on the producer, the importer and the person who puts their own trade mark on the product.

The defences to a product liability claim are extremely limited. In practice, only two are likely to be significance - the **state of the art** defence and the **subsequent product** defence. The former may allow the producer to escape liability where the **state of scientific and technical knowledge** was not such that the producer might be expected to have discovered the defect.

The **subsequent product** defence effectively shifts the responsibility for a defect on to a producer of another product in which the product in question has been incorporated. This defence can only be made out either where the component supplier has had to adopt a particular design by reason of the design of the **subsequent product** or where the design was adopted in response to instructions from the supplier of that product.

In the UK there have been no reported cases of claims based on the Consumer Protection Act 1987 to date. So the legislation may well not be as draconian in practice as it might seem.

The Driver's Role

Suppose a CAS fails to operate properly, and an accident results. The basic position on the responsibility in law when the system is defective is that outlined above. But what if the driver has contributed to the accident? Both under the law of negligence and product liability, the doctrine of "contributory negligence" allows the courts to reduce the damages otherwise payable where the claimant can also be shown to be at fault.

In contract, on the other hand, the contributory negligence concept does not apply and the law rests on the notion of a chain of causation. Only if that chain is broken will the car dealer not be liable for the ultimate consequences.

The introduction of sophisticated automated products like CASs raises a specific issue in relation to the responsibility of the driver. For example, it is likely that a driver will drive less carefully that he or she might otherwise have done, thinking themselves safe in the knowledge that the CAS fitted to the car will be sufficient to avoid an accident. But what if the CAS fails and an accident results?

Would the courts be prepared to accept in such circumstances that the driver has either no responsibility or a reduced responsibility for the accident? Whilst there can be no certain answer to such a question unless and until it is tested in court, the likelihood is that, as UK law currently stands, the driver would indeed bear some responsibility for the accident, at least to the extent that carelessness on his part caused or contributed to the accident.

The courts would expect reasonable behaviour on the part of the driver. But there are policy issues too. A finding that the driver bore no responsibility at all for the accident would be tantamount to encouraging less safe driving by those whose vehicles were equipped with a CAS. The precise allocation of liability as between the defective system and the driver may depend on the **interface between the driver and the system. In** other words it could depend on the extent to which the driver **has the reasonable opportunity of effectively overriding** the system.

If the system reduces or removes responsibility from the driver in a way which is sanctioned by the law, as would be the case with automatic CASs, it is primarily for the manufacturers of the vehicle and of the system to ensure that it operates correctly although those responsible for its operation and maintenance could also have a liability in negligence. The driver is unlikely to be held liable if the system malfunctions and an accident results, at least if he has followed the instructions given by the vehicle manufacturer and acted otherwise reasonably in the eyes of the court: the likelihood is though that only the clearest possible indications about a CAS's suitability for a particular use would serve to excuse the manufacturer from liability. On the other hand, where the ability to intervene exists, as is the case with collision warning, there could be some liability on the driver. This point about **controllability** is important and not only for reasons of liability as will become clear later.

Could Liability Be Reduced or Excluded?

It has been suggested that there some kind of special category of system with ring fenced liability might be created. Presumably one criterion to justify inclusion in such category would be that the system offered increased safety in a large majority of cases. This concept would be breaking new ground. It is hard to see how it would sit easily with existing safety and consumer protection legislation. And it is also hard to see legislators tackling such a thorny issue, particularly if there were more than a very small element of increased risk and those affected were not confined to a very small minority of cases.

The UK Consumer Protection Act expressly prohibits the exclusion of liability in respect of defective products. But, as noted earlier, there are specific defences in the Act. The most obvious defence in the case of CASs is the **state of the art** defence. If a software defect in a CAS could be shown to be attributable, say, to a defect in a standard (as distinct from a failure to satisfy the standard) the courts would almost certainly take that into account and limit damages. It is also quite conceivable that the UK courts would take a similar view of the recommendations in a Code of Practice or Guidelines even if they are not legally binding. A court is much more likely to consider a CAS manufacturer to have acted reasonably if he can show that he was aware of such recommendations and had made an honest attempt to apply them and had a sound documented justification for those he had not applied.

The state **of the art** defence may offer an opportunity for manufacturers to avoid liability although one significant problem is that the defence operates by reference to the time of **sale** of a product rather than to the time of its manufacture. This strongly indicates a need for continuous monitoring to ensure that CASs manufactured but not yet sold are modified or if need be withdrawn if any developments in the state of the art suggest that they may be defective.

How CASs are **advertised** could be very significant. There could be very important differences in seeking to defend a legal action if a CAS has been sold as a passive safety system that, rather like an airbag, is there just in case another driver does something silly. And one sold on the basis that it will improve journeys by allowing the driver to think about other things.

Section Summary

To the extent that CASs take over the driving function, the liability of manufacturers will undoubtedly increase. That suggests a need for emphasis on fail-safe features for prevention. And good insurance cover! If it is not already doing so, perhaps the motor industry should discuss the particular insurance needs of CASs with the insurance industry, to see if a cost-effective approach can be agreed and if so what the implications would be: automatic data recording perhaps, to help establish liability in accident. In the European view there seems little or no scope at present for 'ring fencing' or excluding liability as regards the people who suffer loss from a defective CAS. The creation of a standard is probably the nearest Europe comes to providing a means for a manufacturer to introduce a system which can be claimed to be 'safe' and with a 'state of the art' defence. But even this does not 'ring fence' liability. Only diligence in manufacture and a careful approach to contracting with others in the supply chain will help to reduce liability. So designers and manufacturers will need to make a virtue of necessity.

Three consoling thoughts occur. The first is that you can warn the driver: if CASs are provided with diagnostic facilities to alert the driver immediately if the system is not functioning properly and the driver is able to intervene, that should in principle reduce the level of liability on the manufacturer. But the warning must not fail! The second consoling thought is that CASs have already been encountered elsewhere - in the aviation industry. Perhaps the automobile industry should look there to see how that industry manages the associated liability implications. And whether useful lessons can be learned in readiness for the widespread use of CASs in road vehicles. The third consoling thought (at least for potential manufacturers of CASs for use in Europe) is that historically levels of liability in Europe generally have been significantly lower than those seen in America: there is no obvious reason why this position should change. But in either continent, the message is clear. Those involved is designing, manufacturing and selling CASs should act on the assumption that they *will* normally be liable; should take out appropriate insurance: and should then plan for and price CASs accordingly.

3. A POSSIBLE PROGRESSIVE APPROACH TO COLLISION AVOIDANCE

CASs can be considered in the context of developments in the automotive field characterised by gradually increasing interpretation of driver intention in terms of the vehicle delivering the desired effect. This progression is broadly as follows: *beginning* with safe control entirely within the driver's demand: such as anti-lock brakes, where it is quite clear that the driver wants the control he or she has pressed (brakes), *through,* for example, traction control, where the momentary application of braking not demanded by the driver helps serve his or her demand for safe acceleration; and currently *ends* at increasingly strategic control such as anti-skid handling to facilitate normal driving in abnormal treacherous conditions. This might envisage this evolutionary approach being extended using the examples of enhanced braking and enhanced Autonomous Intelligent Cruise Control (AICC).

Enhanced Braking

There is a potential system that interprets the rate of application combined with high pedal pressures as an emergency and delivers the highest possible level of braking consistent with safety. This has the advantage of avoiding unintended underbraking by the driver (or, in the case of the motorcyclist, applying some deliberate underbraking for fear of loss of control) and delivers a higher braking level than the driver may have strictly demanded.

Enhanced AICC

This is an extension of an existing system and it could be argued that the driver will be familiar with such systems generally as they develop from those marketed as comfort and convenience systems with limited levels of deceleration. And that they also allow progressive increases in maximum permitted deceleration and use in very specific areas eg motorways and dual carriageways. The level of awareness may vary in different countries: for example the widespread use of cruise control in the USA may create greater awareness level amongst US drivers there - though AICC is likely to become more popular in the relatively dense European traffic situations.

Collision Avoidance: Some Factors

Envelope limitations

Collision avoidance is more difficult in complex situations. Real life is a complex situation of potential and developing hazards. In such circumstances, even on a motorway, judgements are difficult. The ability of the information gathering, image processing and decision taking electronically is one aspect which may limit the ability of the system to take optimum and prompt decisions. Perhaps more worryingly, even with the benefit of hindsight and a Cray computer, there may sometimes be several different choices and the optimum choice in terms of the most probable anticipated sequence of events is **not necessarily** the right one if events in the hazard actually unfold in less likely ways. And, perhaps more importantly, it may differ from the “best” collision avoidance option perceived by the driver, whether that view is right or wrong.

Other permutations and combinations exist, for example, where the system does nothing either because it is outside its operational envelope or because it cannot react in the time available.

Flexibility

The element of flexibility is especially important in a developing field and a diverse industry. Over-regulation would have its own dangers and formal regulation is never entered into lightly. Moreover measures need to be **cost-effective** and there is always the danger of being proved very wrong with the benefit of hindsight. The “red flag” Act illustrates the point. Current approaches to vehicle systems are more flexible, their core being to focus only on key precisely measurable agreed performance figures/factors, leaving the choice of technical solution **to** the manufacturer. However, even this more enlightened approach is likely to evolve to address some areas of advanced systems. For example, HMI aspects do not lend themselves readily to precisely repeatable and cost-effective approval testing of the sort traditionally applied to motor vehicles.

The most effective way to deliver safety with flexibility sometimes lies in guidelines which reflect a well researched technical and expert consensus. The UK's Development Guidelines for Vehicle Based Software [6] and their supporting reference documents [7] - [15] are a good example of this approach, which is likely to become increasingly important in Europe. These Guidelines were drawn up by the Motor Industry Software Reliability Association (MISRA).

Timing and value of the Guidelines

The MISRA Guidelines are an important element in this process of achieving safety with flexibility and their production in November 1994 is timely both for current systems and for maintaining consumer confidence as more advanced systems emerge in future. As their title implies, the Guidelines do not just concern software in CASs: but they will be particularly germane to software in CASs.

The Guidelines, based on industry experience and input from government and research. address technical factors while allowing a degree of flexibility for software to be developed in a way that best matches a company's individual strengths.

How can the MISRA Guidelines contribute to safety?

Although they do not reduce casualties directly, the Guidelines should make an invaluable contribution indirectly by helping industry to continue to deliver safety improvements while minimising software risks and any associated loss of confidence in new technology which might inhibit progress. A rough homely analogy is the role of a sensible diet in ensuring a sturdy child that can cope with the rough and tumble of life.

As stated in the Department of Transport's foreword to the Guidelines, they reflect a responsible and serious industry attitude to safety issues. This is especially appropriate not only because of the liability implications mentioned earlier but also because in the final analysis, it is the attitude, level and breath of expertise and efforts of individuals and companies that produce safe products. Standards or guidelines are at best only an aid in the process. The benefits of this approach will continue to be felt, even though its operation, like much technical activity, may be unseen by the ordinary motorist.

Purpose of and background to the Guidelines

The purpose of the Guidelines is to assist the automotive industry to create and apply safe and reliable software within a vehicle system. Ensuring software reliability is one element that makes the achievement of reliable CASs especially challenging. The Guidelines have been drawn up in the belief that a unified approach to software development across the automotive industry, using agreed techniques, is both desirable in itself and will facilitate confidence in complex electronic systems.

MISRA formed eight subgroups to research specific issues relating to automotive software; eg. integrity, software in control systems, human factors in software development, and verification and validation. Each subgroup produced a report [7] - [15], the recommendations from which are incorporated in the Guidelines.

There are important differences between software and other forms of automotive engineering and components:

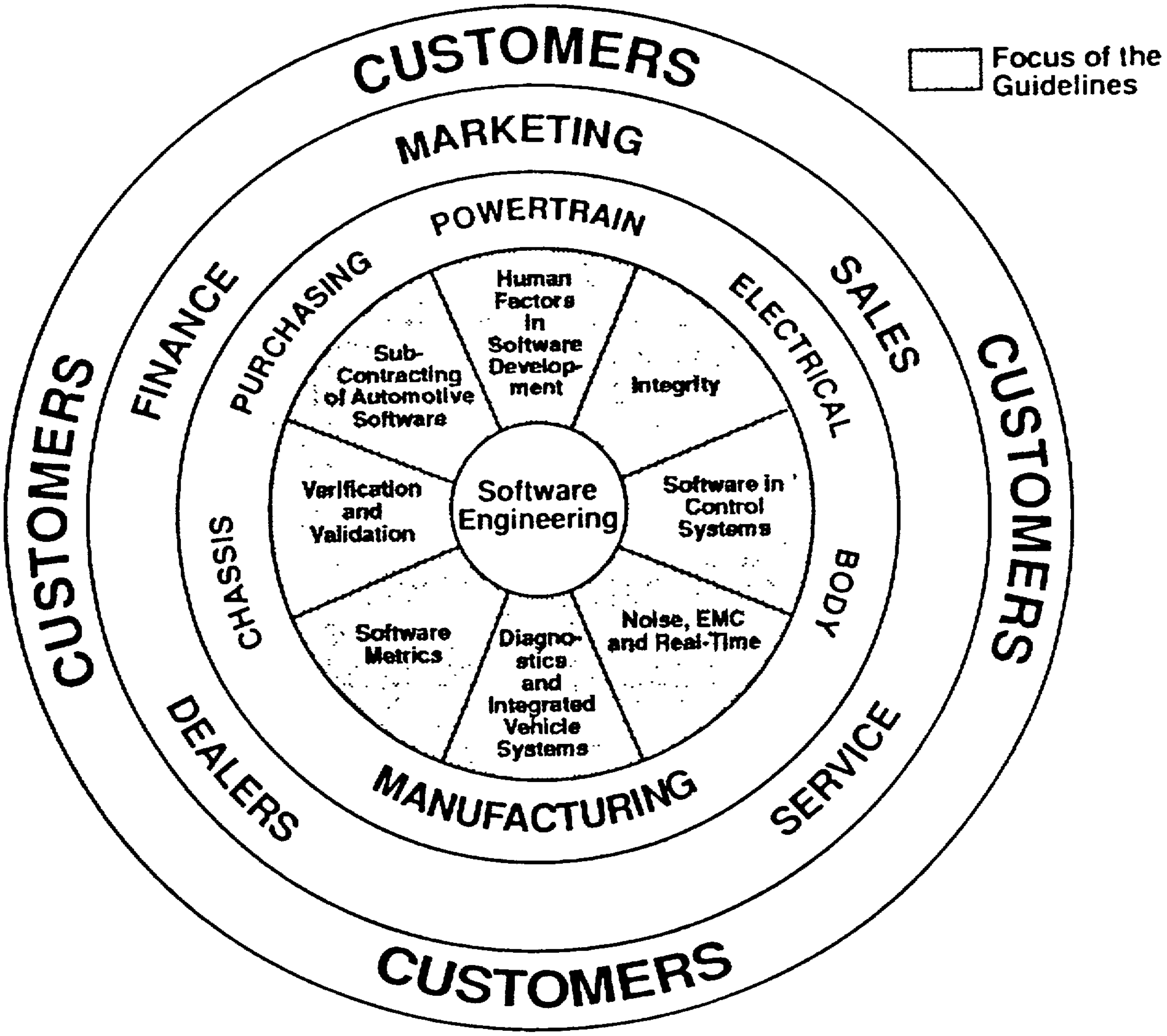
(a) Software is primarily a **design,** with no manufacturing variation, wear, corrosion or ageing aspects.
(b) It has a much greater capacity to contain complexity.
(c) It is perceived to be easy to change.
(d) Software errors are systematic, not random.
(e) It is intangible.

There are also differences between automotive software applications and applications in other industrial sectors.

Scope

The Guidelines take a broad view of software, recognizing that many concerns attributed to software reliability are as much systems issues as software engineering ones. The Guidelines therefore cover system issues insofar as they are considered to influence software development. The scope of the Guidelines is shown schematically in Figure 1. The fact that the Guidelines address only part if the total system must not be overlooked: as has pointed out, the four pillars of a unified assessment framework are safety, security, environment and reliability. But there is as yet no unified procedure incorporating all four [16].

Figure 1: Scope of the MISRA Guidelines



Basic safety principles

The Guidelines reflect the following basic safety principles:

(a) Safety must be - *and be seen to be* - present.
(b) The greater the risk, the greater the need for information.
(c) Software robustness, reliability and safety, like quality, should be built in rather than added on.
(d) Where safety requirements conflict with other requirements, safety must take precedence.
(e) System design should consider both random and systematic faults.
(f) Robustness must be demonstrated: it is not sufficient to rely on the absence of failures.
(g) Safety considerations should apply across the complete life cycle: from planning, design, manufacture, operation, and servicing to disposal.

How can these principles be applied in practice to some of the key stages of software development for CASs? It is important to stress that what follows gives only a brief flavour of the Guidelines.

Planning for verification and validation

The Guidelines recommend that a **Lifecycle Safety Plan** should be defined *before* the start of a project for the system and the software. Figure 2 shows an example lifecycle. The Plan should aim to ensure that verification and validation are performed *throughout the project* with a rigour appropriate to the **integrity level.** The verification and validation activities should be defined to establish a level of confidence in the software that corresponds to the integrity requirements of the system (Figure 3).

Assessment

The Guidelines recommend that a company nominates a suitably qualified and **independent** assessor and/or auditor to perform assessment, and to act as an advocate for the level of confidence in the safety delivered to the end customer [8].

The higher the level of integrity the greater the independence of assessment required.

The degree of independence [171] should be achieved by one or more of:

- different person
- different department or section
- different company

Figure 2: An Example Lifecycle

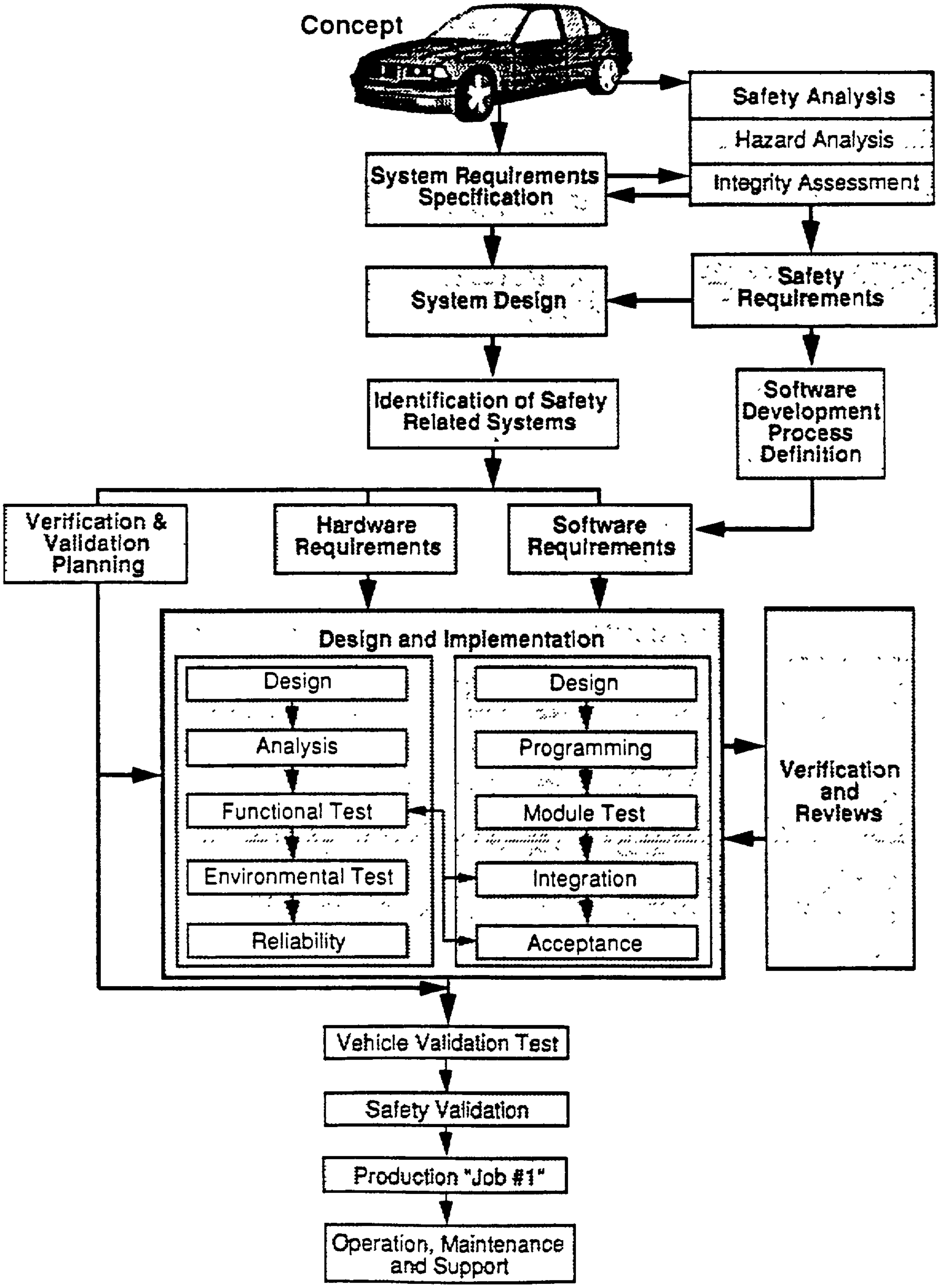
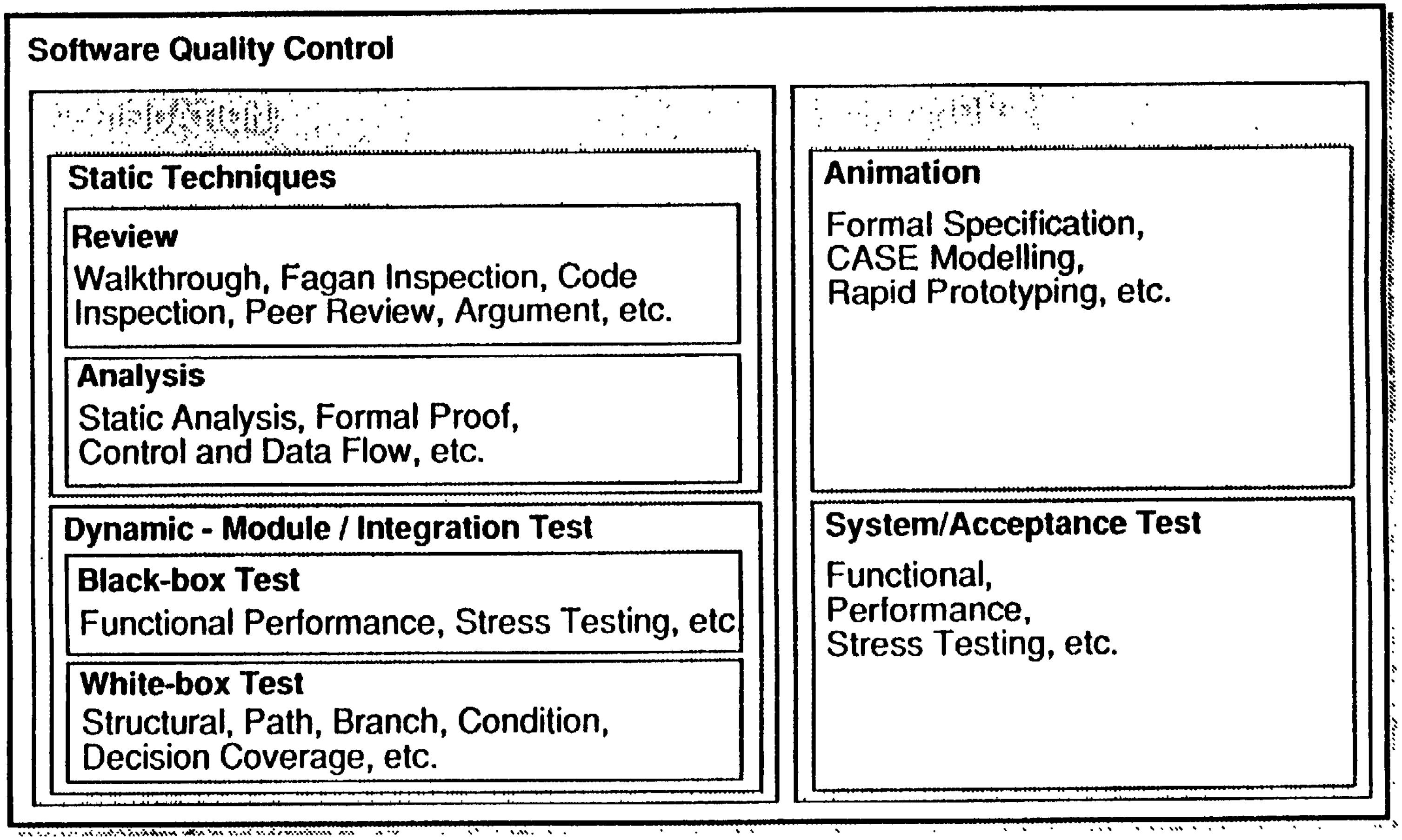


Figure 3: Software Verification and Validation



Software Quality Control

Static Techniques

Review

Walkthrough, Fagan Inspection, Code Inspection, Peer Review, Argument, etc.

Analysis

Static Analysis, Formal Proof, Control and Data Flow, etc.

Dynamic - Module / Integration Test

Black-box Test

Functional Performance, Stress Testing, etc

White-box Test

Structural, Path, Branch, Condition, Decision Coverage, etc.

Animation

Formal Specification,
CASE Modelling,
Rapid Prototyping, etc.

System/Acceptance Test

Functional,
Performance,
Stress Testing, etc.

Integrity

Each system in a vehicle needs to have an appropriate level of integrity because there are requirements that it should not cause:

- harm to humans
- legislation to be broken
- undue traffic disruption
- damage to property or the environment (e.g. emissions)
- undue financial loss to either the manufacturer or the owner.

The use of **integrity levels** permits a reasoned approach to assessing the degree of confidence that one should have in a particular system, which is commensurate with the inherent risk associated with function of that system.

The Guidelines seek to enable:

(a) a system to be analysed to determine what its integrity level is.

(b) a suitable development process to be adopted in order to achieve the confidence level required in the software.

Once an integrity level for the software has been determined, an appropriate development approach should be defined, in order to gain the required confidence in the software.

The higher levels of integrity require more information and more rigorous application of software engineering techniques.

Safety analysis

A preliminary safety analysis [18] should determine:

- the hazards associated with potential failures of the system
- the high level safety requirements necessary to reduce the risk associated with each hazard to an acceptable level [17]
- the initial integrity level.

Once identified, each hazard should be analysed to determine its **controllability category.** Here again is the important concept of controllability, mentioned earlier in the context of liability. The controllability approach was developed by the EU DRIVE Safely project [193.

The categories of controllability are defined as follows:

Uncontrollable: This relates to failures whose effects are not controllable by the vehicle occupants, and which are most likely to lead to extremely severe outcomes. The outcome cannot be influenced by a human response.

Difficult to control: This relates to failures whose effects are not normally controllable by the vehicle occupants but could, under favourable circumstances, be influenced by a mature human response. They are likely to lead to very severe outcomes.

Debilitating: This relates to failures whose effects are usually controllable by a sensible human response and, whilst there is a reduction in safety margin, can usually be expected to lead to outcomes which are at worst severe.

Distracting: This relates to failures which produce operational limitations, but a normal human response will limit the outcome to no worse than minor.

Nuisance only: This relates to failures where safety is not normally considered to be affected, and where customer satisfaction is the main consideration.

The main steps involved in the determination of an initial integrity level are shown in Figure 4:

(a) List all hazards that result from all the failures of the system.

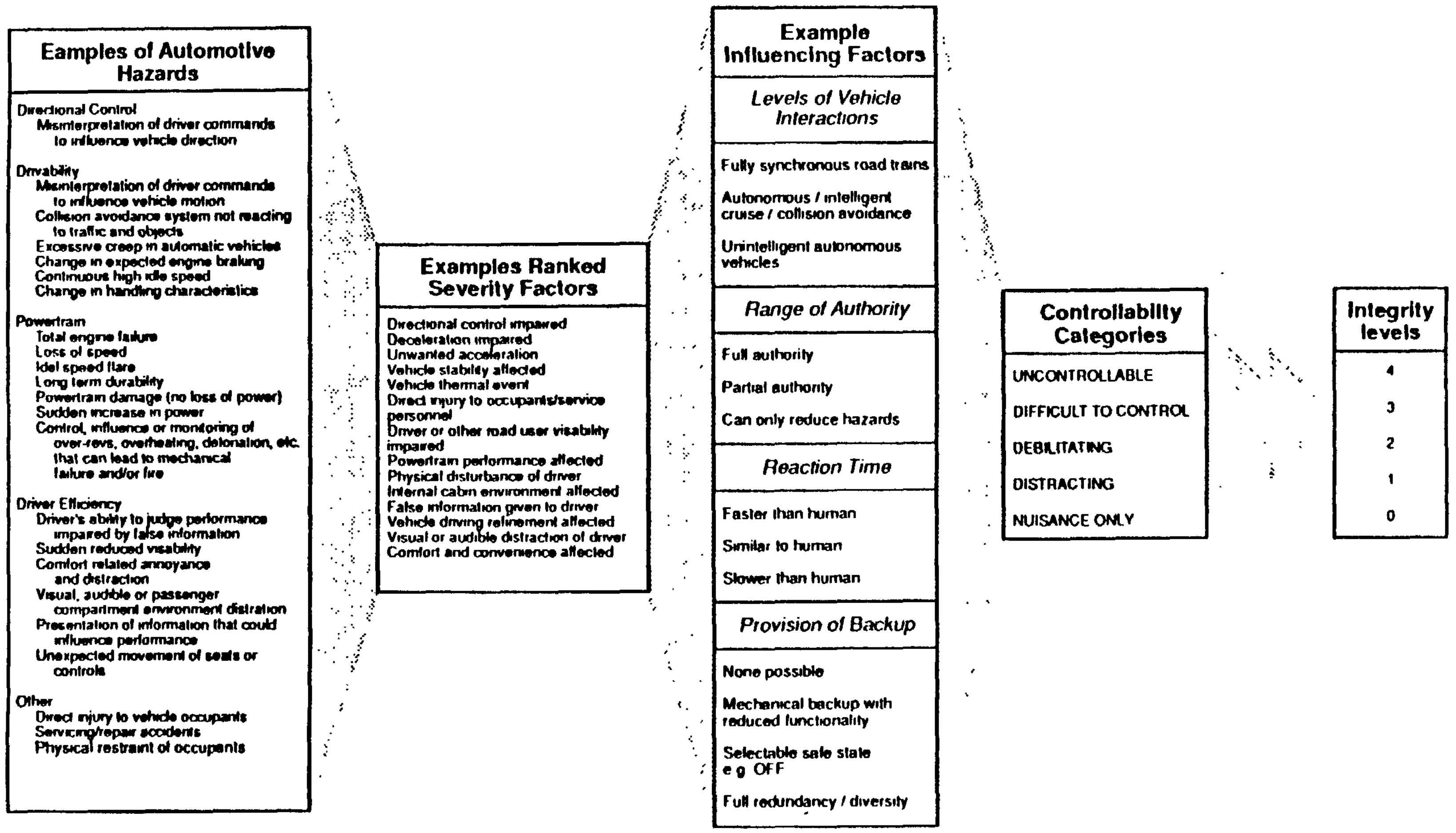
(b) Assess each failure mode identified in step (a) to determine its controllability category.

(c) The failure mode with the highest associated controllability category determines the integrity level of the system (see Table 1).

Table 1 Integrity levels

CONTROLLABILITY CATEGORY	ACCEPTABLE FAILURE RATE	INTEGRITY LEVEL
Uncontrollable	Extremely improbable	4
Difficult to control	Very remote	3
Debilitating	Remote	2
Distracting	Unlikely	1
Nuisance only	Reasonably possible	0

Figure 4: Guide to Assigning Integrity Levels



Eamples of Automotive Hazards

Directional Control
  Misinterpretation of driver commands to influence vehicle direction

Drivability
  Misinterpretation of driver commands to influence vehicle motion
  Collision avoidance system not reacting to traffic and objects
  Excessive creep in automatic vehicles
  Change in expected engine braking
  Continuous high idle speed
  Change in handling characteristics

Powertrain
  Total engine failure
  Loss of speed
  Idel speed flare
  Long term durability
  Powertrain damage (no loss of power)
  Sudden increase in power
  Control, influence or monitoring of over-revs, overheating, detonation, etc. that can lead to mechanical failure and/or fire

Driver Efficiency
  Driver's ability to judge performance impaired by false information
  Sudden reduced visability
  Comfort related annoyance and distraction
  Visual, audible or passenger compartment environment distration
  Presentation of information that could influence performance
  Unexpected movement of seats or controls

Other
  Direct injury to vehicle occupants
  Servicing/repair accidents
  Physical restraint of occupants

Examples Ranked Severity Factors

Directional control impaired
Deceleration impaired
Unwanted acceleration
Vehicle stability affected
Vehicle thermal event
Direct injury to occupants/service personnel
Driver or other road user visability impaired
Powertrain performance affected
Physical disturbance of driver
Internal cabin environment affected
False information given to driver
Vehicle driving refinement affected
Visual or audible distraction of driver
Comfort and convenience affected

Example Influencing Factors

Levels of Vehicle Interactions

Fully synchronous road trains
Autonomous / intelligent cruise / collision avoidance
Unintelligent autonomous vehicles

Range of Authority

Full authority
Partial authority
Can only reduce hazards

Reaction Time

Faster than human
Similar to human
Slower than human

Provision of Backup

None possible
Mechanical backup with reduced functionality
Selectable safe state e g OFF
Full redundancy / diversity

Controllability Categories	Integrity levels
UNCONTROLLABLE	4
DIFFICULT TO CONTROL	3
DEBILITATING	2
DISTRACTING	1
NUISANCE ONLY	0

Human factors in safety analysis

The driver and a vehicle can interact in many different ways, and the mechanism for these interactions needs careful consideration during safety analysis. Aspects that might arise include:

- human reaction times
- ease of recognition of a situation
- attentiveness
- driver experience
- improved safety leading to riskier behaviour
- subversion or overriding of system functions
- smooth and readily perceived transfer of control from a system to the driver
- the workload of the driver, especially at the moment of failure.

It may also be necessary to consider the effects of the range of capabilities relating to:

- vision and hearing
- mental state (e.g. lack of sleep, jet lag)
- physical disability.

Development approaches

The hazard analysis described above should be followed down to the components, in order to determine the integrity level of each component. Using a suitable design, it may be possible to isolate and reduce the number of high integrity components or sub-systems [19 The integrity level of the software might be reduced by the use of hardware measures to manage the more hazardous failure modes. So the analysis needs to be maintained throughout the development.

Once the integrity level of the software has been determined, an appropriate development approach can be defined. Table 2 gives guidance for each integrity level. See [8] for full details.

Verification and validation of software requirements

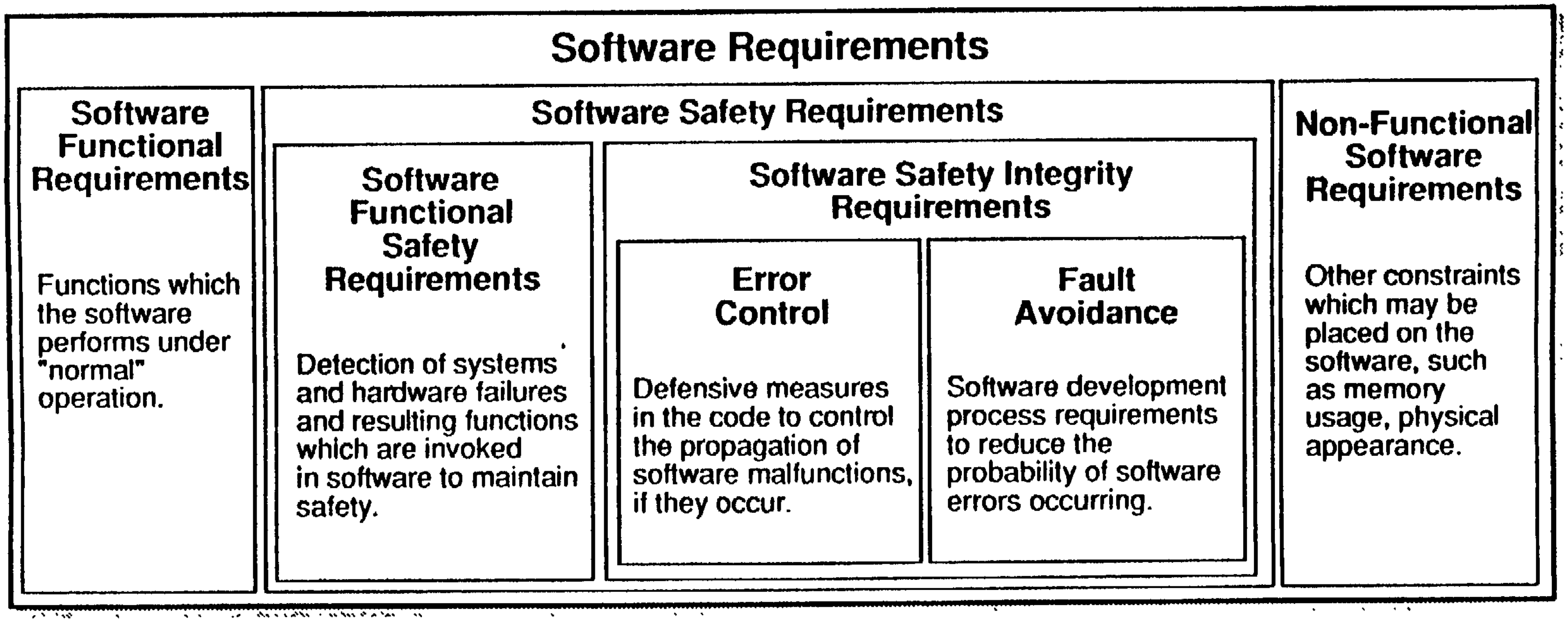
To confirm that the software requirements specification is unambiguous, accurate, complete and can be verified [12] the Guidelines suggest team oriented reviews and analyses should be carried out. The degree to which this should be done depends on the integrity level [8].

The software requirements specification should include the software functional requirements, the software nonfunctional requirements and the software safety requirements. The latter should be specifically identified. The hierarchy of these requirements is shown in Figure 5.

Table 2: Summary of Requirements

Development Process	Integrity Level				
	0	1	2	3	4
Specification and design	I	Structured method.	Structured method supported by CASE tool.	Formal specification for those functions at this level	Formal specification of complete system. Automated code generation (when available)
Languages and compilers	S	Standardized structured language.	A restricted subset of a standardized structured language. Validated or tested compilers (if available).	As for 2.	Independently certified compilers with proven formal syntax and semantics (when available).
Configuration management: products	O	All software products. Source code	Relationships between all software products. All tools	As for 2.	As for 2.
Configuration management. products		Unique identification. Product matches documentation. Access control. Authorized changes	Control and audit changes Confirmation process.	Automated changes and build control. Automated confirmation process.	As for 3.
Testing	9 0	Show fitness for purpose Test all safety requirements. Repeatable test plan.	Black box testing.	White box module testing - defined coverage. Stress testing against deadlock. Syntactic static analysis.	100% white box module testing. 100% requirements testing. 100% integration testing. Semantic static analysis.
Verification and validation	0	Show tests: are suitable; have been performed, are acceptable; exercise safety features. Traceable correction.	Structured program review. Show no new faults after corrections.	Automated static analysis. Proof (argument) of safety properties. Analysis for lack of deadlock. Justify test coverage. Show tests have been suitable.	All tools to be formally validated (when available) Proof (argument) of code against specification. Proof (argument) for lack of deadlock. Show object code reflects source code.
Access for assessment	1	Requirements and acceptance criteria QA and product plans Training policy. System test results.	Design documents. Software test results. Training structure.	Techniques, processes, tools. Witness testing. Adequate training. Code.	Full access to all stages and processes.

Figure 5: Requirements Hierarchy



Software Functional Requirements: Functions which the software performs under "normal" operation.

Software Functional Safety Requirements: Detection of systems and hardware failures and resulting functions which are invoked in software to maintain safety.

Error Control: Defensive measures in the code to control the propagation of software malfunctions, if they occur.

Fault Avoidance: Software development process requirements to reduce the probability of software errors occurring.

Non-Functional Software Requirements: Other constraints which may be placed on the software, such as memory usage, physical appearance.

The software safety requirements should describe the potential system failure conditions, together with the functions that the software should perform as a result. They should also highlight safety integrity requirements and design constraints.

Safety integrity requirements should be divided into process measures to avoid, and design attribute measures to control, both systematic and random failures. These requirements include:

- logical and physical partitioning
- diversity
- redundancy
- condition monitoring
- self-test.

Design for On-board diagnostics [7]

If a detection strategy is to be effective it should

- detect only “genuine” faults
- invoke “limp home” states in a safe manner
- provide a warning to the driver in a reasonable fashion
- store the fault information and make it accessible to repair personnel.

To achieve this, it is essential to lay down clearly and understand the criteria for each part of the detection and diagnosis process. Diagnostic software should be included as part of the overall system requirements and design strategy, not added as an afterthought.

In systems like CA where the performance could degrade as components age and wear, condition monitoring can maintain system integrity by identifying potential failures before they occur. The higher the integrity requirements the more comprehensive the monitoring needs to be.

Design for Fault management [10]

A control system should be specified such that it degrades in a graceful manner in accordance with its integrity and availability requirements.

Careful consideration to the fault management approach is needed for every function and component of the system. For example, in CASs fault management should offer alternative sensor information or mechanical back up wherever possible, and all default definitions should be supported by a well-reasoned diagnostic strategy and objectives.

The basic principle that the Guidelines recommend is that safe states should be derived by reference to the system hazard analysis. And that the default action taken should be appropriate for the controllability category of the hazards involved.

Testing

The limitations of testing software based systems must be properly appreciated. The number of possible paths through a complete program means that **even** in the strictest test regime only a proportion of the paths will be executed.

Testing is one part of the overall verification and validation activities (Figure 6). Its purpose is to discover errors, not to prove correctness.

A software test plan should, for each functional requirement, state the:

- input conditions
- output conditions
- acceptance criteria
- limits of operation
- likely failure modes.

Test data should be derived from the software specification and remain consistent with and traceable to that specification throughout.

Each module should be tested separately and then, after integration, final tests made on the entire system. These should include specific testing to determine whether or not the safety requirements are fulfilled. Test cases should be selected with the objective of uncovering errors, using previous experience where possible.

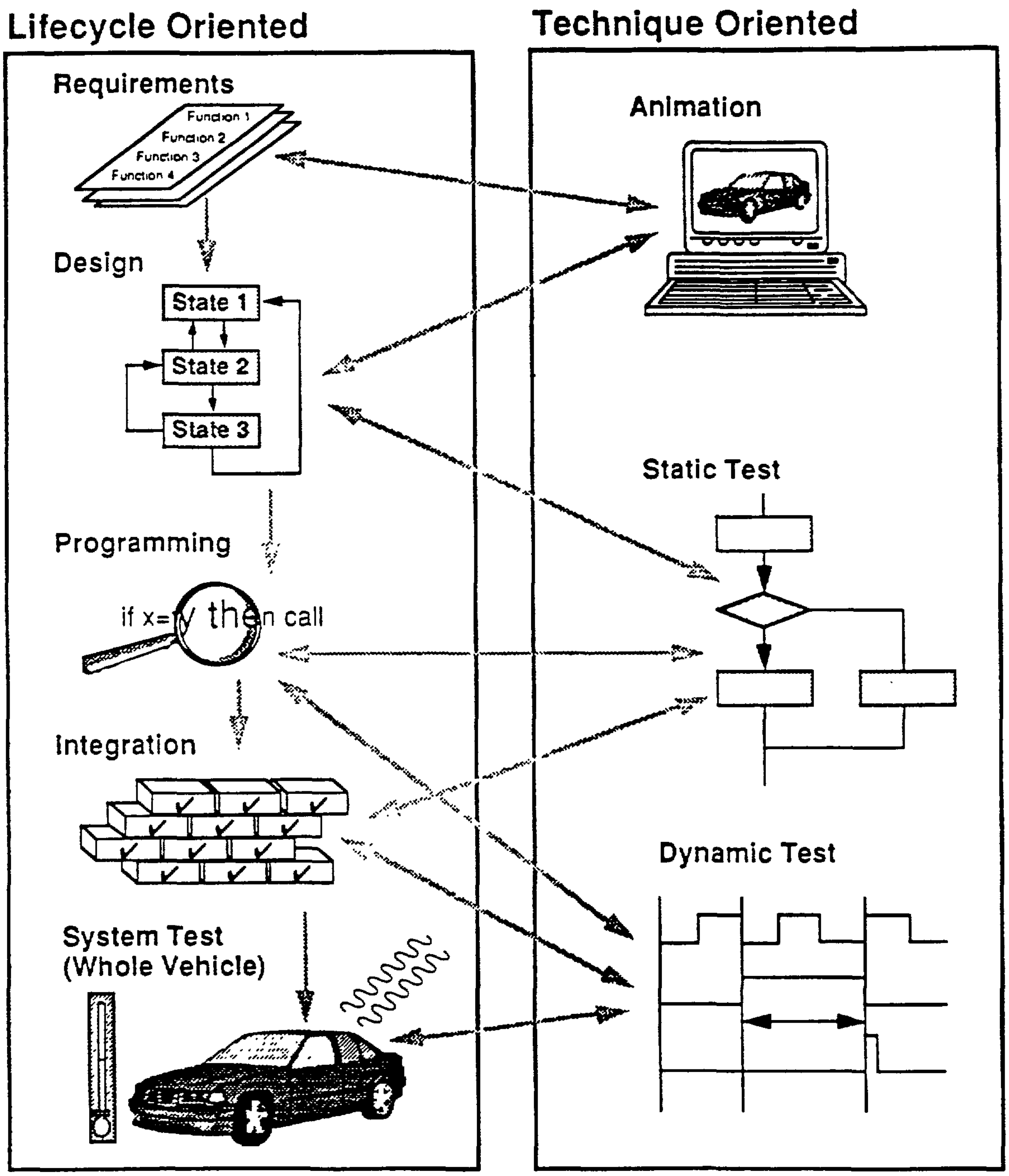
Where possible, final tests should be performed using fully integrated, production intended software and hardware, operating in the real environment under realistic workloads. And the effect on the system confirmed when operated under abnormal workloads.

Quality Assurance

The basic requirement is for organisations involved in the development and procurement of vehicle software to operate a Quality Management System capable of meeting the requirements of IS0 9001 [21] as assessed under the guidelines in IS0 9000-3 [22]. The recommendations in both the Guidelines and the supporting reports can used as the basis of a checklist for assessment of compliance.

Where individual recommendations are not adopted the Guidelines recommend that the justification should be recorded.

Figure 6: Relationship Between Testing Methods



CONCLUSION

From a European perspective, CASs can make a potentially significant contribution to reducing road accidents and casualties and the associated human misery and high cost. Realising that potential will involve CASs achieving very high standards of capability and reliability. This implies very careful definition of the envelope of operation. And this in turn raises questions of liability and this paper concludes that designers and manufacturers of CASs particularly would be wise to assume existing liability principles will apply. And that means their normally shouldering full liability from the outset. And regard anything less in practice as a bonus. European governments are unlikely to grasp the nettle of special liability arrangements on present evidence.

In Europe we will almost certainly assume CASs **will modify behaviour** [4]. Their *advice* **will** be taken as *commands.* (That alone implies an addition to their required integrity). Drivers today who avoid accidents by their own skill **will** gradually lose this skill as they increasingly rely on CASs. And new drivers who have only relied on CASs **will never** acquire such skill. So the responsibility of those make and sell CASs is both very clear and very great. But so are the benefits.

Achieving very reliable CASs will involve a comprehensive and effective approach throughout the entire planning, design, production, operation and maintenance process. And an approach that recognises there are special characteristics and requirements for achieving reliable systems that have software as an integral part. The MISRA Guidelines offer one such approach in the specific area of software. In a recent newspaper article entitled *One road, four wheels, no hands,* Tim Jackson wrote that CASs

> will gain public acceptance only when they are significantly more reliable than people - for accidents caused by faults in the software would generate acres of hostile publicity even though we shrug our shoulders at motorway pileups caused by human error. [23]

The Guidelines suggest that the risks and responsibilities - though great - are manageable within a rational, practical framework. The Guidelines represent a considerable achievement from a Public: Private Partnership, a partnership that recognises that both public and private sectors need to be involved if there is to be progress.

An approach that relies on Guidelines rather than mandatory regulation will not be welcomed everywhere. But it has the very real benefits of pragmatism & flexibility: it is not necessarily practicable or desirable to regulate by conventional means sophisticated and rapidly developing innovations that are anything but conventional. And where performance levels of potential system are still fluid. Formal control - perhaps a European certification scheme [24] or even full blooded regulation - could be introduced in due course if experience and further information suggests this is necessary or desirable. It is hard to envisage a CAS or indeed any safety item, especially one involving automatic intervention, being made mandatory in Europe without extensive analysis and careful judgement on technical, user capability and legal grounds. At the moment, however, we are essentially engaged in finding and studying new ways of doing things. And that means being flexible and keeping options open.

The EU Fourth Framework R&D Programme of (1995 - 1998) is likely to have substantial demonstration content of advance telematic systems including CASs. The UK is pressing for this work to deliver well based, realistic and quantified assessments of likely in-service effectiveness. The significance of common European research is underlined by the fact that motor vehicle safety and emissions are already regulated through agreed European approaches. Any eventual decision to mandate CASs would almost certainly require European agreement. Europe is also looking at using results of the PROMETHEUS programme to improve the performance of secondary safety systems by altering their response depending on the type and severity of an impending accident. Such systems may have parameters chosen such that the road user is no worse off than in an unequipped vehicle if the system does not operate and better off if it does.

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5. Acknowledgements

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The views expressed in this paper are not necessarily those of the UK Department of Transport or any other organisation or individual.

EVALUATING THE SAFETY OF AIR BAGS - *Lessons Learned for ITS*[a]

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ABSTRACT

The success of modern-day supplemental air bag systems is clear, but key challenges remain. Field experience has confirmed that the combination of safety belts and air bags can provide the best overall risk reduction, but only if safety belts are used, and used properly. Continued in-depth field investigation and statistical analysis remain critical to the automotive safety community's understanding of -- "real-world" occupant restraint system performance; the nature and extent of potential air bag deployment "side effects" on vehicle occupants; and new technology as it continues to be introduced.

The purpose of this paper is to outline Ford Motor Company's air bag supplemental restraint system (SRS) field evaluation programs, including both the experience gained with occupant restraint systems, and some observations on the evaluation processes which are analogous to Intelligent Transportation System (ITS) safety evaluation issues, in terms of methodology and institutional relationships.

The success of modem-day supplemental air bag systems is clear, but key challenges remain. Field experience has confirmed that the combination of safety belts and air bags can provide the best overall risk reduction, but only if safety belts are used, and used properly. Continued in-depth field investigation and statistical analysis remain critical to the automotive safety community's understanding of -- "real-world" occupant restraint system performance; the nature and extent of potential air bag deployment "side effects" on vehicle occupants; and new technology as it continues to be introduced, e.g., side air bags.

While manufacturers and suppliers conduct extensive sled and crash tests beyond the levels needed to demonstrate compliance with the Federal Motor Vehicle Safety Standards (FMVSS), these tests can only be surrogates for experience in actual operation. Hence, field crash experience studies are critically important, especially with the diversity of new restraint systems and other safety features being introduced.

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[a] Presented at ITS America Workshop on Safety Evaluations, May 1, 1995.

Clearly “real-world” operational experience is key in bridging the gap to full scale deployment of any new technology. Beyond helping to demonstrate the reliability and benefits of air bag systems themselves, this field experience permitted Ford to gain invaluable experience with our suppliers, the Ford engineering and manufacturing community, and the vehicle distribution, sales, and service operations before going into a large-scale program. The early field programs helped to show the feasibility and practicality of producing, installing, delivering, and servicing air bag systems in large numbers -- over ten million Ford vehicles on the road (August 1995).

The purpose of this paper is to outline Ford Motor Company’s frontal air bag supplemental restraint system (SRS) field evaluation programs, including both the experience gained with occupant restraint systems and some observations on the evaluation processes that are analogous to Intelligent Transportation System (ITS) safety evaluation issues, in terms of methodology and institutional relationships.

The following sections describe several Ford frontal air bag system field evaluation programs followed by some (italicized) *observations* about the evaluation process itself. The emphasis here is on the individual evaluation programs, and the lessons and observations that would be instructive in ITS safety evaluations -- rather than the technological, political, and regulatory environment in which they were conducted. Other papers by Adams et al.[a], Huang et al.[b] describe the Ford air bag system technology and Graham[c] has portrayed the U.S. political and regulatory environment surrounding air bag systems history.

Ford Air Bag System Chronology - Ford pioneered today’s era of domestic supplemental air bag systems. Ford pioneered the early 1970’s era of air bag technology with a trial fleet of 1972 Mercury’s. It was just eleven years ago that Ford announced a contract to install driver air bags in a fleet of 5,000 cars for the General Services Administration (GSA) that pioneered today’s domestic supplemental air bag systems. The Ford supplemental air bag field programs are listed below and the safety evaluation aspect of these programs is discussed in subsequent “CASE:” sections.

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[b] Huang, M., “Dynamics and Animation of an Air Bag Ball-In-Tube Sensor System,” Ford Motor Company, *Crashworthiness and Occupant Protection in Transportation Systems,* ASME Winter Annual Meeting, AMD-106, BED-13, pp81-87, December, 1989.

Huang, M., Green, C., Samson, F. “Structural Consideration in Air Bag Sensor Activation at Low Threshold Test Speed,” Ford Motor Company, 13th Experimental Safety Vehicle Conference, Paris, France, 91-S9-W-40, November, 1991.

[c] Graham, John D. ," Auto Safety: Assessing America’s Performance,” Harvard School of Public Health, Auburn House Publishing Company, 253 pages, 1989.

Fleet Size	Model Yr	Series-Model, Air Bag System	Page
831	1972	Mercury Monterey, Several fleets, Some dual air bags	5
25	1981	Lincoln Town Car, Local police fleet, Dual air bags	7
5,000	1985	Tempo/ Topaz, GSA fleet, Driver-side air bags	7
34,000	1985-88	Tempo/ Topaz, Driver-side, optional	
55,000	1989	Lincoln Continental, Dual air bags, standard	14
10 million	1984+	Ford overall U.S. air bag fleet (August 1995)	15

The 1972 Mercury prototype fleets were the first Ford “real-world” evaluations of supplemental air bag equipped vehicles. Ford built 831 full-size Mercury Monterey’s with passenger-side supplemental air bags for an 18-month fleet trial by Allstate (203 cars), Allied Chemical Corporation (101), Eaton (323), Ford (79), and U.S. Department of Transportation (DOT) (125 cars). Eaton Corporation also installed driver-side air bags in the steering columns of its fleet of Mercury Montereys.

There were two other subsequent prototype evaluation fleets during the 1970’s: one thousand model 1973 Chevrolet Impalas and seventy-five 1975 Volvos followed by 10,281 model year 1974-76 Buicks, Oldsmobiles and Cadillacs sold to the public for a total of 12,187 air bag equipped cars during the 1970’s.a/ It should be noted that all these early fleets involved past-generation large car designs with technologically different air bag systems than are in today’s vehicles. Evaluations continued into the early 1980’s with a small fleet of twenty-five 1981 Lincoln Mark VI and Town Cars with dual air bags, for use by a local police department.

Before supplemental air bags could be installed in large numbers of’vehicles, the feasibility of a reasonably safe, reliable, effective and practical system had to be established, and there had to be confidence in greatly increased belt usage. The massive initial research and testing and advancements in air bag technology during the late 1970’s and early 1980’s led to a belief that reasonable air bag system practicability could be established. There also was hope that the vast majority of the U.S. population would be covered by safety belt mandatory use laws (MUL). Both system practicability and broad MUL coverage in fact occurred. So far, all but two states have mandatory use laws.

In February 1984, GSA announced its order of 5,000 model year 1985 four-door Ford Tempos equipped with a driver-side air bag supplemental restraint system (SRS). The Tempo/ Topaz air bag system was a derivative of the experience and experimental design developed for the 1981 Lincoln Town Car. The government paid Ford $35 million for the fleet, with GSA paying $5,950 per car and DOT paying $1,050 per car

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a/ “A Summary of the Accident Experience of 1970’s Vehicles Equipped with Air Bags - As of July 1, 1985, ” National Highway Traffic Safety Administration, July, 1985 for the air bag system. The first-SRS equipped Tempos were delivered to GSA by February of 1985.

In August 1984, Ford decided to try a new approach to breaking the historical air bag regulatory “logjam. ” Ford petitioned NHTSA to count cars with driver-side air bags and manual three-point safety belts as “one-credit” cars as an alternative towards meeting NHTSA’s passive restraint quotas. Ford believed this was a way to encourage air bag offerings. “One-Credit” cars would open the door for the introduction and sale of driver-side air bags as a viable design and sales alternative to the conventional dual automatic safety belt restraint systems of the day.

In the Fall of 1984, Ford was the first domestic manufacturer to offer driver-side supplemental air bags as options for government and other fleet use.b/ Ford announced the availability of the 1985 Tempo/Topaz air bag SRS as a Limited Production Option (LPO) on fleet purchases. The SRS was initially offered to fleets because they had the field assignment and service tracking maintenance sophistication that allowed Ford to gain more experience in field tracking and service. Also, most fleet operations have a strong policy requiring driver safety belt usage.

In August of 1985 NHTSA officially approved Ford’s petition to count cars with a driver-side air bag as “one credit” toward passive restraint compliance quotas.“’ Ford responded by announcing optional driver-side air bags on the 1986% model Tempos and Topazs for purchase by all customers -- the first popularly priced automobile to offer driver-side supplemental air bags as a Regular Production Option (RPO).b/ Chrysler and General Motors soon revealed plans to follow Ford’s lead.c/ Ford was able to offer its driver-side air bag system as an RPO in its Tempo and Topaz lines after the NHTSA announcement because of the successful field experience with the GSA fleet and other fleets -- the consequence of the orderly, evolutionary development of that system, provided Ford with enhanced confidence in its reliability and effectiveness. JOB #l (first production) for the RPO was March 1, 1986.

- ***Sometimes a cooperative private-governmental spirit can help foster better ideas, even in the face of regulatory and political hurdles.@***
- ***Strong field experience is fundamental to the confidence needed for a fill-scale system implementation.***

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b/ Ford Engineering *World*, August, 1989, Vol. 14, No 3.

a/ NHTSA Docket 74-14, Notice 41, 50-FedReg-35233, August 30, 1985.

b/ “Ford to Offer Air Bags os Option on ‘86 Compacts,” New ***York Times, Nov. 3,*** 1985, p37.

c/ Graham, John D.,” Auto Safety: Assessing America’s Performance,” Harvard School of Public Health, page 200, 1989.

d/ Italicized lessons or observations about the evaluation process itself.

Total sales of the 1985-1988 model year Tempo/ Topaz vehicles equipped with the air bag option were 34,000, with under 8,000 in each of the first two model years and over 11,000 the next two model years (Table 1).

Table 1. 1985-to-1988 Tempo/ Topaz Air Bag Option Sales

Buyer	**Tempo/ Topaz Model Year**				SALES TOTAL
	1985	1986	1987	1988	
GSA	5,000	- -	1,500	- -	6,500
Fleet	2,400	3,700	4,800	3,100	14,000
Retail	- -	100	5,400	8,000	13,500
TOTAL	7,400	3,800	11,700	11,100	34,000

Ford was also the first U.S. manufacturer to offer dual (driver- and passenger-side) air bags as standard - on the 1989 Lincoln Continental, following the Tempo driver-side air bag fleet experience. The 1989 Lincoln Continental introduction initiated the Ford phase-in process for right-front passenger air bags, just as the Tempo and Topaz started the phase-in of driver air bags when they were introduced.

In 1990, the dual air bag system was also made standard on the Lincoln Town Car, until a March 1990 interruption in the supply of air bag modules due to an explosion at a suppliers facility that suspended production of passenger-side air bag modules for the Continental and Town Car for over twelve months. Air bag propellant manufacturing is not risk-free because sodium azidee/, while not an explosive, can form explosives. Over a two and one-half year period (February 1988 to August 1990) the manufacturers of air bag propellant for the U.S. automotive industry had a dozen sodium azide related fires, resulting in a number of interruptions and injuries”‘. And, since January 1993, TRW’s Mesa plants have had 25 fires or explosions, including one fatality.“’ As the issues that caused these interruptions continue to be resolved, air bag manufacturing continues to be a developing industry.

- ***Safety studies should also consider system production and implementation.***

Currently, driver- and passenger-side air bags are standard on all 1995 model year Ford Motor Company domestic U.S. cars. As of today, over three and a half million Ford

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e/ Sodium azide is the most commonly used chemical in propellent compounds.

a/ General Accounting Office, “Motor Vehicle Safety - Information on Accident Fires in Manufacturing Air Bag Propellent,” Sept. 1990.

b/ *Automotive* News, “Risky Business, ” pp 1, 22-24, May 22, 1995.

cars and light trucks equipped with dual supplemental air bag systems **are** on the road. With the addition of driver-side-only air bags, over ten million Ford Motor Company cars and light trucks equipped with supplemental restraint systems (SRS) are on the road (August 1995). These vehicles are estimated to have traveled some 260 billion miles and have been involved in over a million crashes, including 130,000 severe enough to activate the air bags.

CASE: 1972 Mercury, First "Real-World" Air Bag Deployment

- ***Observations relevant to ITS evaluations***

It was 5:00 pm on Monday, October 9, 1972 in Santa Barbara, California.
Mr. Neal Wagoner, a 52 year-old claims adjuster for Allstate Insurance, slowed his 1972 Mercury Monterey Custom sedan to 15 mph as he turned left at an intersection into the path of an oncoming garbage truck. Both the driver of the 24,000 lb. Reo truck and the California Highway Patrolman following the truck confirm that the truck was traveling at 35-to-40 mph when it struck the right-front corner of the 4,500 lb. Mercury.

The impact resulted in the first-ever air bag deployment in a "real-world" accident involving a human occupant. The direction of impact to the Mercury was between one and two o'clock (30 to 60 degrees). The maximum frontal crush was about two feet. Mr. Wagoner, a 6-ft. tall, 150 lb. sole occupant of the Mercury, was using his lap-belt at the time of the crash and sustained only minor injuries from vehicle interior contacts.

- ***Initially, this might be misinterepreted as the first air bag 'effectiveness' story.***

HOWEVER, the occupant protection potential of the experimental air bag was not tested since the passenger-side air bag system installed in this Mercury covered only the right-front occupant position and that seat was not occupied. Since there was no right-front passenger, there is no way to evaluate the degree of protection.

- ***This is a big 'however.' Be careful of preliminary and/or incomplete case investigations. The early reports may not be as 'bad' or 'good' as inferred. In this case, what might seem like an air bag 'effectiveness' story was simply a successful deployment story, as the full report states."***

Mr. Wagoner indicated that he experienced a pronounced ringing sensation in his ears immediately after the accident, but that it had disappeared within a few hours. He also indicated that he has occasionally experienced a similar but less-pronounced sensation in his ears ever since he was a small boy.

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c/ Yost, c., "Investigation Report of the First Air Bag Deployment in a 'Real-World' Accident," Ford Motor Company, ***Proceedings of the American Association For Automotive Medicine,*** pp124-128, October 1972. Note: Most of this section was directly extracted from Yost paper.

- ***Again, a less thorough investigation could have missed the driver's underlying propensity and prior history of ringing sensations.***

Significantly, Mr. Wagoner stated he previously did not regularly wear a lap belt and probably would not have been wearing the lap restraint had it not been for the ignition-interlock system that required him to either use the belt or go to the trouble of bypassing the system before the car could be started.

- ***Be sensitive to other effects/ results that were not expected or planned for study.***
- ***This case is also a reminder that while some technological safety measures may be operationally effective (e.g., ignition-interlocks), they can be social 'failures.'***

This experimental passenger-side air bag/ lap-belt restraint system used an Allied Chemical Corporation air bag module, and was one of 203 cars delivered to Allstate Insurance Company beginning in March 1972. John Pflug, Ford chief engineer, noted at the time that “although general production of air-bag equipped cars is highly premature, we are continuing intensive research with air bags. We consider a limited and carefully controlled field trial program with air bags supplementing seat belts to be a vital part of this development program. These field-trials should provide valuable additional information on the reliability of air bags in actual usage.“” In fact in preparing the cars for delivery to Allstate, Ford detected a problem with the air bag system’s sensor module circuitry on two of the first 83 Mercury’s built with the system installed. The problem was in the circuitry that “senses” whether the entire system is ready to function properly and employs a warning light to indicate this. On recommendation of the supplier. the modules were replaced in all 83 units.

- ***“Real-world” experience, even on a limited basis, is crucial.***
- ***Any safety evaluation should include all aspects of system production /installation, delivery, and service.***

Altogether, the 831 Mercurys in the field program were estimated to have accumulated over four million miles and have been involved in 36 collisions without a deployment, before this ‘first’ deployment incident. Ford’s Body Engineering Office had two four-person teams ready to go anywhere at a moment’s notice, to study air bag system performance under actual field conditions. The teams included a scientist, a photographer, and two engineers. Each team member was assigned a particular task in the investigation. They were concerned with what happened to the vehicle(s) and occupant(s) during the impact sequence, not the accident causation factors or why the crash occurred. Throughout the study the teams found no air bags that failed to deploy when needed and none that deployed accidentally, an early public concern.

- ***Sometimes there is a long wait for relatively rare incidents (e.g., deployment).***

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a/ **Ford “News** Release,” March 1972

- ***Field evaluation of any new system requires intensive in-depth investigations to gain early insights, long before "statistical" results are available.***

CASE: 1981 Lincoln Town Car, Trial Fleet

- *Observations relevant to ITS evaluations*

To gain "real-world" experience with system components, suppliers, vehicle installation, and reliability with a dual air bag system a fleet of twenty-five 1981 Lincoln Town Cars and Mark VI's equipped with an experimental dual air bag system was built.

Because police fleets have a relatively higher crash rate per year, the Lincolns were provided to a small local police department for a twenty-month (4/8 1 to 12/82) evaluation in traffic. While Ford expected the police fleet would be exposed to rough driving and experience many deployment level impacts. almost nothing happened. The police became exceptionally careful drivers, basically because if they damaged their 'brand new' Lincoln's they would then have to drive existing 'regular' police vehicles.

- ***The participant's behavior can be totally altered in a field evaluation program.***
- ***Safety evaluations can look at critical factors beyond "crash" results.***

In the twenty month's time there were 3 1 crashes, including two with air bag deployments in relative minor severity incidents, without injury: i.e.. too little experience to evaluate the systems injury risk reduction performance. On the other hand, the fleet was driven over 1.7 million miles and was then subjected to post-field-trial vehicle tear-down evaluations. Ford obtained valuable air bag system component durability insights that were absolutely critical to next generation system component designs. It turned out that crash sensor interior contamination deposited during the assembly process significantly deteriorated the crash sensor performance over time.

- Very minor and unexpected factors can ultimately have a major system impact.
- "Real-world" experience, even if limited, is crucial. Any safety evaluation should include all aspects of production, installation, delivery, service, and disposal.

CASE: 19851988 Tempo/Topaz Driver-Side Air Bags

- Observations relevant to ITS evaluations

To gain early on-road experience with air bag systems that differed in several ways from earlier generations of experimental systems, Ford signed a contract to install supplemental driver-side air bags in a General Services Administration (GSA) fleet of

5,000 model year 1985 Tempo cars. A comprehensive three-way system to track the GSA Tempo fleet field experience was established between the GSA, NHTSA and Ford.

A unique and valuable aspect of the Tempo fleet experience was the provision by GSA of notices of all Tempo impacts. This is the first air bag fleet field experience in which all impacts have been reported, including all non-deployments, those with minor damage, and with no police report. As an extra effort, beyond their normal fleet management activities, GSA carefully monitored field operations of the vehicles so that crash information and vehicle mileage could be accurately obtained. All the notices supplied to Ford were placed in an Air Bag Collision Digest (ABCD) computer file for analysis.

- Participating institutions can often institute special data collection programs for predetermined periods that are above-and-beyond their normal operations.

Ford estimated that the 23,300 air bag equipped Tempo/ Topaz cars sold as of January 1988 had experienced about 1,500 crashes and had traveled some 320 million miles - based on a GSA rate of 0.12 deployments per crash’ and 0.55 deployments per million milesb/. This careful GSA monitoring provided accurate deployment involvement rates, until the impact of several FoIA (Freedom of Information Act) demands for hard copies of GSA’s extensive air bag fleet incident records. These burdensome FoIA requests made it impractical for GSA to continue the detailed fleet monitoring after September 1986. Beginning in October 1986, GSA started reporting only significant impact notices (impacts with over $2,000 initial damage estimate or notable injury).

- ***Consider the legal implications and consequences of evaluation programs. and related data collection and analysis.***

While precise, the deployment rates derived from the GSA experience may be atypical because, as we learned, the fleet drivers frequently were young male” military recruiters traveling on government business (e.g., during daylight hours). Both the recruiters’ risk of being involved in a crash and their risk of sustaining an injury when a crash occurs are atypical. While the typical young male driver population may “drive hard,” these fleet drivers were likely in above average physical condition and their driving exposure tended toward daytime traffic.

- ***Any unique study participant demographics must be identified and understood.***

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a/ As of September 31, 1986, the GSA had received notices of all (461) impacts, including (57) deployment level impacts, for a rate of 12 deployments per impact notice.

b/ As of January 31, 1987, the GSA experienced 55 deployment level impacts per 100 million miles (70 deployments/ 127 million miles) and 7.7 per thousand vehicle years of operation (70*12 months/ 109,750 vehicle years.)

c/ As of March 1987 there were 94% male drivers (88 males, 6 females) in deployment impacts.

Field Investigations - Notices of GSA fleet deployments were provided on a thorough and timely basis through the GSA Fleet Management Centers and the NHTSA-Coast Guard ‘800’ notification system. Notices of private and insurance fleets were obtained from NHTSA, fleet operators, Ford dealers, and the Ford ‘Hot-Line’ phone. There was no reporting of non-deployment impacts by non-GSA fleets. Both Ford and NHTSA were immediately notified of each deployment so that the crash investigations could be performed either by Ford staff and/or NHTSA-sponsored special investigation teams in Arkansas, California, Indiana, New York, Tennessee, and Texas.

- ***Evaluation programs can benejit from cooperative access to a wide range of information resources, e.g., Coast Guard “Hotline,” Dealer parts orders.***

The first reported Tempo air bag deployment crash was on April 13, 1985 in Toms River, New Jersey. In the beginning of the program almost every deployment impact was investigated. In many early deployment cases the NHTSA sponsored team and Ford investigators would arrange to arrive together and concurrently document the crash evidence. As expected, many first case reports were of minor impacts. Since a) it was observed that the air bag system seemed to be operating as intended, e.g., no inadvertent on-road deployments and b) the frequency of crash notifications quickly grew as more fleet cars were placed into service, the field investigations were limited to more significant deployments, i.e., those with injury and/or vehicle damage or loss over $2,000. Individual cases were selected that were most likely to expand the understanding of system field performance, e.g., new or unique impact configurations were given priority for field investigation. By end of 1989, air bag equipped vehicles from other manufacturers presented NHTSA with new field safety evaluation challenges that supplanted the need for continued coverage of the early Tempo/ Topaz fleet.

- ***Case selection flexibility and judgment are key to the collection of antidotal in-depth crash investigations. That way, limited resources can be dynamically targeted at field performance issues as they evolve. For example, to conserve resources, staged levels of case investigation thresholds can be used as performance experience is gained during a study.***

Field results were shared throughout the study. NHTSA and Ford shared copies of individual case documentation. A series of joint GSA-NHTSA-Ford discussions of study results and process was held from 1985 through 1988, including presentations by NHTSA field team investigators. The NHTSA has published some of their observations.[a] Ford gained extensive practical experience with air bag installations, operations, replacements,

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[a] National Highway Traffic Safety Administration, “Research Notes: Recent Air Bag Field Performance,” NHTSA, National Center for Statistics and Analysis, April, 1956.

Backaitis, S.H., Roberts, J.V., “Occupant Injury Patterns in Crashes with Air Bag Equipped Government Sponsored Cars,” National Highway Traffic Safety Admin., SAE-872216, 1987.

Reed, R.T., “Air Bag Crash Investigations,” NHTSA, Korean Road Traffic Safety Institute Annual Conference, December 1994.

and field performance. Feedback from key participants indicated they considered this to have been one of the most cooperative and fruitful public-private collaborative projects in which they had participated.

- ***Public-private cooperative studies can be very successful.***

Application: 1986 Taurus/ Sable Crash Sensor System - An air bag crash sensor study was made to find the ‘best’ sensor system for the 1986 Taurus/Sable structure. Fundamental to the study was the development of a series of vehicle crash tests, representative of real-world crashes. Vehicle impact patterns, varying in terms of damage area, direction, damage width, damage height, brake ‘dive,’ and object contacted and multiple impacts were studied and coordinated with field data from the existing Tempo/Topaz air bag fleet to design the crash tests.b/

- ***Field evaluation studies do influence product design.***

While this application was not specifically anticipated at the beginning of the Tempo/Topaz field evaluation program, a review of the field reports made it clear that deployment level crashes varied in terms of: vehicle damage area (both frontal and side impacts were important), impact direction (half were not 12 o’clock), damage width (half had a third or less overlap), damage height (half overrode the bumper or missed the front structure), object hit (most hit other vehicles), and multiple impacts (90% of primary frontal impacts were the first event). These trends were confirmed through a comparison with a subset of frontal impact data from the 1984 National Accident Sampling System (NASS) collected by the NHTSA. The general observation was that all possible vehicle impact patterns do occur, and only a few full-overlap 90 degree fixed-barrier impacts occur.

- ***Field studies are often used to help answer questions not originally anticipated.***

Air bag systems are designed to be activated in frontal impacts above a certain crash severity threshold. A key issue is the determination of the ideal threshold criteria.

> A short digression may be helpful to explain “threshold.” The level of frontal crash severity required for an air bag deployment is called the “deployment threshold.” In the Ford design, for example, air bags are designed to deploy at impact speeds over approximately 14 mph in a head-on collision into a solid barrier under normal ambient conditions for crash test facilities -- what is called a 14 mph “barrier equivalent velocity” or BEV. Some manufacturers design their air bag systems to deploy at other, lower or higher, crash severity thresholds.

!’ Adams, Huang, Hultman, Marsh, Henson, “The Development of an Advanced Air Bag Crash Sensing System,” Ford Motor, Paper ***No.*** 905140, ***XXIII FISITA Congress,*** p159, May 1990.

> The over 14 mph BEV has been the typical printed explanation of “deployment threshold” provided in owner manuals, for example. The air bag system, in fact, has three deployment zones. The intention is that air bags “deploy” over 14 mph BEV and “not deploy” under 8 mph BEV. In other words, generally one does not expect “non-deployments” over 14 mph or deployments below 8 mph BEV. Crashes between 8 and 14 mph BEV are in a “may deploy” zone that reflects the variability in, for example, crash sensor and vehicle structural crash performance. Real-world deployment thresholds also vary because few crashes are into a fixed 90” barrier.

From this sensor study, a threshold “value was chosen based on a review of earlier design criteria and testing, and the limited field experience of air bag fleets [below] and national accident sample data. In fact, none of the data reviewed in this study supported lowering or raising the threshold criterion from that used by the 1985 Tempo fleet.“/

Since very little crash severity data, e.g., delta-V mph, was available from the field investigations. the GSA initial “estimated dollar damage” was used as a rough surrogate measure of severity. This comparison was considered reasonable, since all the cars in the sample were the same model, all were maintained and repaired as part of the GSA fleet, and only relative comparisons were made.

The distribution of GSA estimated dollar damage for deployments and non-deployment frontal crashes is displayed in Figure 1. The proportion of injury, portrayed in the lower portion of each bar, consistently increases with each damage level. The distribution crossover around $2,000 is indicative of a crash deployment threshold. It was observed that the Tempo air bags deploy at a severity level consistent with the onset of potential driver injury. They tended to deploy when there was the possibility of injury and not otherwise. The few injuries in the non-deployment frontal crashes were all superficial injuries unrelated to the supplementary protection offered by an air bag system.

- With care, surrogate measures can be used.

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a/ Ibid. page 160.

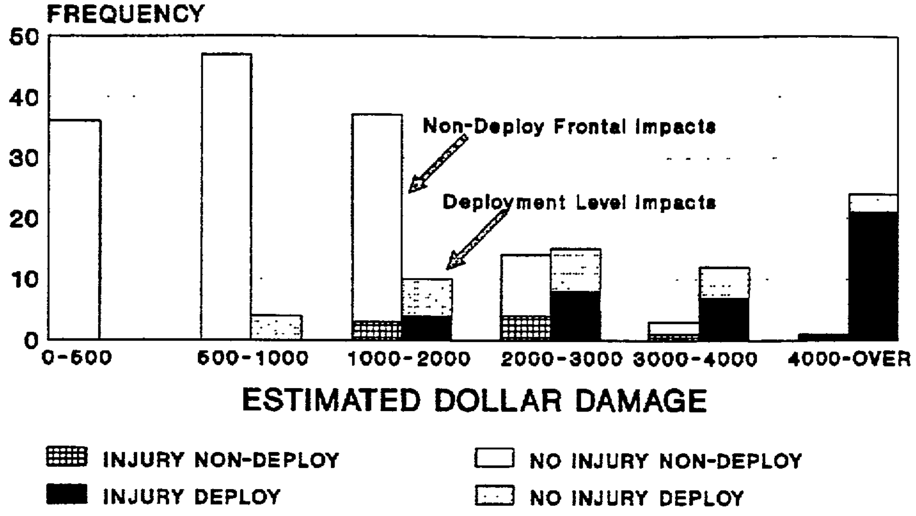

Figure 1 - Estimated Dollar Damage by Non-Deployment Frontal and Deployment Impacts, GSA Tempo Air Bag Fleet

Application: Safety Belt Usage & Injury - As of March 7, 1988 a total of 188 deployments had been reported in crashes, mostly from the GSA fleet (107). An 86% (123/143) safety belt usage was reported in these 'deployment' crashes (Table 2). While this usage rate seemed exceptionally high for late 1980's, careful investigation of several cases confirmed the 'belt used' reports. Belt usage was atypical since most of the deployments were in fleet vehicles, typically driven in daytime by males[a/] who were encouraged to wear safety belts while on the job.

Table 2 - Injury severity vs. Safety Belt Usage in Deployment Level Impacts

	Injury Severity (AIS)					
Belt Used	None, Minor (AIS 0,1)	Moderate (AIS 2)	Serious (AIS 3)	Maximum (AIS 6)	TOTAL	AIS 2 - 6 (% Total)
Yes	113	10	0	0	123	8
No	14	2	3	1	20	30%
Unknown	44	1	0	0	45	-
TOTAL	171	13	3	1	188	9%

Of particular interest, note that the percentage of moderate-or-higher severity injury is lower when belts were used in this population of deployment crashes (Figure 2). While other factors have not been directly accounted for in this display, e.g., driver proneness to risk taking, this fleet experience and individual case experience have illustrated that the

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[a/] As of March 1987 there were 94% male drivers (88 males, 6 females) in deployment impacts.

combination of safety belts and air bags do provide discernible injury risk reduction if safety belts are used properly. Even with an air bag deployment, safety belt usage is still important.

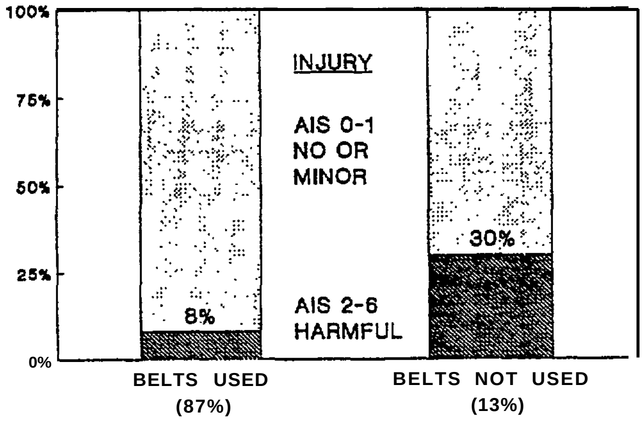

Figure 2 - Injury Severity and Belt Usage, Tempo/ Topaz Air Bag Deployments

CASE: Overall Safety Belt Usage in Air Bag Cars

- ***Observations relevant to ITS evaluations***

Because of the limited nature of the Tempo fleet driver population, a key question remained - Will the installation of air bag systems affect drivers' safety belt usage? To address this question, Ford observed 3-point manual safety belt usage in 221 model 1988 Continentals without air bags, compared with 136 model 1989 Continentals equipped with dual air bags at the same location one year later (Table 3). The Mark VII (without air bags) was included in both the 1988 and 1989 surveys as a control group (306 observations). Belt usage was observed unobtrusively, as customers stopped their vehicles at a new car owner satisfaction survey check-in station. Obviously, one would like to see safety belt usage rates maintained or increased in cars equipped with air bags. In fact, no decline in active belt usage with air bags was observed.

Researchers at the Highway Safety Research Center (HSRC) at the University of North Carolina, Insurance Institute for Highway Safety (IIHS), and NHTSA have also found encouraging results in more extensive studies. The HSRC has been conducting a series of passive restraint usage observation studies since early 1 989.a/ A 199 1 HSRC update

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a/ Reinfurt, D.W., Cyr, C.L., Hunter, W.W., "Usage Patterns and Misuse Rates of Automatic Seat Belts by System Type," Highway Safety Research Center, University of North Carolina. In ***34th Proceedings of the Assoc. for the Advancement of Automotive Medicine,*** pp 163-179, October, 1990.

combined all 8,175 observations from the earlier five studies.b/ A more recent belt usage study by IIHS includes 9,155 observations of 1986-1990 model cars with air bags or manual belts only." The 1990 NHTSA 19-city study reported 17,486 manual and air bag restraint observations.d/

- ***Sometimes non-crash measures/ observations are needed.***

CASE: 1989 Lincoln Continental with Dual Air Bags

- ***Observations reievant to ITS evaluations***

While several thousand driver-side air bag deployment cases have been reported by government and insurance industry sources, reported field experience with today's passenger-side Supplemental Restraint Systems has been extremely limited because of the relatively small number of passenger air bag equipped cars on the road and infrequent deployments with a right-front seat passenger. Of the over 1,300 NHTSA special investigation cases to-date involving air bag equipped vehicles, fifteen were Ford vehicles with passenger-side air bag deployments and a front-right seat passenger.

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b/ Reinfurt, D.W., Stewart, J.R., Weaver, N.L., Green, A.M., "Occupant Restraint Monitoring Program. Usage Patterns and Misuse Rates of Automatic Seat Belts by System Type: An Update" Highway Safety Research Center, University of North Carolina, HSRC-PR183, pp 17-27, 1991.

c/ Williams, A.F., Wells, J.K., and Lund, A.K., "Seat Belt Use in Cars with Air Bags," Insurance Institute for Highway Safety, ***Amer. J. of Public Health, 80: 12,*** pp 15 14- 15 16, 1990.

Wells, J.K., Williams, A.F., "Seat Belt Use in Air Bag Equipped Cars: 1988-92 Models," Insurance Institute for Highway Safety, February, 1992.

d/ Datta, T.K., Guzek, P., "Restraint System Use in 19 U.S. Cities, 1990 Annual Report," Goodell-Grivas, NHTSA, July, 1991.

Table 3 - Air Bag Installation and Safety Belt Usage

Belt Usage with:		Sample Time	Reference Source:
Air Bag	No bag		
73%	73%	1988-89	Ford, Auto. Safety Office
74	76	1989-90	Reinfurt, et al., HSRC, 1990
75	75	Fall'89	Williams, et al., IIHS, 1990
50	51	1990	Dana, 19-City, NHTSA, 1992
70	71	1989-91	Reinfurt, et al., HSRC, 1991
79	78	Mid' 91	Wells & Williams, IIHS, 1992

Starting in 1989, Ford sponsored the University of Michigan Transportation Research Institute (UMTRI) to coordinate notification of passenger-side air bag deployments in Lincoln Continentals and to conduct field investigations. Several sources were utilized to provide notification, including air bag replacement orders through the Ford Parts and Service Division, computer-assisted collision damage estimate reports (ADP Audatex nationwide data base), insurance companies (State Farm and USAA), and direct reports from owners, dealerships, and repair shops. The University of Michigan "early alert" system uses a toll-free "800" number and a "Wanted" poster to draw attention to the program (Attachment A). The "Wanted" poster was subsequently copied by others for use in their own notification programs. Deployment notices from the program were also shared with NHTSA.a/ To date, twenty-two passenger-side air bag deployment crashes involving Ford vehicles with a front-right seat passenger have been investigated by UMTRI in this on-going study of passenger-side air bag performance.

The State Farm Insurance Companies, Research Department, also began a program in May 1989 to evaluate air bag performance by monitoring all insured vehicles with air bags through the computer-assisted damage estimate writing systems, Audatex and Mitchell-matrix.b/ State Farm estimators are asked to complete an electronic repair estimate on all air bag deployments no matter the extent of damage. The claim supervisor provides an accident and injury description whenever an air bag deploys.

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a/ Huelke, D.F., Roberts, J.V., Moore, J.L., "Air Bags in Crases - Clinical Studies from Field Investigations," University of Michigan Transportation Research Institute, 13th ***Experimental Safety Vehicle Conference,*** Paris, Paper No. 91-Sl-W-19, November, 1991.

b/ Bill, S., "State Farm Passive Restraint Study; Preliminary Accident and Performance Statistical Report," State Farm Insurance Companies, presented at 1991 ***SAE Future Transportation Technology Conference,*** [#?], August 7, 199 1.

The Research Department then contacted each driver for a telephone interview when practicable and appropriate. State Farm has recorded 7,780 air bag deployments and investigated 3,850 cases as of January 1992, including 24 Ford passenger-side air bag deployments with a front-right seat passenger.

- ***Other traffic crash notification schemes can be used, beyond police reports.***
- ***Requests for crash notifications should be periodically reissued as reminders.***

CASE: Overall Air Bag Fleet Performance

- ***Observations relevant to ITS evaluations***

Back in 1984 the U.S. National Highway Traffic Safety Administration (NHTSA) projected that air bags "when used" in conjunction with properly worn safety belts were slightly more effective as a restraint system than safety belts alone for reducing overall risk of fatalities and injuries (Table 4).a/ These estimates are for each restraint system "when used" 100% of the time.

Table 4 - NHTSA Restraint System Effectiveness Estimates for Front Seat Occupants of Cars (1984)

	Injury Level	
Restraint System	Fatal	AIS 2-5
Three-point Belt	40-50 %	45-55 %
Automatic Belt	35-50	40-55
Air Bag Only	20-40	45-55
Air Bag with a Three-point Belt	45-55	50-60

With the growing number of air bag equipped vehicles on the road, now over 33 million cars, and with almost all new 1995 model year passenger cars equipped with dual air bags,b/ both NHTSA and IIHS (Insurance Institute for Highway Safety) researchers have, in the last few years, begun to estimate the real-world effectiveness of air bag systems. While the studies all confirm that driver-side air bags, combined with current safety belt usage, have been saving lives, the IIHS reported effectiveness has tended down with time

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a/ National Highway Traffic Safety Administration (NHTSA), "Occupant Crash Protection; Final Rule," NHTSA Docket 74-14. Notice 36, July, 1984.

b/ Ferguson, S.A., Lund, A.K., Greene, M.A., "Driver Fatalities in 19851994 Air Bag Cars," Insurance Institute for Highway Safety, 9 pages, April, 1995.

(Table 5) and their results also vary by type of analysis methodology (Table 6).[c] Clearly, the overall effectiveness results for supplemental restraint systems have not yet stabilized.

- ***Be patient for overall results. Effectiveness evaluation results vary over sample time, sample size, sample subgroups (e.g., car size), and analysis methodology.***

Table 5 - IIHS Driver Air Bag Effectiveness Results by Year

Comparisons by Location of Impact	**Percent Driver Fatality Reduction**			
	1991	1992	1993	1994
Overall	19	20	16	14
Frontal Impacts	29	28	24	23

Table 6 - IIHS Driver Air Bag Effectiveness Results by Analysis Method

Fleet Comparison Method:	**Percent Driver Fatality Reduction**	
	Overall	Frontal Impacts
Location of Impact	14	23
Fatalities/ Registered Cars	15	19
Account for Differences in Vehicle Age and Increasing Belt Usage by Year	13	14

Both NHTSA and IIHS have provided several broad studies that compare the field performance of vehicle fleets with and with out air bag systems. These have been "as used" restraint effectiveness studies, since the fleets were compared without direct knowledge or analysis of specific air bag or safety belt usage within the comparison fleets. Analysis has been done with the current restraints "as used" in the comparison fleets. This is a valid approach since all evidence points to equivalent levels of safety belt usage in air-bag and non-air-bag fleets. While these studies have demonstrated discernible overall fatality risk reduction in an air bag equipped fleet, no definitive "when used" study has been published, i.e., what is the effectiveness of supplemental air bag systems by safety belt usage - "when used" and not used? It has been eleven

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[c] Ibid.

years since the 1984 NHTSA “Air Bag Only” and “Air Bag with a three-Point Belt,” (i.e., when used) effectiveness rates were estimated (Table 4). Clearly more detailed evaluations will become more realistic as the amount of “real-world” experience continues to accumulate. To date, the entire 1989-93 NHTSA national accident sample, available for statistical analysis of air bag injury effectiveness and patterns, consists of just 829 vehicles involved in crashes with air bag deployments.?’

- ***Don't expect early evaluation study results to provide stable and precise measurements of overall system effectiveness.***

Recall that the evaluation of safety belt effectiveness was a point of controversy for decades, and is still being argued in an anti-mandatory belt use suit in Canada that claims that safety belt usage is, overall, harmful to the motoring public. Air bag claims found in the media range from “Air Bags Saved My Life” to “Air Bags Can Be Hazardous and Lead to Injury.” Importantly, the scientific community must retain its objectivity and insist on a full investigation and understanding of the specific circumstances when confronted by these differing views.

- ***Be cautious of potentially inflated "+ " or "- " media reports.***

While safe, reliable, and effective, there can be potential “side effects” of air bag deployments. Several estimates suggest that approximately a quarter to a third of drivers in an air bag deployment crash sustain an air bag contact related injury. The most recent March 1995 IIHS study suggested that “43 percent of air bag deployments cause an injury,” but almost all were minor (96.4%).a/ Clearly, field evaluation challenges remain in the areas of deployment “side effects.” passenger-side air bags, and introduction of new air bag systems technology. On the other hand, the acceptance of air bag systems by the motoring public is exemplified by a 1994 IIHS sponsored follow-up survey of North Carolina drivers who had been in a deployment crash. While about a third reported minor air bag contact injuries, the vast majority (76%) said their air bag protected them “a lot.” And, almost all ☎✇⌛🔔✆ wanted air bags on their next new car

- ***Potential countermeasure “side effects” must also be considered and evaluated.***

The limited field experience to-date has demonstrated that the combination of safety belts and air bags now provides the greatest overall risk reduction, but only if safety belts are used, and used properly. It is important that front seat occupants be properly restrained and sit back from the air bag. While safety belt usage in the U.S. has risen from the low teens to close to seventy percent today, there is obviously room for further progress -- there are still too many motorists not using available safety belts.

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a/ Insurance Institute for Highway Safety, “Air Bag Injuries Are Mostly Minor But a Handful Are Serious, Even Fatal,” ***Status Report,*** Vol. 30, No. 3, March 18, 1995, page 2.

a/ Insurance Institute for Highway Safety, “Air Bag Injuries Are Mostly Minor But a Handful Are Serious, Even Fatal,” ***Status Report,*** Vol. 30, No. 3, March 18, 1995, page 2.

The critical need to promote the proper use of safety belts continues.

Field experience involving air bag-equipped vehicles also will present fresh challenges for both field investigators and medical personnel as they observe new and unique occupant complaints and injury patterns.

- ***New field investigation techniques will be needed and implemented as new safety measures are introduced.***

CASE: Air Bag Misconceptions

- ***Observations relevant to ITS evaluations***

Complaints and misconceptions about air bag systems can result when customers do not understand how the systems function. The section outlines and evaluates several misconceptions that result from differences between the consumer's understanding of air bag systems, including their content, function and performance, and the actual system operation in the field.b/ The safety community faces the challenge of recognizing, evaluating, and helping to dispel erroneous information.

- ***Non-operational aspects, such as system acceptance and misconceptions, must be recognized and evaluated. Complaints and misconceptions about safety systems that result from differences between beliefs about a system and the actual system operation and field performance must be evaluated.***

System Differences - Some consumers do not understand the basic elements of supplemental air bag systems. Typical air bag supplemental restraint systems have many components (Figure 3) that can be grouped into three basic subsystems:

- The crash sensors and associated wiring harness;
- The air bag modules with inflators; and
- The diagnostic module with readiness indicator.

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b/ Marsh, J.C., "Supplemental Air Bag Restraint Systems: Consumer Education and Experience," Ford Motor Company, SAE-930646, SAE International Congress, March, 1993.

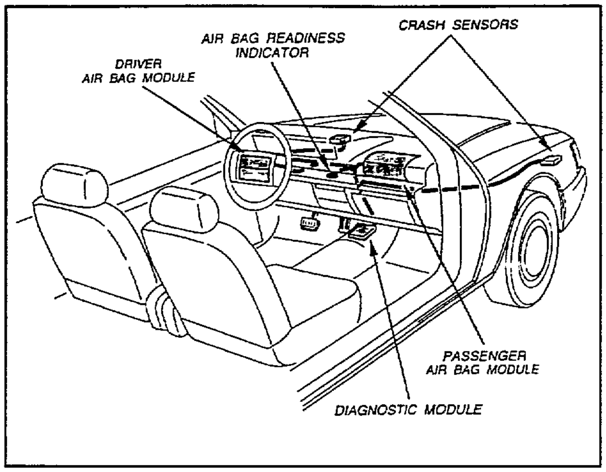

Figure 3 - Air Bag Restraint System Elements

Since the basic elements of an air bag system are common for most vehicle designs, many people conclude that "all air bag systems are alike." But air bag systems are not all alike; in fact, they are quite different. They use:

- Different crash sensors and locations;
- Different gas generation chemicals, filters, and inflation rates;
- Different air bag materials, tethers, and vents;
- Different electronic module designs and diagnostics; and
- Different crash speed and crash mode requirements for deployment.

Because of their distinctive design approaches, different air bag systems generate different field experiences. Sometimes, system differences are reflected in customer complaints. The NHTSA Hotline file of customer complaints provides a good example of the contrasts between customer concerns and what actually happened, for two types of air bag systems: one with a relatively high crash severity deployment threshold and one with a relatively low severity deployment threshold (Figure 4).

The NHTSA Office of Defects Investigation (ODI) operates a nationwide Auto Safety Hotline with a toll-free "800" number. Complaints are recorded on a Vehicles Owner's Questionnaire (VOQ) and put in a data base. While these "complaints" are unconfirmed allegations of purported vehicle "failures," they do reflect the concerns of some customers. The "Air Bag" complaints reported for two specific car models were used for this study; one with a higher crash severity deployment threshold and one with a lower threshold.

As seen in the right-side of Figure 4, vehicles designed with a high deployment threshold are more likely to have complaints about non-deployments in what customers judged to be a serious crash. The system performed as designed, but customers complained that the bag should have deployed. In fact, these complaints occur, to some extent, in vehicles with all threshold levels. Non-deployment complaints usually occur after lower severity frontal crashes, when an air bag deployment was neither advisable nor designed to supplement the protection provided by an active 3-point belt. Air bags are not designed to deploy in every crash. The frontal air bag system is not designed to deploy in side, rear, rollover or lower-severity frontal crashes.

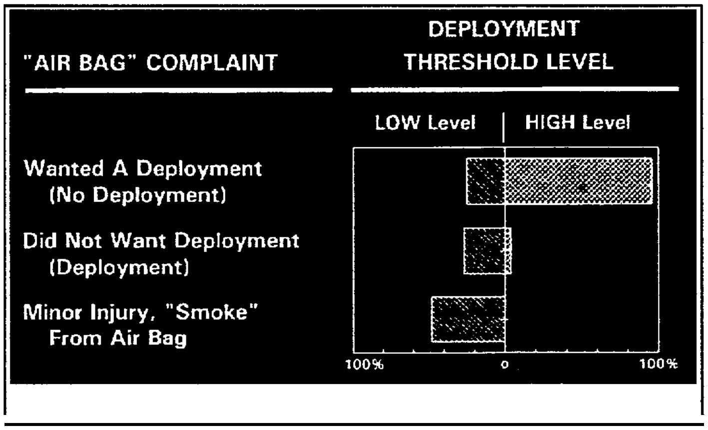

Figure 4 - NHTSA Hot Line "Air Bag" Complaints

> Note that, non-deployment reports are, in a way, "success stories," because they demonstrate the unlikeliness of inadvertent deployments - the air bag system did not deploy when it was not needed, and the safety belt protected the driver. The early concern about inadvertent deployments (before air bag systems were on the road) has been replaced with non-deployment concerns as the most common complaint.

In contrast. vehicles with a low deployment threshold (Figure 4) have more customer complaints because the bag did deploy. The system performed as designed, but the customer was dissatisfied. The customer did not want an air bag deployment in what they judged to be a minor crash; or they were upset by a relatively minor injury or by seeing "smoke" from an air bag deployment. In fact, relatively minor injuries, such as abrasions from contact with the deploying air bag, can occur to a properly seated and belted occupant, even in a crash of moderate crash severity, and some "smoke" (visible particulate matter or powder) is produced in all air bag deployments - minor "side effects" of the countermeasure.

- ***Consider unconventional data sources, such as consumer complaints.***

Deployment Residue - The actions of some emergency rescue crews provides the strongest example yet of how out-of-hand situations can get when people do not understand how the system functions. Following a Union City. New Jersey collision in July 1990, one headline read "Air Bag Bursts, Contaminates 20 More at Scene."/

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a/Ann Arbor News, "After Shower," July 26, 1990.

Newspapers asserted that an apparently malfunctioning air bag “exploded” during a minor car accident, spewing a skin-burning chemical onto the driver and contaminating 20 other onlookers and police officers. A shower was set up in the middle of the street. Anyone who had touched the chemical was isolated, their clothing was removed, and they were showered before being transported to a hospital. Clothes and other personal articles believed to have been contaminated were confiscated. The air bag was cut from the car, placed in a plastic bag, and transported as hazardous waste. Police cordoned off the block for about 4 hours to prevent others from being “infected.” Unfortunately, these extreme precautions were taken based on misinformation about air bag systems.

In fact, the powdery residue the local authorities thought was toxic usually consists of corn starch or talcum powder used as a lubricant, and sodium compounds, like baking soda -- accompanied by minute deposits of sodium hydroxide. The powdery residue may be a slight irritation to the skin and eyes, but poses no long-term health hazard. This powder is not considered toxic in the small concentrations that occur in today’s air bag deployments.

Without going into specifics, it should be emphasized that occupants and rescuers are NOT exposed to harmful levels of chemicals with today’s deployed or undeployed air bag modules. Deployed air bags are not dangerous to crash victims or rescue personnel and there is no reason to delay crash-related emergency medical treatment following an air bag deployment. And further, undeployed air bags are unlikely to deploy during a rescue. Rescuers should disconnect the battery before cutting into the steering column.

Ford[b/], General Motors”, and NHTSA[d/], emphasized these points by publishing rescue guidelines for air bag equipped cars. Chrysler, Ford, General Motors, Morton International, and TRW also sponsored an American Coalition for Traffic Safety, ACTS, video “Air Bags - A Crash Course for Rescue Personnel.“” Clearly, rescue-training organizations and highway safety officials should continue to dispel erroneous assumptions which still exist and continue to be circulated among some of these important safety personnel.

- ***Consider the impact of system misunderstanding and misinformation when introducing totally new technology.***

[b/] Ford, “Rescuer’s Guide for Ford Motor Company Air Bag Supplemental Restraint System,” October, 1990.

[c/] General Motors, “Air Bags in GM Cars, in Emergency Rescue Situations,” June, 1990.

[d/] NHTSA, “Emergency Rescue Guidelines for Air Bag Equipped Cars,” 1990.

[e/] American Coalition for Traffic Safety (ACTS), “Air Bags -- A Crash Course for Rescue Personnel,” Video, January, 1991.

6. CONCLUSIONS:

In summary, the automotive industry has clearly been engaged in rapid growth in safety technology with many new challenges, including a new era of passive occupant restraint systems. The limited field experience to-date has suggested that the combination of safety belts and air bags can provide the greatest overall reduction in the risk of injury and death in traffic crashes, but only if safety belts are used, and used properly. While the initial assessments are encouraging, we must all continue striving: first, to understand and deal with differences between air bag user's experience and possible misunderstandings; and second, to continue investigation and analysis of 'real-world' field experience.

Air bag systems will also present fresh challenges for all field investigators as they observe new and unique restraint systems, occupant complaints, and injury patterns. While the initial assessments are encouraging, we must strive to continue the investigation and analysis of real-world air bag field performance.

While improved crash avoidance (e.g., ITS) and improved crashworthiness (e.g., SRS) call for the implementation of distinctly different countermeasures, there are many commonalities in their "real-world" evaluation, including both the methods (e.g., field studies) and the institutional roles (e.g., public-private cooperation):

1) Field studies are critial. Clearly, strong operational field studies are key in helping to bridge the gap to full-scale system implementation. Indeed, field studies actually do influence future product design and implementation plans. Field evaluation of new system requires intensive in-depth investigations to gain early insights -- long before 'statistical' effectiveness results become available. Public-private cooperative studies can be very successful. Participating organizations can often institute special data collection programs for predetermined periods that are above-and-beyond their normal operations. Evaluation programs can benefit from cooperative access to a wide range of information resources, e.g., Coast Guard "Hotline" and dealer parts orders.

2) Be flexible. Case selection flexibility and judgment are key to the collection of antidotal in-depth crash investigations. so that limited resources can be dynamically targeted at field performance issues as they evolve. For example, to conserve resources, staged levels of case investigation thresholds can be used as performance experience is gained during a study. Also expect to repeat the requests for crash notifications.

3) Expect the unexpected. Very minor and unexpected factors can ultimately have a major system performance impact. Be sensitive to other effects/ results that were not expected or planned in the study. In fact, field studies are often used to help answer questions not originally planned. Note that field evaluation programs can totally alter the participant's behavior.

4) Be comprehensive. Safety evaluations should include all aspects of system manufacturing/ production, delivery/ distribution, implementation/operation, service and life-cycle. Non-operational aspects, such as system acceptance and consumer misunderstandings, must be evaluated, along with user reactions. Some technological safety measures may be operationally effective (e.g., ignition-interlocks), but they can be social 'failures.' Potential countermeasure system "side effects" must be considered and evaluated. Also consider the legal implications and consequences of evaluation programs and related data collection and analysis.

5) Consider the unconventional. Safety evaluations can consider critical factors beyond classic "crash" studies. Other traffic crash notification methods that can be used, beyond police reports (e.g., initial insurance claim reports). Look for insights from seemingly unconventional sources. For example, use of customer complaints and non-crash sources (e.g., road side observation of driver behavior). Trials of new countermeasures may also require new field investigation techniques to be developed, e.g., dealing with minimal brake markings left by ABS.

6) Be calm, do not overreact. While "real-world" experience, even on a limited basis, is crucial, be careful of preliminary and/or incomplete case investigations and early 'statistical' results. The early reported results may not be as 'bad' or 'good' as inferred. Media reports can exaggerate results. Don't expect early evaluation study results to provide stable and precise measurements of overall system effectiveness.

While the "real-world" evaluation of air bag Supplemental Restraint Systems continues. it is hoped that these observation on the process to-date will be instructive in future evaluations of the Intelligent Transportation System revolution.

PRECURSOR SYSTEM SAFETY ANALYSIS OF THE AUTOMATED HIGHWAY SYSTEM (AHS)

R. D. Leis

This paper presents the results of research conducted by the author for Battelle Memorial Institute, Columbus, Ohio, as part of its overal PSA contract for the FWHA. The opinions and findings expressed in this report reflect the position of the author, and not necessarily that of Battelle or the FWHA. A copy of the full report, upon which this paper is based, is available through the FWHA

> ***The Secretary (of Transportation) shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed... The goal of this program is to have the firstfully automated test track in operation by 1997. This system shall accommodate installation of equipment in new and existing motor vehicles***
>
> ***ISTEA of 1991, Part B, Section 6054 (b)***

1. INTRODUCTION

This paper summarizes the results of the safety analysis of an automated highway system. This analysis was performed as part of the "Precursor Systems Analysis" (PSA) portion of the FWHA's program to comply with the above mandate. The work supporting this paper was performed by the author as part Battelle's PSA work.

1.1 Background

The concept of a fully automatic vehicle-highway system is not new. For decades transportation theorists have been infatuated with the prospect of marrying the convenience and flexibility of the private automobile with the corridor capacity of fixed guideway train systems. By replacing the current manual methods of lateral and longitudinal vehicle control with electronic and mechanical equivalents, proponents suggest that existing highway capacity could be increased by a factor of 2 or 3. Eliminating the human control component suggests the potential for eliminating human error, related to over 90 % of automobile accidents. Potential monetary benefits are suggested that reach hundreds of billions of dollars.

Recent research under the IVHS program has moved this concept closer to reality by furthering the technology of various required aspects of an AHS; such as advanced control systems, traveler information systems, and automatic vehicle routing. Automotive advances have also addressed some of the required system capabilities; such as, ABS, anti- slip drives, run-flat tires, and very reliable drive trains. On the roadway side, some capabilities are in use to monitor environmental effects such as road surface temperatures to predict ice conditions, wetness indicators, and impending fog detection. At the present time, all of these advances function through the human driver --- providing a valuable service by assisting him/her in making the judgments necessary to safely control the motions of an automobile.

The ISTEA mandate carries these efforts to the next level: further technological development and integration of control to permit hands-off, feet-off, and brain-off operator involvement while the vehicle is under automatic control. The schedule demanded by ISTEA is very ambitious, even to the most optimistic observers --- complicated by the fact that there is not even a generally accepted concept of an AHS configuration, let alone the identification and definition of all required components, subsystems, and systems that must function together for a successful system.

In response, the FWHA used a wise, but rather unusual, contracting approach to tap the collective national intelligence regarding potential problems and otherwise questionable areas to be addressed by the AHS. Through the PSA program, 15 research teams addressed issues and risks for an AHS in 16 activity areas, ranging from specific technical areas such as lateral control, to very soft areas such as human factors and societal/institutional considerations. The PSA program was structured such that each of the activity areas was addressed by at least three separate research teams. In addition. to focus their investigations, each team was charged with defining at least 3 representative system configurations (RSC’s). Many configurations were offered in a range bounded by having all intelligence in the vehicle, following simple magnetic lane markers (the “smart vehicle, dumb highway”) to having all intelligence placed in the infrastructure commanding all vehicle motions (“smart highway, dumb vehicle”). Many variations existed to represent differing allocations of control, different interfaces to manual traffic, and different separation strategies down to very small fixed separations (-3-5 ft). These RSC’s were negotiated among the research teams to ensure that virtually all possible AHS configurations would be addressed by at least one team.

The issues and risks identified through this program were to become (and did become) a database for use by the National AHS Consortium (NAHSC), charged with developing the prototype system.

1.2 PSA Safety Analysis

The safety mandate placed on an AHS has been defined by the FWHA: provide a collision free environment under normal operations. Normal operations are defined as "operations in the absence of system malfunctions". Activity area N of the PSA program established the objective of identifying the issues and risks associated with achieving this goal.

Most research teams approached this task by examining national data bases of accidents to establish intelligence regarding the types and significance of various highway accidents. Some very good work was done to identify the threats that would appear to require exclusion from an AHS roadway as well as issues associated with providing necessary malfunction resistance of critical AHS functions to reduce collisions. As a broad observation, these teams focused on principles of threat exclusion to eliminate certain threats and functional competence of critical control systems to manage other threats.

Through coordination of approaches among the research teams (another unusual approach), Battelle elected to take a complementary view. We assumed adequate functional competence of key vehicle motion controllers. For example, we assumed that the technical community could develop a functionally adequate "separation controller" that could reliably control vehicle motions to achieve an established separation with forward threat agent. Our view then focused on the issues and risks associated with establishing an appropriate separation algorithm to direct this controller. Additionally, we assumed that no threat exclusion technique can be assumed to be 100% effective. Finally, we adopted a zero tolerance for collisions and examined the implications for operations and separation management under this posture. As a result, we examined the following areas:

- The implications of minimum safe separations for all AHS separation concepts, with all expected threat agents,
- The problems of separation management; that is establishing the correct engagement strategy and calibrating it for existing conditions
- The problems of navigating between engagement states in a deliberate and fail-safe manner
- The problems of transition maneuvers between steady state engagements
- Possible fault intervention to minimize the extent and severity of collisions.

1.3 PSA Safety Analysis Relevance to ITS Initiatives

The relevance of the AHS safety analyses is direct. The most likely path to an AHS is considered to be evolutionary from the driver enhancements under current ITS initiatives. However, these current ITS developments are driver aids and will require a significant enhancement to adapt them to true automation, addressing the concerns expressed in this paper. For example, current collision avoidance capabilities most directly parallel an automation of the function of maintaining an established separation. They do not yet contain the capability to establish what this separation should be. This exemplifies the need to automate judgments --- a theme repeated throughout this paper.

Therefore, this AHS analysis establishes the beginnings of the next plateau of performance requirements for ITS initiatives. From the standpoint of serving as an example of safety assessment techniques; that is, the quantitative determination of safety benefits that can be used for objective cost/benefit analyses, existing AHS activities have not yet arrived. AHS development and deployment ***can*** serve as a model for such analyses if the process follows established formal system safety design principles. (This theme was repeated by all teams addressing AHS safety under the PSA contract). Very briefly, this approach begins with a rigorous interpretation of safety goals into functional performance requirements and allocating these to all systems and subsystems, a process similar to reliability allocation procedures. As each requirement is established, at each allocation level, test requirements for performance verification and validation are established --- to become the basis of subsystem and system testing performed during the development process. Thus, the verification and validation test “plans” evolve during the design process.

However, these tests would most likely be of a technical nature; measuring values for performance variables assumed to represent reasonable proximate measures of safety. Therefore, even with a rigorous system safety program in place, we are still faced with the fundamental problem of relating these proximate measures of safety to ***real*** safety. Creative verification and validation thinking can lessen this problem, but not eliminate it. Therefore, instead of thinking in terms of the relevance of current AHS analyses to existing ITS activities addressing this problem; we should think in terms of the converse. The former is definitely obscure, whereas the latter is clear --- current ITS activities addressing safety assessment is relevant to the future testing plans for the AHS.

2. RESEARCH APPROACH

As indicated previously, the objective of this analysis was to identify issues and risks associated with achieving a specified safety goal for undefined system configuration. Therefore, instead of examining the safety performance of a defined system with specified characteristics, the more traditional safety analysis approach; we evolved the general system requirements based on a specified safety goal. Our emphasis was directed toward a subset of all safety threats that may exist on an AHS. This subset concerned the issues and concerns associated with the elimination of in-line collisions; that is collisions between an AHS vehicle, on an AHS controlled facility, and all threat agents that may exist on that facility. (For vehicle-to-vehicle collisions, this is the classic rear-end collision). This definition is expanded in the following parts.

2.1 Threat Situations Considered

Figure 1 is a very high-level fault diagram that relates the general range of unsafe occurrences that will be faced by an AHS. The shaded nodes represent our focus area. As shown, we concentrated on “in-line” collisions, that is, collisions between an AHS vehicle and threat agents that may exist ***on an AHS lane*** --- from all possible sources.

Figure 1 also illustrates our inferred safety goal. The demand for AHS safety is “to provide a collision-free environment under normal operations”. “Normal operations” exist “in the absence of system malfunctions”. We extended this demand for innocent vehicle isolation --- even if there are collisions elsewhere in the system. Therefore, as shown in Figure 1, the in-line collisions within our focus area are divided into four categories, based on the major initiator of the collision. The first of these is termed “normal collisions”. These are collisions that occur under conditions that appear to be within the design envelope of the AHS. There is no malfunction that alters a vehicle’s performance such that induces a collision. This class of collisions is directly related to established safety requirement of an AHS: the elimination of collisions under “normal” operations.

The next two collision categories were added, based on our recognition that the -sophisticated separation management capabilities of an AHS to handle normal collisions can (and should) be effectively utilized to provide some intervention control over these collisions:

- Collisions that are induced by malfunctions that alter the safe separation requirements between vehicles such that an existing separation relationship becomes invalid. The malfunction may be real, as in brake failure, or perceived, as in a loss of knowledge that the brakes are functional.

- Collisions that are induced by a sudden intrusion of a threat agent onto the AHS lane at a position such that the distance ahead of the following vehicle, already on the lane, is less than the minimum safe separation required under the normal engagement capabilities of the following vehicle. Collision avoidance cannot be accommodated by the stopping capabilities of the threatened vehicle.

The requirement for high capacity in an AHS will involved small separations that can be safely maintained under a no-failure assumption. In general, as we decrease separation to achieve this goal, we increase exposure to collisions if a failure should occur. Therefore, the AHS is forcing exposure for an innocent vehicle. We believe that the normal separation management capability be charged with the responsibility, to the degree possible and practical, for managing this exposure.

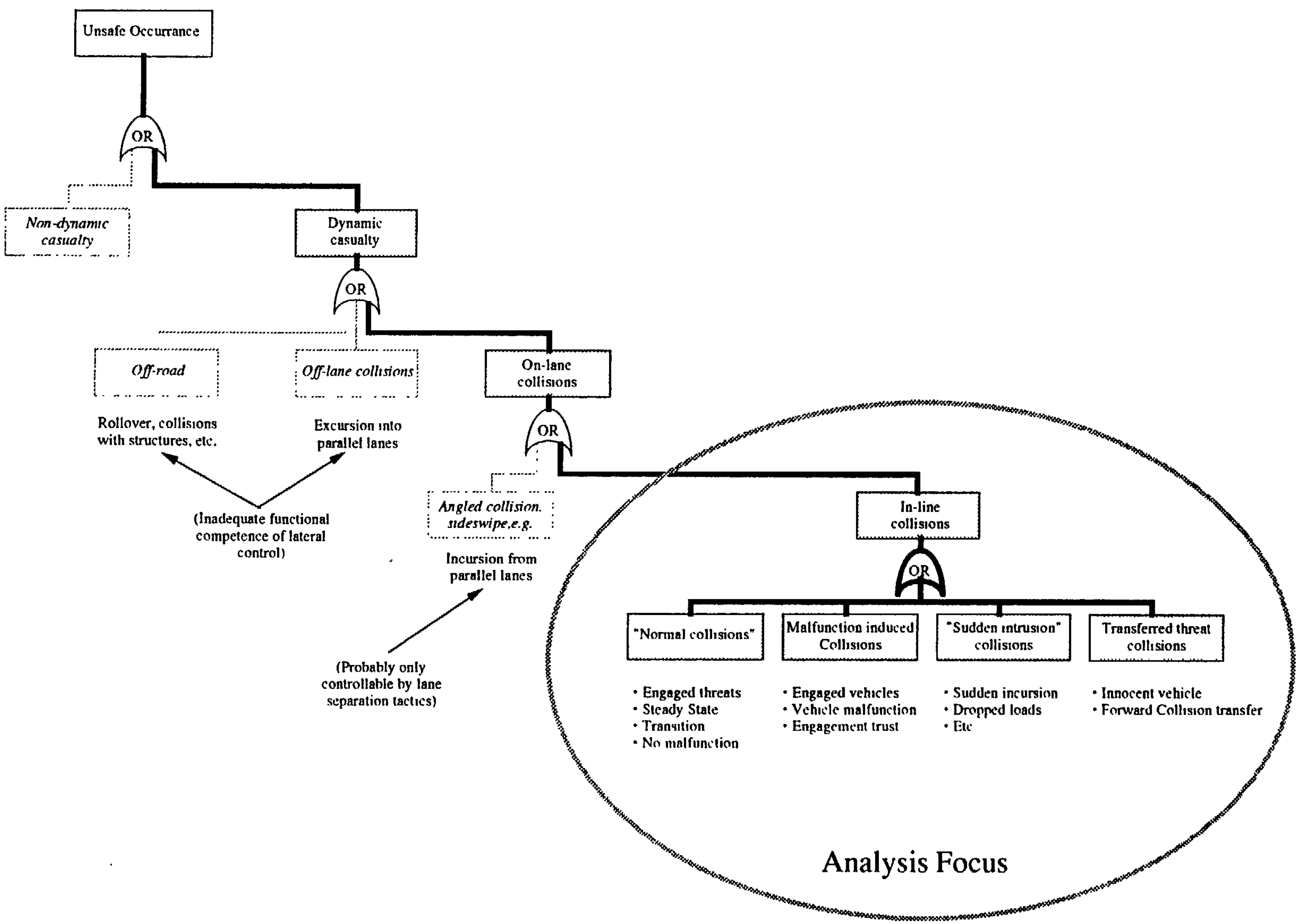

Figure 1. General Fault Path Identifying Threat Situation Emphasis

The last category is termed “transferred threats”. These are collision threats to a vehicle that result from the forward collision threats faced by the adjacent leading vehicle. Again, these threats may be real or imagined. The obvious concern here is the actual collision transfer. However, control options should not wait until a forward collision occurs to begin taking an avoidance action. These actions should be taken while the threat of a forward collision is still a threat. We consider that controlling these threats should be a high priority in AHS design. These collisions involve an innocent vehicle because of its proximity to another failure or collision -- a proximity established by the AHS separation strategy. While we recognize the best strategy for eliminating transferred threats is to eliminate collisions; we also recognize that collisions will occur, and the AHS should be charged, within the normal control system, with the responsibility to alleviate the resulting domino effect within the normal capabilities of the separation management system.

Figure 2 is a graphical representation showing the relationships between these various threat situations.

2.2 Threat agents

The collision situations considered all involve an AHS vehicle and a threat agent. The following threat agents were considered:

- Fixed objects. Fixed objects are those threat agents that represent a conflict that has no ability to move out of the way. All collision avoidance capability must be provided by the subject vehicle. Included in this category are stopped vehicles, all lane fouling objects from adjacent lanes, dropped loads, intentional placement, people, animals, etc. We have made no distinction on the basis of object size. Fixed objects are interpreted as Phantom Vehicles, with an infinite braking rate.

- Rogue vehicles. A “rogue” vehicle is a vehicle that, for whatever reason, is not known to be under some level of AHS control. More than likely, this will be a non-AHS vehicle, on the AHS lane either by design or inappropriate intent.

- Other AHS vehicles. An AHS vehicle, in our analyses, was always meant to be an AHS-controlled vehicle --- controlled, in full, as intended by the particular control law in force at the time.

We considered AHS vehicle capabilities to safely coexist with the first two threat agents to be “obligatory” engagements. While a number of AHS concepts use various techniques to exclude these agents, we consider it unwise to assume absolute effectiveness of these exclusion approaches. An AHS vehicle, for whatever the reason, may revert to manual control or may suffer a malfunction rendering its control reliability suspect. Such vehicles would have to be engaged as a rogue vehicle. Furthermore, AHS operations in rural areas will probably require mixed traffic engagement capability. Therefore, in terms of AHS engagement strategies, we must include fixed object engagement and rogue vehicle engagement.

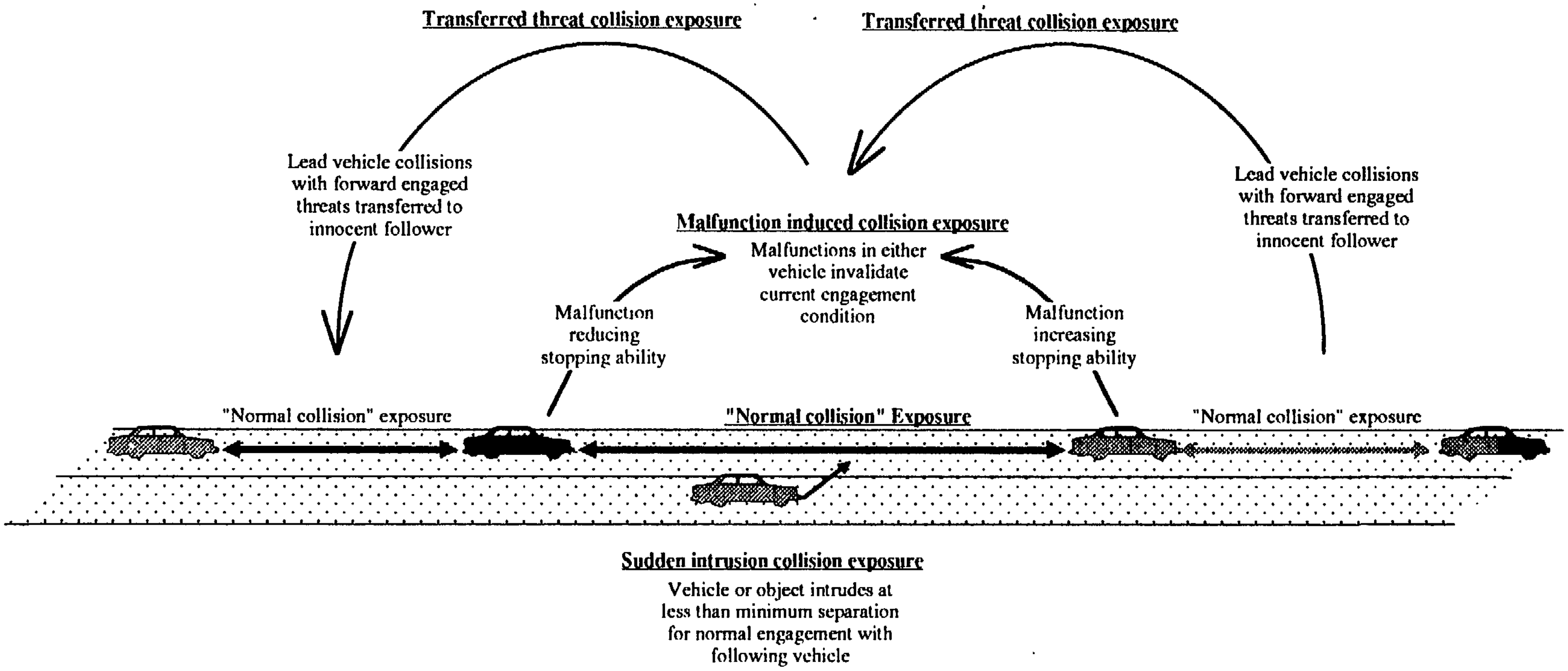

Figure 2. Relationship of "Normal Collision", Malfunction Induced Collisions, Sudden intrusion Collisions , and Transferred Threat Collisions

Engagements other AHS vehicles is also obligatory; but there are a number of engagement options available. Depending on the demand for system capacity, AHS vehicle may be engaged with different engagement strategies. We considered three in this task:

AHS compliant engagement; where separation is based on the "as is" maximum braking capability of the coupled vehicles. This is the minimum capability that must exist for an AHS. It is most nearly represented in the spectrum of concepts by terms such as "autonomous control" and "independent control". AHS vehicles coupled by this engagement strategy adjust separation on the basis of "as-is, unmodified" capabilities for the engaged vehicles.

(1) Loose platoon engagement; where brake suppression is employed to reduce braking rates of all AHS vehicles to match that of the minimum capable vehicle. Because the vehicles are similar in braking performance capability, the average separation between vehicles can be less than that required under an AHS compliant engagement.

(2) Tight platoon engagement; where further brake capability management techniques are used to allow small intra-string separations, on the order of 3-5 ft.

2.3 Analysis Approach

Figure 3 expands our "normal collision" to provide some further definition and to illustrate a further narrowing of emphasis. In this figure, two nodes are crossed out:

(1) The node that recognizes the potential of a capability to "steer around" a forward threat agent. Some options using this capability can probably exist. However, they are sufficiently problematical that we do not believe that they can be expected as a routine option for collision avoidance (as discussed later, this option as a possible extreme emergency response). If full automatic control is not available for off-line maneuvers, a transition to manual control is required. However, such a transition would come at a very difficult time, under the specter of an imminent collision (an "extremis" condition). Operator performance in this situation cannot be expected to have sufficient consistency to utilize it as an integral part of extremis management. Furthermore, to do so would require the operator to be in a "hands off, feet off, ***brain on"*** operating mode. While we should seek to utilize his/her involvement under these conditions, we must expect that they don't exist, and design to accommodate the safety of the operator in a ***"brain*** off" mode. Therefore, we structured our collision avoidance capability to consider only in-line stopping capabilities.

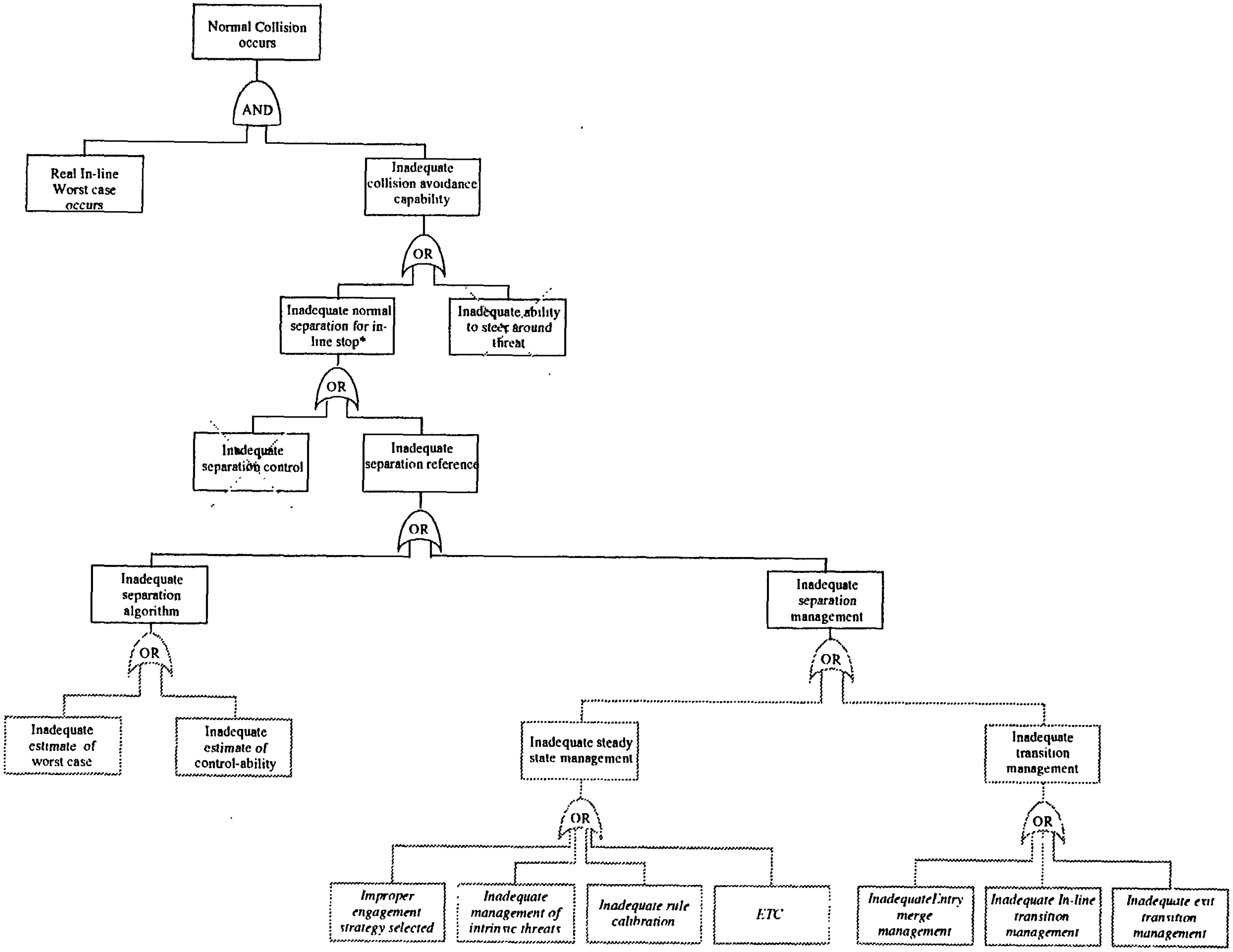

Figure 3. General In-line Collision Fault Path Identifying Rejected Control Options

(2) The second node eliminated addressed the consideration of "separation controller" faults as enabling an inadequate separation. We assumed separation controllers can be developed to maintain separation relative to some established reference value (adequate "functional competence"). We recognize that this is not a trivial assumption. However, we believe the much larger problem lies in establishing the desired reference values such that they reflect real minimum safe requirements. This latter requires the availability of an appropriate separation algorithm and the management ability to properly apply it.

Therefore, our concerns were focused on the faults associated with inadequate separation algorithms and inadequate separation management capability. Analysis of the issues and risks associated with these nodes involved the following activities:

(1) Detailed analyses to investigate the separation implications of various engagement strategies and engaged threat agents. These analyses served not only to characterize these separation requirements, but also to identify issues and concerns associated with the requirements for the algorithms and management capabilities.

(2) Initial specification of the functional requirements for the separation management function --- the development of a basic "concept of operation" for the separation manager.

While a crucial part of safety management is to divert the fault paths that enable a collision, this is only the first line of defense. We must also include capabilities to accommodate breaches in this line. The key to accommodating these breaches is conceptual: never consider that failures in these preventive measures must inevitably result in a collision. Until the collision actually occurs, purposely introduced intervention strategies can be effective; if not to eliminate the collision, at least to reduce its severity. A number of analyses were conducted to explore the effectiveness of various intervention strategies. The results of these analyses were folded into the functional requirements and concept of operation for the separation manager

3. COLLISION AVOIDANCE CONSIDERATIONS

The elimination of in-line collisions is often assumed to be a significant benefit of an AHS. At the same time, we are led to believe that this benefit will accrue as a natural by-product of automation --- based on data that suggests that most of these collisions are caused by "human error". Because automation will replace the human on the control loop, it is assumed that this accident cause will naturally disappear. Not only is this a false hypothesis, there is a growing perception that human error in this context is not nearly as related to "error" as might be implied.

Insightful analyses of human error caused accidents supports a thesis that "human errors" are rather a reasonably expected response under the conditions of information and control capability that exist at that time. This slant tends to label such factors as "human frailties" and label their influence as "enabling" rather than causal. In other words, the standard of performance used as a reference for determining error is itself being questioned. Without a doubt, when we automate the human driving functions, we will demand greatly enhanced capabilities in situation awareness, decision prowess, and control options than we currently have available in our manual system. It is important to understand these distinctions to ensure that the AHS does not simply automate the same frailties that currently exist in the manual systems.

3.1 Separation Management From the Human Perspective

It is rather easy to identify the cause of in-line collisions as human error because it is so bottom-line oriented. The bottom line cause of in-line collisions is inadequate separation --- for whatever reason. Because safe separation management and control is delegated to the driver, it is clearly his/her fault, generally expressed as “failure to maintain assured clear distance”. In fact, these collisions are frequently reference as violations of the “assured clear distance rule”. Another cause less frequently mentioned is “driving too fast for existing conditions”. Even this cause, however, is related to insufficient separation under the conditions that exist at the time. This is all rather obvious: if a collision occurs, it is clear that the separation prior to the collision was insufficient to enable the trailing vehicle to respond to the demands imposed by the motions of the leading vehicle. However, this is less than enlightening when we are tasked with its elimination.

To develop an appreciation for this problem we needed to identify the components of safe separation management inadequacies. Was the separation inadequate because we could not or did not maintain a desired separation (functional error)? Or, was the cause a failure to establish the correct desired separation (judgment error)? Over the last 25 years we have had many occasions to reflect on precisely the relationship between these error forms. We have analyzed hundreds of accidents, from all transportation modes, to gain an understanding of the role of the human operator. These analyses have led to the following observations that occur with such regularity that one suspects a physical law is involved:

(1) The human operator is quite adept at following a defined course of action --- executing an hypothesis. A small portion of human error may involve actual mechanical errors of function (steering the wrong way, accelerating when we should be braking, etc.). However, humans, as a group are quite competent and consistent in this role. Our greatest faults in this regard are associated with maintaining diligence: complacency, fatigue, boredom, expectancy, habit interference, drug/alcohol influences, and the like.

(2) The majority of human frailties are associated with the formation of the hypothesis --- the judgments and decisions that establish the reference values that drive the “mechanical” control actions. This type of error has led to a concept of “guided collisions”, where a vehicle was unknowingly driven, under full and purposeful control, into an extremis situation (a situation where an accident is imminent). The common descriptor of cause is “operations under false hypothesis continued”

Clearly, functional errors are leading candidates for elimination as a natural by-product of automation. In its minimal form, any separation controller must be capable of maintaining some desired separation value or set point. The separation controller is an operating system --- the tool used by a “separation manager” function to execute the separation requirements it establishes.

However, simply addressing these mechanical errors (i.e., automating “function”) will not achieve our safety goal. This goal can only be reached by ***successfully automating the “judgment” involved;*** that is the judgments and decisions that establish the correct desired separation. Again, our accident analysis background offers insight into the influencers of this judgment frailty. There are two, and these represent a recurring theme in almost any human control inadequacy:

(1) We tend to underestimate the magnitude of the threat, and

(2) We tend to overestimate our ability to control it

The implication of these is that we tend to drive at a separation that would be technically less than safe. By almost any yardstick for measuring minimum safe separation, observed separation on today’s highways is inadequate. It is almost axiomatic that if a vehicle rapidly brakes, a collision will result. Examples of our purposeful entry into unsafe situations are:

(1) We readily close on a lead vehicle in a passing maneuver. We approach to small separations with a significant speed differential, under the assumption that the lead vehicle will maintain its speed.

(2) We readily close on a vehicle slowing for a turn or lane change under the assumption that it will vacate the lane space before we need it.

(3) We readily close on a merging and accelerating vehicle under the assumption that it will get out of our way.

(4) We readily merge into gaps that, sometimes, are barely longer than the vehicle under the assumption that both vehicles will accommodate the intrusion. There is a lot of trust involved in this maneuver.

If any of the assumptions in these maneuvers proved to be invalid, a collision would probably result. Many more examples would only reinforce the illustration that we deny the potential for a worst case demand occurring at a very vulnerable time. However, this is a ***calculated*** risk. We use confidence and trust that the lead vehicle will not behave in an unexpected manner. If it begins operating in an erratic behavior, that is, invalidate the trust, we increase our cushion. We use “threat transfer” management techniques to isolate us from conditions that may force a sudden and drastic maneuver by the lead vehicle by looking ahead and identifying situations that may cause this and taking action before the lead vehicle forces us to respond in an emergency manner. In these cases we actually use a “negative delay” --- an approach very similar to “braking from the rear” approaches in AHS concepts. Further, in very close quarters, our threat concern may cause us to be ready to apply brakes in fractions of a second, compared to the l-2 seconds we may exhibit in a more leisurely environment.

3.2 Separation Management From the AHS Perspective

The bottom line of manual separation management is that, although we are guilty of not maintaining a adequate separation, we have no quantitative information regarding what constitutes “adequate” (except for some rules of thumb). We have ample evidence of what is not adequate --- whatever it happened to be before the rear-end collision occurred. ***The AHS will not be allowed to operate in this intelligence vacuum. Establishing and maintaining separations based on a sound perception of real minimum safe separation requirements is the fundamental requirement of the separation manager if we are to achieve a no-collision environment.***

3.3 -General Principles of Safe Separation Management

Figure 4 shows the general relationship between three separation types and the variables influencing them: (steady state conditions)

(1) **Operating minimum separation (Operating min** A). This is the separation established as a desired value by a operational decision. This is the separation “set point” used as the reference value for the separation controller. This may be set as a constant or a variable dependent on some dynamic parameter such as separation time or vehicle velocity. Operating separation is an operational decision. Any algorithm is acceptable, as long as it results in separations greater than the real minimum safe separation.

(2) Perceived minimum required separation (Perceived Min req A). This value is the minimum separation for a no-collision situation based on calculations of assumed interactions of perceived values of assumed influencing variables. This is our best estimate of the real minimum required separation. This calculation is based on the expected “worst case” stopping trajectory of the forward threat object and the expected “best case” stopping capability of the following vehicle.

(3) Real minimum required separation (Real min req A). This is the result of the ***real*** interaction of the ***real*** influencing variables at their ***real*** values as they influence the ***real*** worst case threat agent stopping profile and the ***real*** maximum stopping trajectory of the following vehicle.

For a no-collision situation, under the worst case conditions, these separations must be related as follows:

Operating min A > Perceived min req A > Real min req A

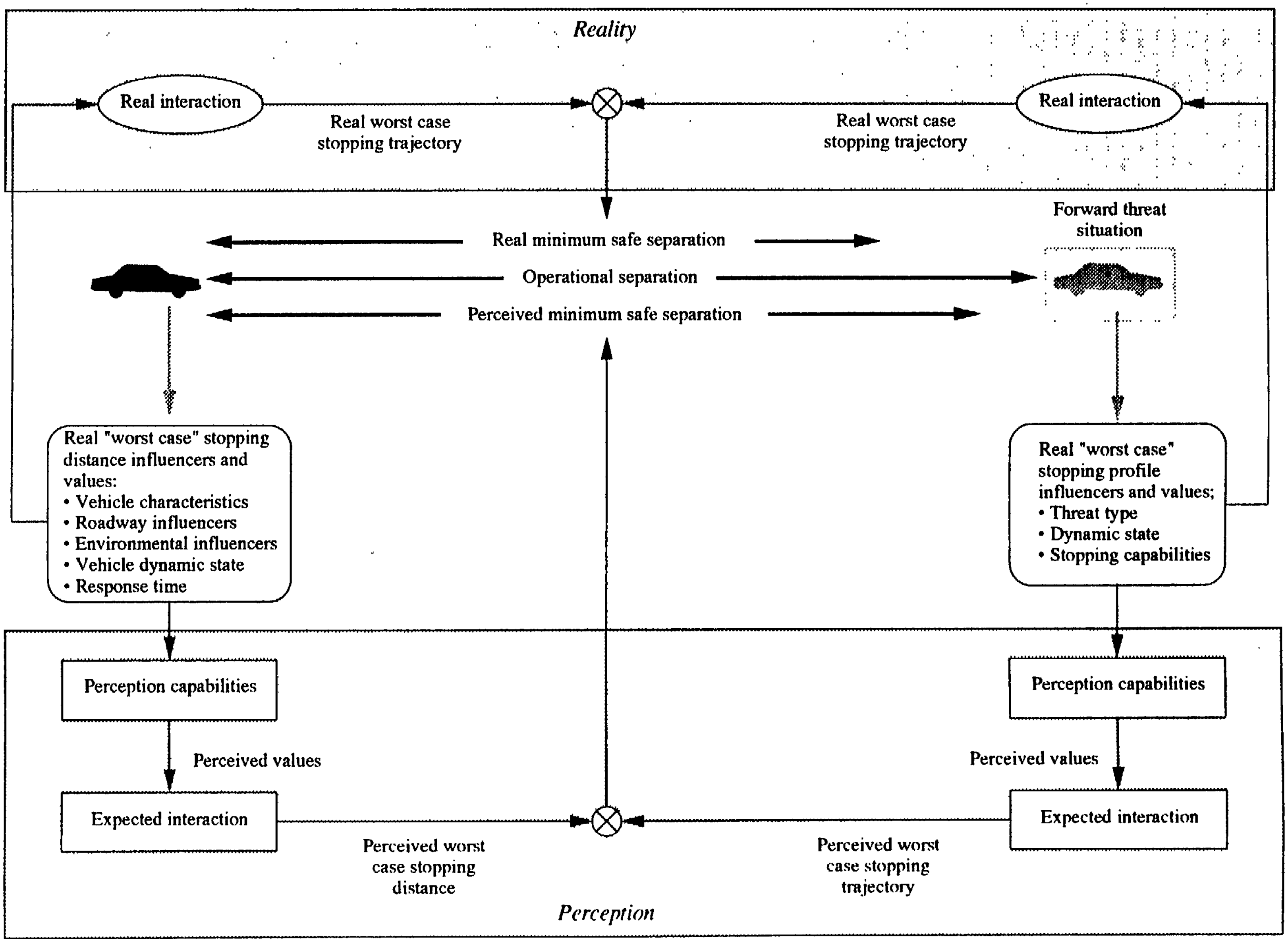

Figure 4. Safe Separation Perception & Reality

In the absence of any demand for capacity, the “Separation Manager” (performing the perception function) has a very easy task: estimate reality using a very unsophisticated approach and very conservative estimates for the influencing variables. The problem is that capacity of the highway is completely destroyed. At 60 mph, the resulting separations would be several hundred ft, resulting in capacities well below 1,000 vehicles per hour.

The separation manager, therefore, cannot operate in such an unconstrained environment. The demand for capacity that significantly surpasses current freeway values creates a “pressure” on the separation manager to allow decreased separation without sacrificing collision avoidance goals.

The first opportunity to reduce separation centers around eliminating the first inequality expressed above: increase the functional competence of the separation controller to increase the precision with which it can control actual separation about a set point. This allows the set point to become very close to the perceived minimum separation requirement. However, in this scenario, this will be of little value.

To further reduce separation and ensure safety requires removing the second inequality. This requires sharpening the perception of the real separation requirements --- enhanced knowledge of all influencing variables and their qualitative and quantitative role in determining real minimum safe separation. It also be requires operating in “real time” (as-is conditions) to enable adjustments to requirements as conditions change (weather, etc.) An implicit corollary requirement is the need for enhance situation awareness capabilities to provide the precision necessary to support this as-is decision capability. Incorporating this capability into the separation management function can result in significantly reduced operating separations while maintaining confidence in the collision avoidance capability. However, required separations may still be unacceptable (from a capacity view).

The above approaches all treat the minimum safe separation as the dependent variable --- responding to the characteristics of independent threat agents. Separation management focuses on managing the separation as dictated by the characteristics of the threat agents. This situation is appropriate when an AHS vehicle must engage threats imposed by fixed objects, rogue vehicles, or unconstrained AHS vehicles (operating under AHS compliant rules). Reductions in safe separations depend on the precision with which the real minimum safe separation is estimated, providing sufficient confidence in that estimate that it can be used as an operating separation. We cannot do any better that in an unconstrained threat environment.

To achieve smaller separations, it is necessary to reverse the dependency relationship --- establishing some desired separation profile and controlling the characteristics of the engaged threat agents such that they can be accommodated at the specified separation. With this approach, separation management involves controlling the vehicles that are allowed to participate in such an engagement. This is the principle behind various platooning arrangements for AHS vehicles.

4. "Normal" Collision Avoidance Implications - Steady State

Initial analyses focused on the steady state safe separation implications for collision avoidance. A collision was defined as straight line trajectory interference: the worst case maneuver of the threat agent creates a boundary that cannot be crossed by the braking trajectory of the following vehicle. In most cases, where the worst case trajectories can be approximated as constant accelerations, trajectory interference will occur at the end of the maneuver and the separation requirement resolves itself into the difference in stopping distances. For engagements where the braking capability of the following vehicle is greater than that of the threat agent, endpoint control is not a valid indicator of trajectory interference. Even if end conditions are satisfied, trajectory interference will occur during the maneuver.

In these analyses, minimum safe separation is defined as the perceived minimum separation that will allow an AHS vehicle to avoid trajectory interference with a threat agent. The avoidance capability is constrained to straight line braking. (As discussed previously, we did not include lane changing or other evasive maneuvers as a viable collision avoidance strategy for these "normal collisions").

4.1 Separation Analysis Assumptions

The models used for the analyses of separation requirements were not sophisticated: they were the basic equations of motion. Where possible, all analyses used a common set of assumptions. Unless otherwise indicated, the following assumptions were used:

(1) All accelerations for both worst case and response trajectory definition were assumed to be constant.

(2) Acceleration changes were assumed to occur instantaneously (infinite jerk)

(3) All reaction or response times where assumed to be 0.3 seconds. This represents the time delay between the time a worst case demand is initiated and full application of braking rate by the threatened vehicle. While this value may include signal delays. once the signal is received, it becomes perfect with no delay. This means that the virtual reality developed by the signals is a perfect representation of reality.

(4) A "Kv" factor (Kv= velocity of following vehicle/velocity of leading vehicle) was established at 1.05.

(5) Trajectory interference assumed zero separation as acceptable (tangent trajectories during the maneuver). No allowance was established for a minimum separation at the end of the encounter.

(6) All braking rate estimates were based on conditions that represent test conditions used by popular automotive magazines for production automobile brake test (clean,

smooth and dry road conditions). The minimum and maximum vehicle braking capabilities were based on the results of these tests for recent production vehicles, most equipped with ABS. These maximum braking rates rang between 0.72g's and 1.2g's.

4.2 Engagement Strategies Analyzed

Five steady state engagement strategies are examined --- generally classified on the basis of the expected worst case maneuver. The first two examine the separation implications for an AHS vehicle to safely engage the various threat agents identified previously as "obligatory":

(1) Fixed objects. It is difficult to grasp the concept of a "steady state" engagement" with a fixed object. Therefore, we considered a fixed object to be a leading "phantom" vehicle with an infinite braking rate, traveling at the same velocity as the following vehicle. With no intervening vehicles, we assume this phantom vehicle is just outside the stopping distance of the following vehicle. This establishes the minimum forward sensor range.

(2) Rogue vehicles. A rogue vehicle is any vehicle not known to be under AHS control. Therefore, as a forward threat agent, its potential worst case capability must be assumed to be the stopping capability of the most capable production vehicle (1.2g's).

For the third obligatory engagement, other AHS vehicles, three different concepts of engagement were assumed, reflecting the range of options reflected in most AHS concepts:

(1) AHS Compliant. Braking rates for both a following and leading vehicle cover the range available in current automobiles (0.72g's - 1.2g's). Separation requirements are based in differences in stopping characteristics.

(2) Loose platoon. Braking rate for a loose platoon leader as well as platoon members was set at the least capable production vehicle (0.72g's). Separations can approach fixed time, with a minimum approaching the braking delay time.

(3) Tight platoon. Braking rate of a tight platoon leader was set at 0.3g's The rate for platoon members is variable, depending on location in the platoon. Separation is a small and fixed value (3-5 ft typically).

4.3 Steady State Separation Implications

This section illustrates the implications on separation requirements to provide adequate avoidance capability for collisions under the engagement strategies listed above. Data are presented to illustrate the influence of selected variables within the context of the strategies outlined above. It is emphasized that these are for ***illustrative*** purposes only. They ***are not intended to be definitive,*** in the sense that they could be translated into real operational strategies. Their purpose is to indicate relationships that may not otherwise be considered and to foster some appreciation for the level of intelligence and control rigor that accompanies these strategies.

Figure 5 contains curves that illustrate separation requirements between selected AHS configurations and forward threat agents. Each specific curve is identified by a Ka ratio. Identification of the engaged pair can be determined by relating the values in this Ka ratio to the translation given in the figure.

Figure 6 is a tabulation of the required separation values for selected engagements at 60mph (from Figure 5). The last row in this figure introduces the concept of a “Rear Phantom” vehicle. The rear phantom vehicle serves the same purpose as the forward phantom: it serves as a reasonable threat condition to establish a minimum rear range requirement in the absence of any other rear threat. We defined the characteristic of this phantom vehicle as a rogue vehicle, traveling at a speed in excess of the legal limit (e.g., 70 mph). possessing a braking capability less than the least capable production vehicle (e.g., 0.7 g’s), and exhibiting a reaction delay more closely aligned with human performance (1 .O sec.). This entry is appropriate for later discussions on dual engagement responsibility.

As discussed earlier, the intra-platoon separations of a tight platoon are established as a desired condition, and the safety management function involves adjusting braking rates of successive vehicles as necessary to safely accommodate the established separation. Figure 7 illustrates the implications of this approach. The curves shown represent safe separations under various values of Ka. The conditions used in determining these are the same as those used for developing Figure 5. As shown, at a velocity of 60-70 mph, the established separation (arbitrarily set at 4.4 ft) can only be considered safe for a vehicle capable of generating a braking rate of 1.2g’s following a vehicle with a supressed braking rate of 0.3g’s. The conclusion is that tight platoon can only be 2 vehicles long. The reason for this is the value selected for Kv (1.05).

If Kv is assumed to 1 .O, some platoon length can be supported. Figure 8 shows the braking rate requirements for successive vehicles for selected values of separation, delay, and platoon leader braking rate. All calculations assumed Kv= 1.0. The highlighted curve corresponds to the conditions reflected in Figure 8 with the exception of Kv. As shown, under these conditions, a platoon length of 7 vehicles reaches 0.72g’s, the maximum capability we may assume to exist (the minimum capable AHS vehicle). What is not explicit in this figure is the concept of vehicle “slots” in a tight platoon. In this configuration, for example, the first vehicle behind the leader will require approximately 3.3 g’s braking rate. If it happens to use a higher value, say 0.5 g’s, it has essentially used up the allocation for vehicles 2, 3, and 4, with obvious implications on the remaining vehicles in the platoon.

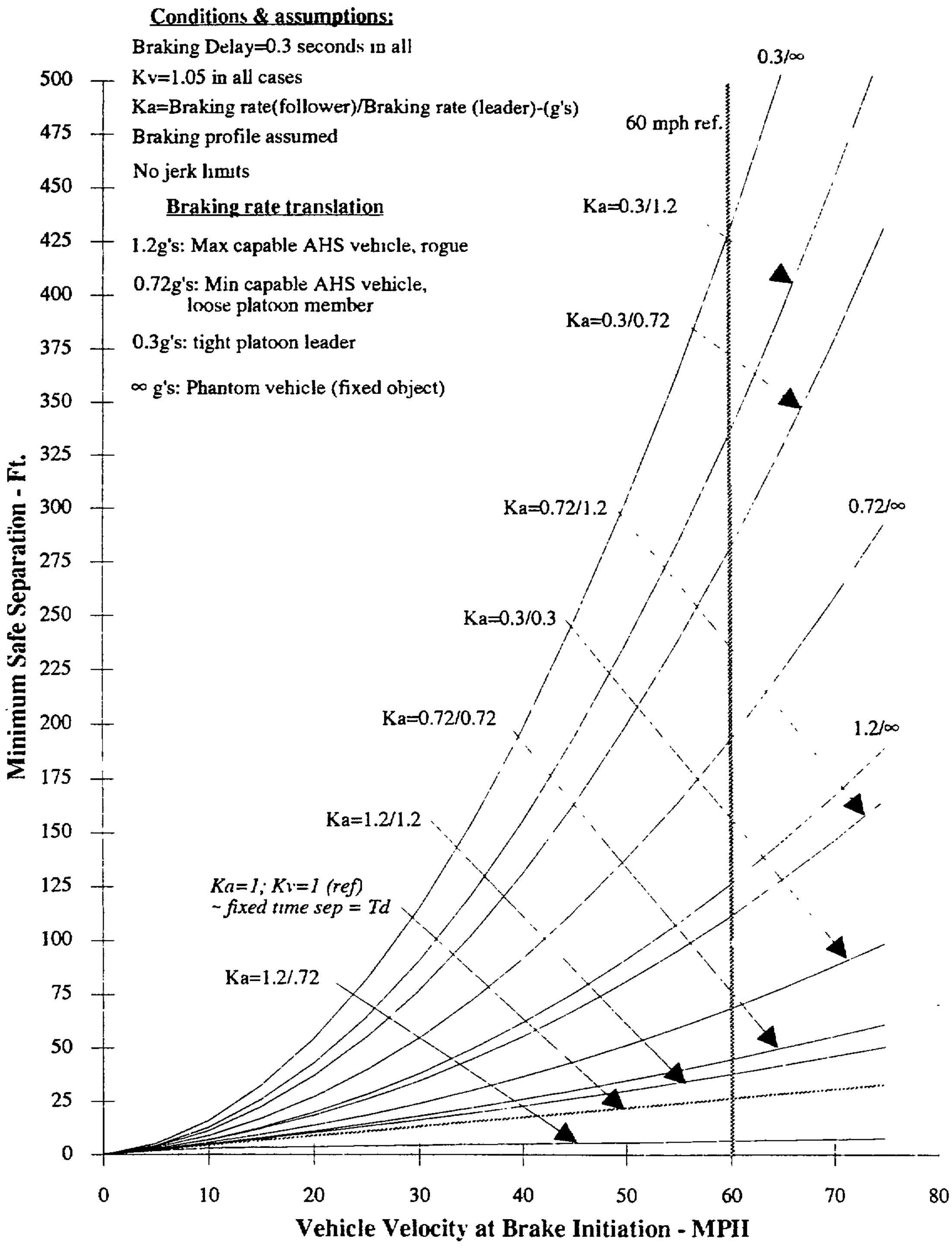

Figure 5. Curves Illustrating Minimum Separation Requirements Between Vehicles with Different Stopping Capabilities

Forward Threat / Following Vehicle		Phantom(1)		Rogue(2)		AHS Compliant				Platoon(3)		Intra-platoon	
						Max Capable		Min Capable					
		Curve(4)	Sep - ft	Curve	Sep - ft	Curve	Sep - ft	Curve	Sep - ft	Curve	Sep - ft	Curve	Sep - ft
AHS Compliant	Max Capable (1.2g's)	6	130	3	40	2	35	1	5	1	5	*	*
	Min Capable (0.72g's	7	195	5	115	5	115	3	40	3	40	*	*
Loose Platoon Leader (0.72g's)		7	195	5	115	5	115	3	40	3	40	3	40
Tight Platoon Leader (0.3g's)		10	435	9	330	9	330	8	280	8	280	*	3-5(5)
Rear Phantom (6)		*	*	*	*	*	230	*	165	*	165	*	*

<u>Notes:</u>

(1) Forward phantom vehicle assumed to be fixed object: i.e., a vehicle with infinite braking rate.

(2) Rogue braking rate assumed maximum available on existing vehicles - 1.2g's

(3) Last vehicle in a platoon assumed to braking at minimum product vehicle rate - 0.72g's

(4) "Curve" identifies the curve number in Figure 5

(5) Intra-platoon spacing for a tight platoon is generally set at values in the range

(6) The rear phantom determines the rear detection range, corresponding to a rogue, at 70mph, braking rate at the low end of production vehicles (0.7g's), and a response delay of 1.0 sec.

Figure 6. Minimum Separation Requirements for Selected Engagement Situations at 60 MPH

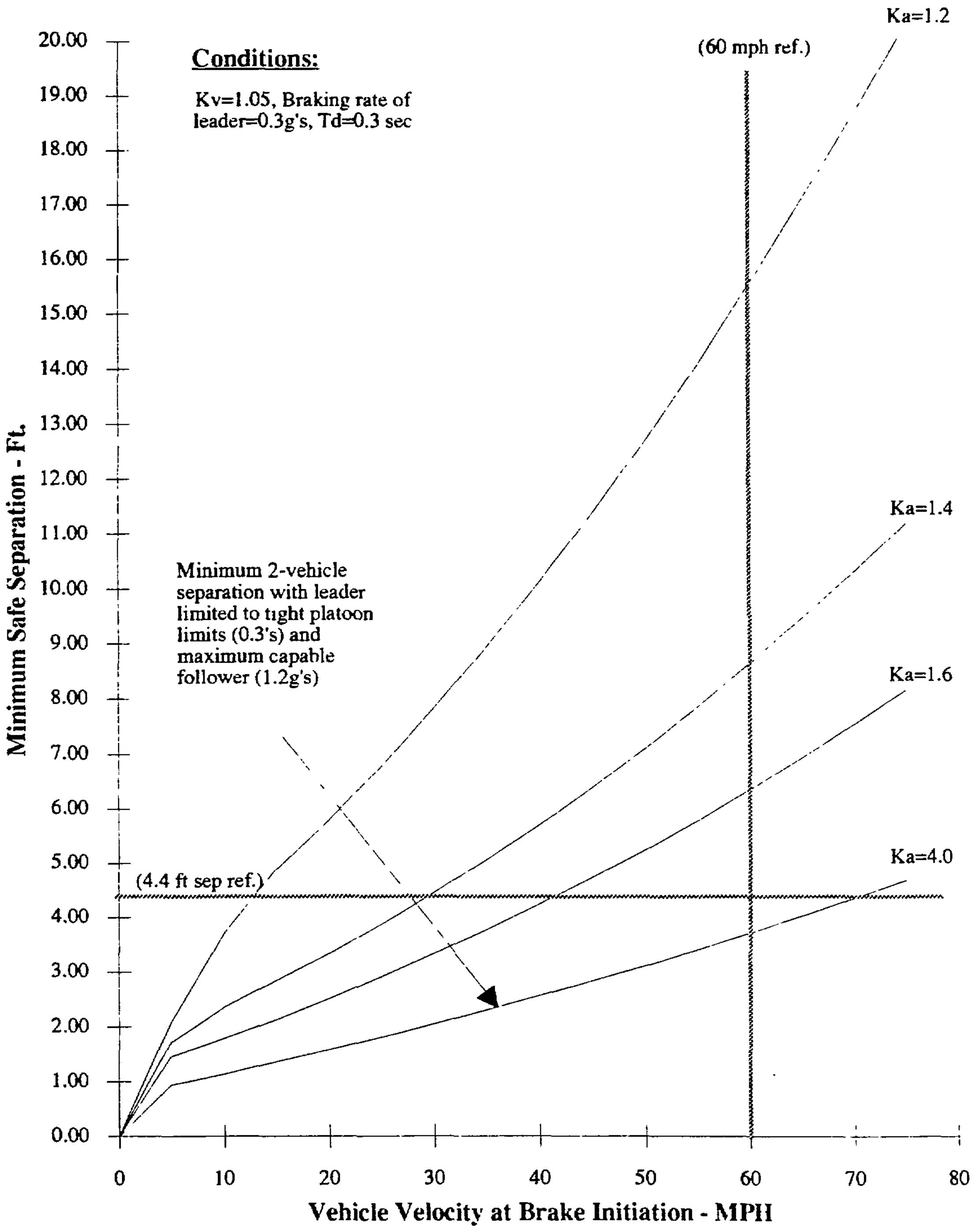

Figure 7. Small Separation Detail for Tight Platoons

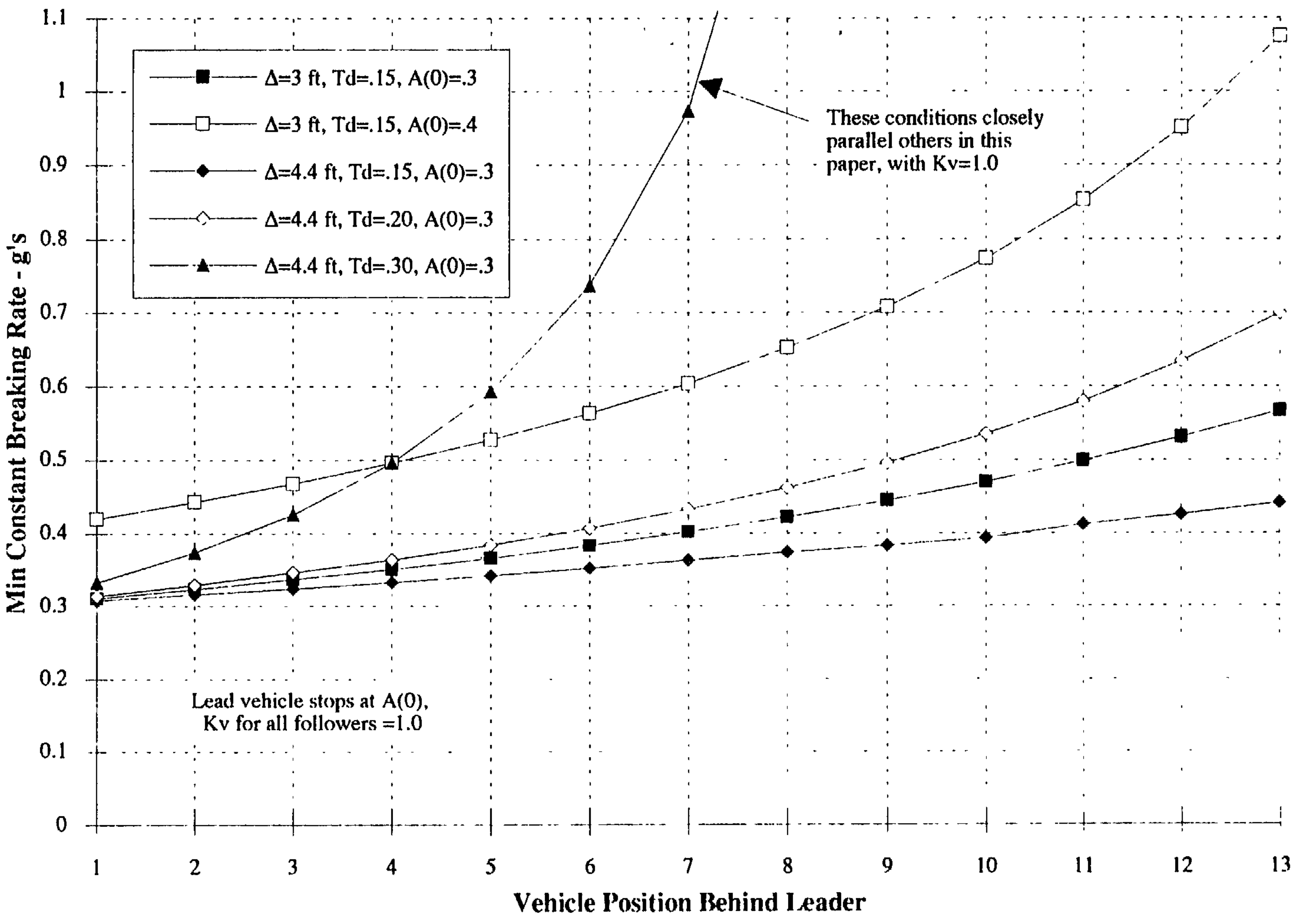

Figure 8. Braking Rate Requirements for Following Vehicles in Tight Platoon under Various Conditions

To eliminate these deficiencies, a tight platoon will require enhanced capabilities:

- Capabilities to greatly reduce delay;

- Capabilities to greatly reduce the influence of successive delays through coordinated braking (where all vehicles in the platoon take their cue from the leader) or braking from the rear of platoon in worst case situations.

We have confidence that tight platoons can be safely accommodated under carefully controlled conditions. The concern here lies with knowing exactly what these conditions are, coupled with the ability to measure the real world with sufficient precision to determine that these conditions are present.

4.5 Minimum Intelligence Requirements

The separation values displayed in the previous section illustrate a range of safe separation requirements depending on the nature of the forward threat. The general intelligence requirements to establish an appropriate separation strategy are:

- Fixed object (forward phantom) engagement. The validity of this engagement strategy requires only knowledge that a forward threat agent exists. This is also a default engagement: if we know nothing about the characteristics of a detected leading object, a fixed object must be assumed.

- Rogue vehicle engagement. The validity of this engagement strategy requires knowledge that a detected forward threat is a moving vehicle. This is also a default engagement if we do not have positive proof that a detected moving vehicle is not under AHS control.

- AHS compliant engagement. The validity of this engagement requires positive evidence that the forward threat is a moving vehicle, under AHS control, and the worst case stopping capability this vehicle possesses. This is also a default engagement: if the vehicle is known to be under AHS control, but do not have evidence that it can tolerate a platoon engagement.

- Platoon engagement. Engaging a platoon as a forward threat requires engagement with the last vehicle in a leading platoon. We have assumed a logical stance that the last vehicle in a platoon always be allowed to use its maximum braking capability, even though its forward separation may be based on something less. As will be discussed this is desirable for malfunction accommodation and transferred threat management. Therefore, as a forward threat, the last vehicle represents an AHS compliant vehicle and must be engaged using the above strategy.

- Intra-platoon engagement (loose platoon). The validity of this engagement extends the knowledge required for a safe AHS compliant engagement by adding the need for positive indication that the leading vehicle is operating under platoon constraints. This is also the default engagement if we know a vehicle is operating under platoon constraints but do not have positive evidence that it is operating under constraints required by tight platoon rules.

- Irma-platoon engagement (tight platoon). The validity of this engagement requires the most information: all the requirements of a loose platoon with the added positive indication that the vehicle is currently operating under tight platoon braking constraints, as well as the precise value of that constraint.

Establishing the intelligence require to form a valid engagement requires that communication be established and maintained. This function is a key element for the separation management concept of operations discussed later.

4.4 Principles of Shared Engagement Responsibility

All of the preceding analyses have taken the view of forward threat engagement. The implications of these engagement scenarios is that engagement strategies are one-directional and the responsibility for managing safe separation rests solely on the following vehicle. This is not a correct inference. A forward engagement for one vehicle is a rear engagement to another. A specific engagement rule links two vehicles; with each vehicle playing a separate and distinct role relative to that engagement to ensure its validity. One vehicle is considered to be “burdened” and the other is considered to be “privileged”. These terms, borrowed from marine navigation Rules-of-the-Road imply certain responsibilities and rights with respect to each other:

- A privileged vehicle has the right-of-way; but in exercising this right has the responsibility to provide a consistent and predictable worst case profile against which the burdened vehicle can manage its avoidance strategy. In return, the privileged vehicle has the right to expect the burdened vehicle to “keep clear”.

- A burdened vehicle has the responsibility to keep clear of the privileged vehicle. In return, it has the right to expect consistent and predictable maneuvers from the privileged vehicle.

The burden is assigned to the vehicle most capable of avoiding the collision; that is, possesses the most control-ability and has the least constraints on maneuvering options.

The principles of burden and privilege establish a number of characteristics of an engagement and the roles played by each vehicle. We have chosen to state these as pseudo-theorems and corollaries, without proof other than the logic they contain.

Theorem 1: An engagement rule is always suspended between two vehicles (expressing a fixed object as a phantom “vehicle”).

Theorem 2: One vehicle of an engaged pair must be privileged while the other must be burdened. The validity of an engagement depends on the ability of each vehicle to properly execute the responsibilities of their role.

> **Corollary A:** An engagement cannot connect two privileged or two burdened vehicles.
>
> **Corollary B:** If both vehicles in an engaged pair are under AHS control, the lead vehicle assumes the role of a privileged vehicle while the trailing vehicle assumes the burden to keep clear.
>
> **Corollary C:** The acceptance of a vehicle to perform the duties of one role depends on the confidence it has that the other vehicle will successfully perform its role. A valid engagement is based on this trust.
>
> **Corollary D:** Because a rogue vehicle is not under a trusted control, its performance cannot be trusted. Therefore, by corollary C, a rogue vehicle can never be accepted as a burdened vehicle A rogue vehicle must always be treated as privileged to other AHS vehicles, regardless of its relationship to those vehicles.
>
> **Corollary E:** Because the performance of a malfunctioning AHS vehicle cannot be trusted, it can never be accepted as a burdened vehicle. It must always be treated as privileged to other AHS vehicles, regardless of its relationship to those vehicles.

Theorem 3: An AHS vehicle is always suspended between to engagement rules --- one connecting it to the vehicle ahead and another connecting it to the vehicle behind.

> **Corollary A:** If a string of vehicles consist solely of AHS controlled vehicles, each vehicle functions in a burdened role with respect to a leading vehicle and in a privileged role to a trailing vehicle.
>
> **Corollary B:** Any vehicle that is not known to be under full automatic control is privileged in both directions.
>
> **Corollary B:** If an AHS vehicle leads a rogue or malfunctioning AHS vehicle, the healthy AHS vehicle is burdened in both directions.
>
> **Corollary** C: An AHS vehicle cannot use different performance characteristics to perform its dual roles.
>
> **Corollary D:** The ability of an AHS vehicle to perform in one role is constrained by its responsibilities in its other role. For example, the ability to alter its function as a burdened vehicle is constrained by its responsibilities as a

privileged vehicle to its follower. As will be illustrated later, this imposes constraints on the ability of a vehicle to respond to a malfunction or threat transfer situation

The above indicate that an engagement between two vehicles is a negotiated arrangement in which trust in capabilities is critical. From a fail-safe standpoint, an AI-IS vehicle must always enter an engagement under the assumption that it is burdened; i.e., it takes the stance that it must protect itself from threats ahead and behind. Only after successful negotiation with another vehicle will it share this burden, by delegating its rearward protection to a following vehicle. Therefore, in a string of AHS vehicles, each vehicle concentrates on forward collision avoidance (its role as a burdened vehicle) and trusts rear collision protection is being adequately managed by the following vehicle.

When an AHS vehicle is burdened in both directions, it is in a very difficult position. This vehicle is charged with the responsibility for collision avoidance from a rear threat, but has no direct means to control separation. While communications may be used to signal the rear vehicle to adjust separation, compliance cannot be assured. The only positive action a lead vehicle has regarding rear separation is to accommodated it by adjustments to its braking capabilities to permit it to “keep ahead” of the follower in a severe maneuver. However, this option is limited by its responsibilities a burdened vehicle in its forward engagement. For example, the AHS vehicle could increase its separation from its leading vehicle to allow it to stop with reduced braking rates.

4.4.1 4.7 Steady State Separation Concerns

There are trends implied in each if the previous engagement strategies --- implications on precision, level of knowledge, etc. and how these are influenced by different separation strategies. In general, almost every implied requirement for safe separation increases as separation decreases: knowledge, situation awareness, quality and precision of calibration. It is obvious that the complexity of safe separation management increases as separation decreases. Attaining these performance levels is a definite concern. However, we believe that their attainment is possible.

In addition to this general concern, five other, more specific concerns exist:

(1) The adequacy of the a specific rule to truly provide the necessary tolerance to a worst case maneuver; that is, the validity of the worst case assumptions, and the validity of the control-ability assumptions. Most concerns are derived from a concern that all the factors that influence the real minimum separation requirements are considered. Simply stated, the concern here involves the credibility of the perceived separation requirement as a safe representation of reality.

(2) The second concern is the adequacy of the separation management function to know which rule to apply and to keep it properly calibrated to account for changing as-is conditions. The former requires exceptional capabilities of situation awareness in terms of the threat environment. The latter requires equally exceptional capabilities with regard to the effects of changing values for the influencers of safe separation; e.g., rain, snow,

sand, etc. Without such capability, we would be forced to establish our minimum separations with such a large ignorance factor that capacity would be severely limited.

(3) Whenever we base decisions on uncontrolled variables, such as weather, we expose ourselves to a class of threats that we have termed “intrinsic threats”. These result from the sometimes subtle shifts in values for the influencing variables that can result in a degradation in control-ability. Changes in road surface, amount of rain, temperature, etc. Therefore, to counter these intrinsic threats, the corollary requirement of precision is the obligation to establish metrics for these variables and to monitor these metrics to enable the separation to be continually re-calibrated to ensure that the minimum separation remains safe under all operating conditions. This process is complicated by the fact that we must know the conditions and effects of these conditions on our control-ability ***before we encounter those conditions*** If a wet or snow-covered road ahead will affect our braking capability, we need to adjust our separations before we get there.

(4) Platoon operating strategies require braking capability suppression tactics to force a population of vehicles with appropriate capabilities to support small separations. We do not consider the accomplishment of this function to be trivial.

(5) A significant concern is that an AHS have the capability to operate under a variety of engagement strategies. We believe that a “portfolio” of rules must be available to the separation manager to safely accommodate all the situations that may exist. We believe that a number of options need to be available for engagements between AHS vehicles to accommodate transitions and relaxed engagements if the pressure for capacity is not present.

It is important that situation awareness requirements not be trivialized. If we are to achieve the desired capacity improvements; we must push vehicles to the limits of their capability. If we are to do this safely and by design: we must improve not only our qualitative and quantitative understanding of the variables that influence these limits; but also our ability to adequately measure these variables, in real time, to enable us to determine these limits. We feel situation awareness, in all its facets, will present a very significant challenge to an AHS.

5. Normal Transition Implications

All engagement strategies discussed previously were all based on steady state conditions. While not intending to diminish the difficulties associated with establishing and maintaining these steady state aspects of separation management, a more difficult problem exists with transition situations. During transition maneuvers, large variations in relative vehicle motions are present. Our analysis of transition maneuvers addressed some of the implications of the relationship between the relative motions of the involved vehicles and the minimum safe separations that are required to accommodate these motions.

Three transition situations were analyzed:

(1) A merging situation as it may occur at a point of entry to an AHS lane. The issue examined is the gap requirements to enable a safe maneuver. The relationships established are also applicable to merging situations from parallel AHS lanes on a multiple lane system.

(2) In-line transitions, that is transitions between engagement states, without the complicating factor of another vehicle disturbing the process. Two situations were analyzed: an overtaking situation, where the following vehicle needs to slow to engage a slow moving vehicle and the transition involved when closing from a loose platoon to a tight platoon.

(3) Exit transitions, where our concern relates primarily to the transition from operations on the automated lane and the manual world that must be accommodated in this transition.

5.1 General Analysis Procedure

In simple terms, the procedure used to analyze separation requirements during transitions involved visualizing a variable length "probe" to the front of the following vehicle and another leading forward from the rear of the merging vehicle. The lengths of these probes represents the stopping distance of each vehicle as determined at each point along the way. A no-collision criterion required that there be no conflict between the trajectories defined by the forward ends of these probes.

Figure 9 illustrates a portion of the analyses performed to determine the separation requirements. With the exception of the curve labeled "Closing Condition", all curves in this figure reflect separations involved in an entry merge situation. As shown, the worst case exposure under the desired closing algorithm does not occur at the instant of merge (where the merging vehicle enters the lane and immediately stops at its rated braking rate. Rather, it occurs during the maneuver. The task of merge management, therefore, involves not only management of the initial encounter, but managing it with sufficient knowledge that this may not represent the true worst case.

The various curves shown in this figure illustrate the effects of various changes in the merging conditions. The most effective gap minimizing approaches involve establishing a near steady state engagement, on parallel lanes, prior to the execution of the merge. This option may be more possible if the line vehicle slows to meet the engagement. A limited analysis showed that even a modest slowdown rate by the line vehicle was very effective in moving the gap requirement closer to that required on the basis of initial conditions.

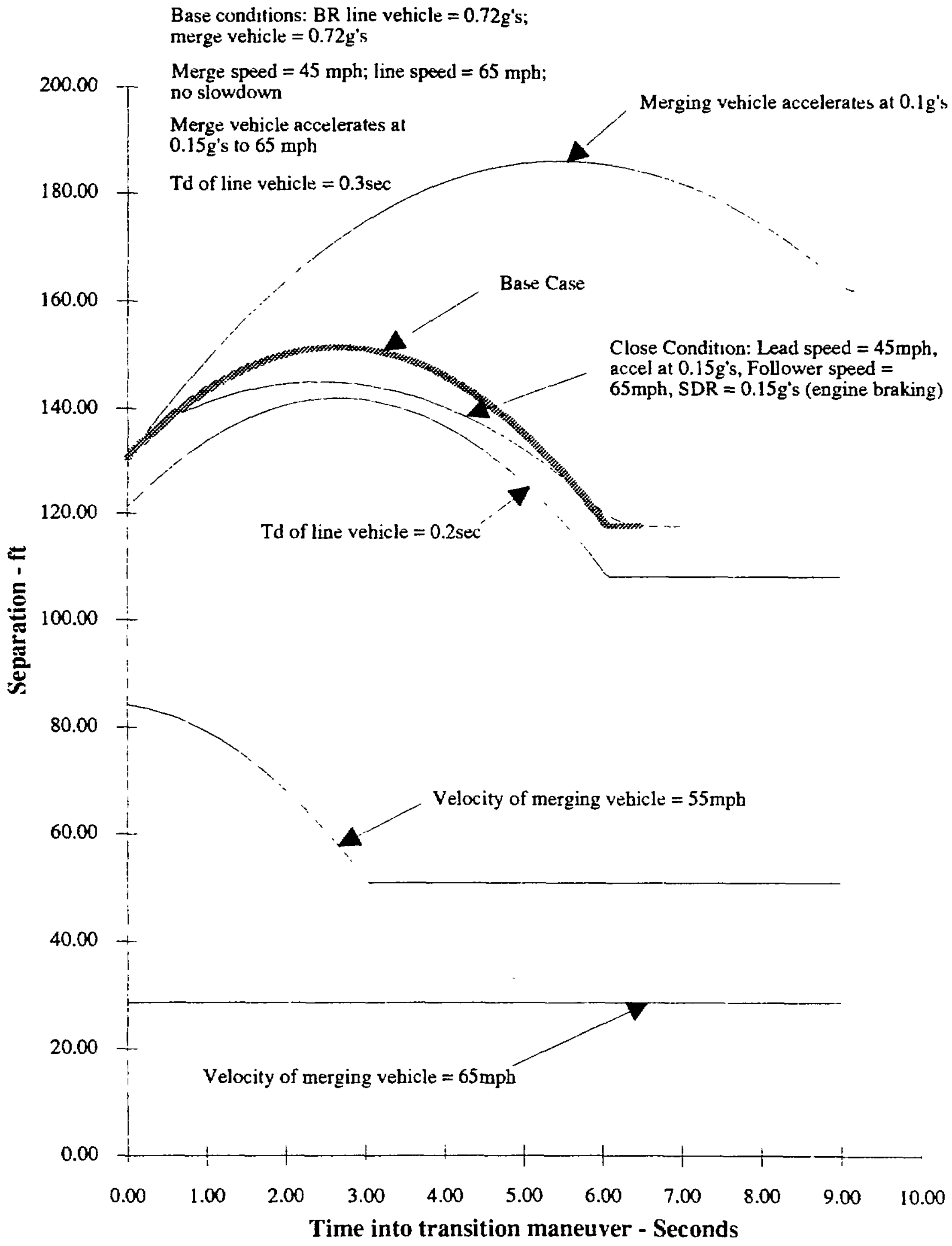

Figure 9. Curves Illustrating Transition Interference During Transistion Maneuvers

5.2 Summary Transition Concerns

Merge Transitions: The previous examples assumed a fully controlled merging vehicle, during a fully controlled merge situation. Additionally, the entry facility was assumed to be finite and dedicated to entry only. Even though the analyses were very simple and the conditions optimum, a number of questions arise:

(1) An existing vehicle pair must be identified between which an appropriate gap must be created to accept the merging vehicle. Since an appropriate gap must be created in time to physically match the merging vehicle's position, how are these vehicles selected from a string of vehicles? How fast must the gap be created? What slow down rate is appropriate?

(2) How are the commands transmitted to the line vehicle to begin gap creation? How are communications and coordination of motions between the pair of line vehicles and the merging vehicle managed?

(3) The minimum gap required consists of a minimum forward separation and a minimum rear separation (plus the length of the merging vehicle). The merging vehicle must insert itself into this gap at the right location. Therefore the gap must be presented in a proper relationship to the merging vehicle. How are we going to manage the logistics of this?

(4) Merge management requires the designated following vehicle to split its allegiance between two vehicles; the merge vehicle and, not to be forgotten, its previously engaged lead vehicle, that must remain engaged until the merge is completed. How do we handle such dual allegiance?

(5) Because the forward and rear portions of the gap is based on the merging vehicle's state when it enters the automated lane, the motions undertaken after it is on the lane, and the engagement dynamics between the merging vehicle and its partners, is there some optimum entry strategy?

Considerations such as these suggest that merging situations are least problematic when a near steady state engagement can be established between the designated following vehicle and the merging vehicle, even though they are on parallel lanes. A merge conducted under these conditions would be truly "seamless". However, this would impose significanr requirements for the entry facilities --- to function almost as aparallel AHS lane.

If the actual merge is manually controlled with respect to longitudinal and lateral guidance, the entire process of safe gap creation and merge accommodation becomes fundamentally flawed. The concept of a safe merge is based on coordinated maneuvers, which, in turn, are based on certain expectations of the merging vehicle. If any aspect of this expectation is invalid, a safe merge cannot be guaranteed.

If we move away from the dedicated and finite entry facility to the mixed traffic transition lane concept, the merge problem is compounded. It is very difficult to conceive of an ability to treat mergers from this kind of entry facility as anything other than "sudden intrusion" threats.

In-line transitions: In-line transitions are not as problematical as merging transitions --- there is no gap formation or coordination requirement. Three specific concerns exist:

(1) As with any transition, the problem of assuming the worst case situation to be that defined by the initial approach conditions exists. Approach strategies must account for potential conflict situations that may occur during the maneuver.

(2) The above concerns were directed toward the transition to a closer engagement. Similar conditions exist for disengagement from a close engagement to a more relaxed engagement. We do not suspect the worst case shift exhibited above, but the process of sequencing actions (e.g., removing brake suppression) must be carefully established.

(3) Finally, any process of transition must have the capability to abort the maneuver and return to a safe engagement. No action should be taken that places the vehicle in an untenable situation if, for any reason, the transition must be undone.

Exit transitions: As difficult as the previous transitions appear, they have a common characteristic: they are controllable (in theory). The exit transition does not enjoy this privilege. It is complicated because it not only involves the physical transfer of the vehicle from the controlled confines of the AHS to the uncontrolled roadway, it also involves the transfer of control from the AHS to the vehicle operator. This latter consideration requires that the automatic systems never turn over control of a vehicle in a state that is beyond the control capabilities of the human operator.

Prudence would seem to indicate that the physical vehicle transfer and the vehicle control transfer should not occur simultaneously. Prudence would also suggest that the transfer of control should only occur when the vehicle is in a stable steady state conditions, with a velocity and forward spacing sufficient to enable manual control and to allow the re-acquisition of control by the AHS if, for any reason, the control transfer does not take place. To accommodate an exit transfer, 3 subsystems must be prepared:

(1) AHS lane preparation --- specifically the actions the adjoining vehicles on the AHS lane must take to accommodate the transfer safely. These preparations include adjusting engagement calibration and/or engagement strategy to accommodate a vehicle leaving an engagement. Included in this general activity is the need to adjust the focus of the existing following vehicle to a new "privileged" vehicle. The leading vehicle also is

similarly affected. It must break its current trusted rear engagement and re-establish a new one.

(2) Exiting vehicle preparation --- specifically adjusting its motions to be compatible with the control demands it will face in its new environment and the control capabilities anticipated from the vehicle operator. Also involved is the removal of any encumbrances in place; i.e., removal of brake suppression controls.

(3) Operator preparation --- specifically integrating the driver back into the control loop, calibrating his/her abilities to assume control, and providing sufficient situation awareness to prepare the operator for the control demands he/she will face when manual control is assumed.

By considering the alternative exit options and situations, as well as the inherent problem of control transfer, a number of desired conditions were developed:

(1) The final transition from AHS facilities to an uncontrolled environment should be made under full manual control. The facilities should be sufficient to allow the vehicle operator to adjust the vehicle's velocity as he/she considers necessary to make this final transition (e.g., traffic, weather, road conditions, etc.). This should include the option of coming to a full stop before proceeding.

(2) The transfer of control should be made under completely stable and steady conditions.

(3) Steering control may be transferred before longitudinal control if necessary. However, we do not see a safe scenario when longitudinal control transfer precedes steering control transfer.

(4) Whenever and wherever control transfer takes place, the AHS should be capable of directing the vehicle to a stopped condition at a safe location if the expected control transfer is not completed.

(5) AHS control should never be relinquished under an assumption that manual control will be exercised. Control transfer should only be authorized as a result of overt action by the operator. The bias of the AHS should be to maintain control and take the vehicle to the safe place referenced above.

(6) Automatic exit into an uncontrolled environment is sufficiently problematical that it should not be considered. This specifically applies to exiting, under automatic control, into a parallel, mixed traffic and uncontrolled facility.

(7) If control transfer takes place on the AHS lane (that is, the exit maneuver is under manual control), we have a maximum disruption situation. This vehicle now has the characteristics of a rogue and must be re-engaged as a rogue or an AHS compliant vehicle.

(8) If automatic ejection of closely spaced vehicles is employed to minimize disruption, the exit facility **and** control-ability must be sufficiently long to allow the disengagement off -line.

By considering these conflicting requirements, a concept for a model exit scenario emerges. To minimized disruptions to line vehicles, it is desirable to exit the AHS lane under full control. This exit facility would be an AHS subsystem, dedicated to the transition of vehicle and operator to a manual control while still on a controlled facility. This exit lane would be physically separated from the AHS lane (after the exit zone) to prohibit re-entry. It would also be separated from the adjacent manual traffic operation. After a vehicle enters this lane, it is still under AHS control, and will continue to be under AHS control to a safe bull pen if the operator does not seize control.

Exit transition is complicated when the exiting into a mixed traffic transition lane. As indicated above. we consider this option to be viable only if it is accomplished under full <u>manual</u> control. The full process of disengagement and re-engagement must be performed on-line. Also, there must be some provision to re-establish AHS control if the vehicle, after the transfer to manual control decides not to exit.

A particularly difficult exit transition occurs at the end of a segment of automated roadway. If all vehicles are forced to exit the AHS via an exit facility, severe requirements are imposed to handle the capacity of the line.

If the vehicles simply leave the zone of automation and continue under manual control, all transitions to manual control must be made on-line, before the last option for automatic vehicle management (to a safe area).

6. Collision Threat Intervention Strategies

Figure 10 illustrates the general concept of intervention. As indicated previously, the intent of a fault intervention strategy is to create a torturous path for a fault path to reach a collision. In fault tree representations, intervention actions are introduced as strategically placed “AND” gates:

(1) The first is positioned such that it can intervene in fault paths involving an operations under an invalid engagement strategy, by employing strategies for urgent separation modification to achieve a safe separation before a worst case is imposed on a vehicle.

(2) The second is positioned to intervene in extremis situations, where a collision is imminent and operational strategies are desired to minimize the collision transfer to following vehicles by employing “extremis actions” to reduce the extent and severity of the collision transfer effects.

6.1 Urgent Separation Modification Strategies

The collision threat from an invalid engagement is greater if the engagement involves small separations. Therefore, the actions taken to correct an invalid engagement are always directed toward increasing separation: the most powerful tool to minimize collision occurrence and extent is distance --- specifically the separation before the initial collision inducing event. To establish distance, this translates to time --- time to establish a more tolerant separation before the potential collision is induced. In every collision, the collision does not occur until a worst case maneuver is executed. Even seconds before a worst case maneuver is executed is valuable time available to adjust separation to more accommodating values.

To accomplish a separation correction prior to a collision, four elements are required, as illustrated previously in Figure 10:

(1) Intelligence that an invalid engagementexists, before it evidences itself in an extremis situation.

(2) Motivation to affect the desired changes required. An obvious motivation could be some signal suggesting a bad engagement. However, this is not a preferred method --- it is not fail safe. As will be discussed later, a preferred method is to consider any engagement to be “normally open, held closed”, with the holding force being evidence that the key conditions of validity for that engagement exist.

(3) Urgent response capability to take appropriate action with urgency. Urgent tactics can be employed to enable us to move away from the affected vehicle quickly.

(4) Time ties it all together, and is an uncontrolled variable. This underscores the need to take all accommodating actions with a sense of urgency. This translates into preparation to take action. Therefore, urgent action possibilities should be anticipated by the separation manager before they are required, based on the constraints imposed by the existing engagement. Contingency plans should be available at all times, with due consideration of existing engagement obligations.

The requirements for separation correction intervention are dependent on the reason the engagement is invalid. This directly influences the type of intelligence required under (1) above. In the sections that follow, these differing requirements will be discussed.

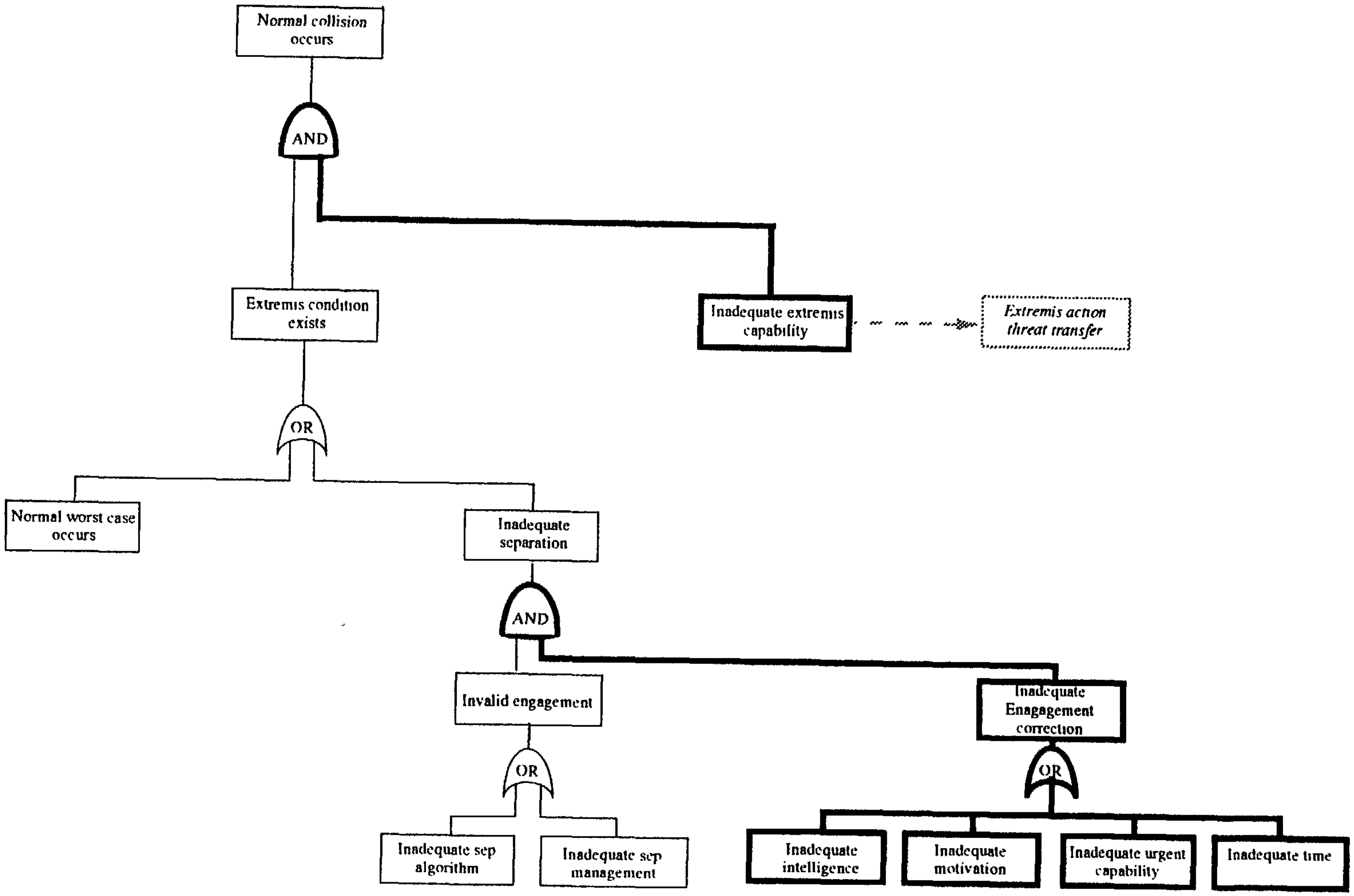

Figure 10. General Fault Path Identifying Intervention Options and Components

6.1.1 Normal Collision Threat Intervention

Normal collision threats reflect fundamental flaws in the fidelity of the separation rule to adequately represent the real separation requirements or in the fundamental capability of the separation manager to properly assess the situation and make the correct decision for the selection of the proper algorithm as well as its calibration.

If the inadequate separation is a result of these fundamental flaws, the ability to provide intervention at a corrective level is probably non-existent, or, at best, of limited value. We would probably have no basis to question the engagement validity: the same flawed capabilities would be judging the wisdom of a previous decision. We probably would not be aware that the separation was inadequate until it was demonstrated in a collision --- the same problem we face in the current highway system.

These basic flaws, however, are not the only factors that may enable an invalid engagement. A more likely fault path involves the failure to respond to situation changes, during a trip, that degrade control-ability (intrinsic threats). This can result in the invalidation of an initially valid separation strategy.

In any event, the decisions leading to the selection of the appropriate engagement rule as well as its calibration to be based on an hypothesis regarding the situation as viewed by the separation manager. The validity of the engagement depends on the validity of the hypothesis.

From the standpoint of corrective intervention, a false hypothesis is assumed, and the real fault is continuing to operate under this false hypothesis. To initiate an intervention action, the separation manager must be aware that an invalid engagement exists. This requires the separation manager to have the capability to constantly challenge its own wisdom regarding previous decisions. This means that an existing separation strategy is to be considered as “momentary’, based on the best information available at the time, and that the process of establishing and calibrating an engagement is a continuing process --- continually monitoring relevant data and re-executing the decision algorithm. Any engagement should be considered “normally open, held closed” with the holding force being represented by constant re-affirmation of the validity of the selected engagement strategy. This should be an integral part of the separations manager’s function.

Another source is information that suggests the separation manager is not completely healthy. Such information would render any previous decision suspect. Because of the critical role played by the separation manager, constant self health appraisals are essential, coupled with appropriate strategies for safely managing the vehicle if this health is impaired.

Because an engagement strategy assigns responsibilities to the vehicles at each end, a third source of information would be the observed behavior of the other vehicle sharing the engagement strategy. If any actions are observed that suggest that this vehicle is not playing according to the rules we believe to be in effect, we have a clear indicator of an invalid engagement.

6.1.2 Malfunction-induced Collision Threat Intervention

A malfunction is any occurrence that destroys the validity of an existing valid engagement. Therefore, the malfunction exposure of a specific vehicle is derived from itself and the vehicles with which it is engaged, in both directions.The purpose of malfunction intervention is to accommodate these malfunctions before they result in a collision.

To facilitate an intervention to adjust a malfunction-induced invalid engagement, the separation manager must have information regarding the health of the engaged vehicle as well as its own health. Therefore, there is a need for sophisticated health monitoring capabilities of the functions critical to the validity of a particular engagement. The intelligence required is an indication that the engaged vehicle is healthy, implying the need for health information sharing. In a fail safe environment, this implies the need for wellness indicators as part of the “hold close” conditions of an engagement. It is not necessary to know the specific malfunction. Again, from a fail-safe perspective, any unhealthy indicator is reason to suspect an engagement problem.

Because of the different engagement strategies we consider are necessary to accommodate the range of conditions expected for an AHS, most malfunction situations can be safely engaged as a forward threat. In every situation analyzed, the failed vehicle could have been placed in another already existing threat category, with an already existing safe steady state engagement strategy. For example, a vehicle that loses brake suppression control device is the functional equivalent of a rogue vehicle and could be engaged as such without concern for the malfunction. A malfunction in one vehicle in an engaged pair invalidates that engagement, but not necessarily all engagements with that vehicle. If, before a collision, we could back away from the invalid engagement to one that tolerates the failed vehicle as another threat agent, no collision would result.

However, a malfunctioning vehicle can no longer be considered capable of any engagement with responsibility, it can never be a burdened vehicle. Therefore, its role relative to a forward vehicle changes from burdened to privileged. The lead vehicle now assumes the burden of collision avoidance: we have a rear engagement situation which, as discussed earlier, is a problematic situation. However, the problem is considered to be less than continuing operations under an invalid engagement rule, with no attempt to intervene.

Therefore, a part of a vehicle’s separation management capability should accommodate awareness of its potential malfunction exposure, and have appropriate escape plans selected and calibrated to as-is conditions, including any constraints imposed by the vehicles’s dual responsibilities.

6.1.3 Sudden Intrusion Collision Threat Intervention

The previous sections examined threat management implications from “engaged” threat agents; that is, threat agents acquired and engaged under some separation strategy, with **concern** being related to the validity of the initial engagement and engagements that may have been valid, but become invalid --- through inadequate management **of** intrinsic threats or a malfunction. The third collision potential arises from threats that cannot be engaged through normal engagement strategies. These threats result from the sudden appearance of a threat agent ahead of a vehicle at a distance that is less than that required to allow a normal engagement with that threat agent. Included are leading vehicles that we did not engage at a proper range for normal engagement; rogue vehicles that merge into an AHS lane; AHS vehicles under manual control for merging into the AHS lane; dropped objects, animals crossing the roadway; and accident spill-over from adjacent lanes.

In general, corrective intervention effectiveness depends on how far away the threat is detected. If it is detected close to the AHS vehicle, the situation may be immediate extremis. If detected further away, an urgent maneuver may be possible to avoid the collision or reduce its severity.

If the threat agent is a moving vehicle, there is a chance of using urgent maneuvers to arrive at an acceptable engagement. If the threat agent is not a moving vehicle, we are in an extremis situation at the time it is detected. In either case, the importance of reactive control options is not diminished

For non-vehicle threat agents, however, most of the avoidance capability must be placed on eliminating the sudden intrusion threat. If the threat is present, collision is likely and focus should be shifted to transferred threat management.

6.1.4 Transferred Threat Collision Intervention

Any engagement between two vehicles involves trust that each vehicle will execute its responsibilities according to the roles they play regarding that engagement. A malfunction, as presented in a previous section, involves the loss of this trust. However, an engagement also involves another trust: trust that each vehicle in the engaged pair will execute their <u>other</u> roles adequately. For example, when we close to a few feet to another vehicle, we are also trusting that vehicle to maintain adequate and safe relationships with vehicles or objects in front of it. The smaller the separation, the more significant this implied trust becomes. In placing this trust, a burdened vehicle is expanding the role of its engaged privileged vehicle.

Again, the concept of early intelligence is also a key ingredient of effective corrective action intervention actions. Basically this implies the need for a vehicle to be aware of the situation its engaged privileged vehicle is facing, and all corrective intervention options available for influencing a specific threat situation they are facing is equally valuable for following vehicles. For example, a vehicle could gain advantage from knowing the health of the vehicle two positions ahead of it, as this will influence the likelihood that the vehicle immediately ahead will be involved in a collision. Such knowledge could serve to initiate corrective intervention actions to avoid any secondary involvement.

Similarly, relying on a leading vehicle to safely function as the “eyes” for a following vehicle is not safe. It would be better to see the road ahead of the immediate leading vehicle to verify this trust and initiate corrective action. In addition to protecting itself, a vehicle recognizes that its safety is to a great extent, dependent in the safety of the forward engaged vehicle. Any intelligence about the latter can be factored into a separation strategy in a timely manner.

6.2 Extremis Situation Intervention Strategies

An extremis situation exists whenever a worst case maneuver is executed by a privileged vehicle and the separation to the engaged burdened vehicle is insufficient to permit collision avoidance under its current braking authority. In general, extremis actions involve extraordinary actions to enhance the ability of the burdened vehicle to alter its stopping trajectory sufficiently to avoid the collision or reduce its severity. In an extremis situation, this is the only option available. As noted earlier, all collision avoidance capability is restricted to straight line maneuvers. We have not considered lane change as a viable avoidance option in a design sense. We feel that the sudden lane change requirements, if lane change was possible, would constitute a sudden intrusion threat in the receiving lane. Seeking the shoulder should be an option for the aware driver, but we can’t consider this as a fundamental capability for extremis actions.

There are three fundamental approaches for extremis reactions by an AHS vehicles:

(1) Extremis broadcasts: triggered by the recognition of an extremis situation by one vehicle and broadcast to provide information to following vehicles, prompting their extremis capability;

(2) Coordinated braking: a by product of extremis broadcast, enabling all vehicles to execute extremis actions without the problems of stacked delays that are symptomatic of reacting to lead vehicle motions; and

(3) Extremis braking: applying the full braking capability of the following vehicles.

The first two options are possible for an AHS vehicle engaged under any of the candidate engagement strategies. The last option is , however, available only for platoon engagements. If the vehicle is currently engaged with full capability allowed (e.g., an AHS compliant engagement), no further braking capability exists, and this extremis action option disappears.

However, increasing braking capability is not an action to be taken lightly. Unleashing full braking capability to a vehicle engaged under an assumption of constrained braking rate violates the trust of that engagement and constitutes a threat to following vehicle This conflict potential suggests, rightfully so, that an appropriate extremis action should have the goal of minimizing some overall collision severity measure; considering the number of vehicles involved and the severity of the collisions involved. Therefore, the separation manager should foresee these implications based on the current engagement and have available an appropriate extremis strategy to accommodate an extremis situation resulting from an invalid engagement.

In the situations analyzed in the following sections, the implications of these extremis actions were investigated for selected malfunction-induce collisions and sudden intrusion collisions. In these analyses, we were particularly interested in the more intimate engagement strategies: loose platoons and tight platoons. These engagement strategies have the common characteristic of operating under a suppressed capability. As a result, they are prone to potentially severe failure mode that is not characteristic of other engagement strategies; failures that lead to a vehicle braking too fast --- setting up a more severe worst case situation for all following vehicles.

6.2.1 Collision Response Characteristics

In developing the collision response, the following assumptions were made regarding the multiple collision effects:

(1) A collision “pack” is formed by the colliding vehicles. This pack stays together. As other vehicles collide with this pack, they add to its mass. All vehicles have the same mass.

(2) Between collisions, this pack continues movement under a deceleration of 1 .0g’ s.

(3) An individual collision event (one collision) is completed in 50 milli-seconds.

(4) All individual collision events occur in a straight-line, i.e., front to rear, with no vehicle rotations.

(5) Vehicle crush is a linear function of the relative velocity of the colliding objects (Av). The conversion factor used is 1 foot of crush/20 fps Av. This crush was added to the initial vehicle separations as it represents additional distance available to a following vehicle to act before it collides with the pack.

(6) The maximum severity measure (AV of the colliding vehicle) was computed by allocating the collision velocity on the basis of the relative masses of the colliding vehicle and the pack.

6.2.2 Malfunction Induced Collision Transfer Effects

To assess the implications of employing extremis actions to minimize the collision transfer effects of malfunction induced collisions, 4 situations were analyzed:

Situation 1: Loose Platoon, Brake Suppression Control Failure.

The first situation simulates a condition where a vehicle suffers a malfunction in the brake suppression control device which sets up a situation where a leading vehicle stops too fast. This failure results in a vehicle having its maximum braking capability available --- in this situation assumed to be 1.2 g's (a maximum capable vehicle). This vehicle can no longer discharge its responsibility, as a privileged vehicle, to "present a consistent and predictable worst case maneuver" to a trailing vehicle. The loose platoon steady state conditions are as follows:

- Platoon speed = 60 mph
- Intra-platoon spacing = 26.4 ft
- Response time = 0.3 seconds
- Platoon regulated braking rate = 0.6g's

The collision event was initiated by a 1.2g stop by the leading vehicle. There was no knowledge of the malfunction until the the failed vehicle initiated brake application. The failed vehicle had the capability to detect this and to broadcast an "extremis" (collision imminent) alert to the following vehicles which had the effect of reducing their response time to lag the failed vehicle by only 0.1 seconds behind the second vehicle and to invoke perfectly coordinated braking among all vehicles following vehicle 2. The second vehicle still retained a delay of 0.3 seconds behind the failed vehicle.

Situation 2: Loose Platoon, Partial Brake Failure

The second simulated situation is a partial failure of a vehicle that reduces its braking capability by 50% --- from a loose platoon regulated value of 0.6g's to 0.3g's. This vehicle can no longer discharge its responsibility, as a burdened vehicle, to "keep clear" of the leading vehicle under the latter's worst case maneuver. The loose platoon steady state conditions are the same as those for situation 1, including the extremis broadcast and coordinated braking capabilities.

Situation 3: Tight Platoon, Brake Suppression Control Failure

This malfunction examines the same malfunction used in situation 1, except that the brake suppression control failure occurs on a vehicle in a tight platoon engagement. The tight platoon steady state conditions are as follows:

- Platoon speed = 60 mph

- Intra-platoon spacing = 4.4 ft
- Response time = 0.3 seconds
- Platoon regulated braking rate = 0.3g's

The same extremis broadcast and coordinated braking capabilities exist as existed for the loose platoon situations.

Situation 4: Loose Platoon, Brake Suppression Control Failure, Extremis Braking

This last situation examines a possible means to help alleviate the extensive chain collision exhibited in situation 3. This involves raising the suppression level to more nearly coincide with the available braking capacity; to be used only in extremis situations. This capability would remove the low braking rate which was the major contributor of the long chain collision in situation 3. Therefore, with this new capability, when vehicle 2 senses the extremis situation and broadcasts to the rest of the platoon, this changes the platoon constrained braking rate to a higher level, in this example to 0.6g’s.

Severity summary

The relative severity of the collision sequences discussed in the previous sections is shown in Figure 11. The ordinate values represent the collision severity in terms of the maximum change in velocity (AV) experienced by the colliding vehicle as it joins the collision “pack. The abscissa values represent the position of the colliding vehicles in the platoon prior to collision. These results seem to indicate the following:

(1) A given collision occurring with a small separation operating strategy involves more vehicles than are involved with a larger separation strategy.

(2) However, the relatively few vehicles involved with the larger separation strategy are subjected to a more severe collision than their direct counterparts in a small separation system.

(3) Subsequent participants in the collision, for small separation systems, see an increasingly severe collision, perhaps exceeding those of the vehicles involved in a larger separation system.

As a generalization, it appears that as we decrease separation, we increase the susceptibility to malfunctions that destroy the validity of an engagement. Furthermore, the more we control worst case ability of vehicles, a necessary condition to support small separation strategies, the more susceptible we are to malfunctions that alter that ability.

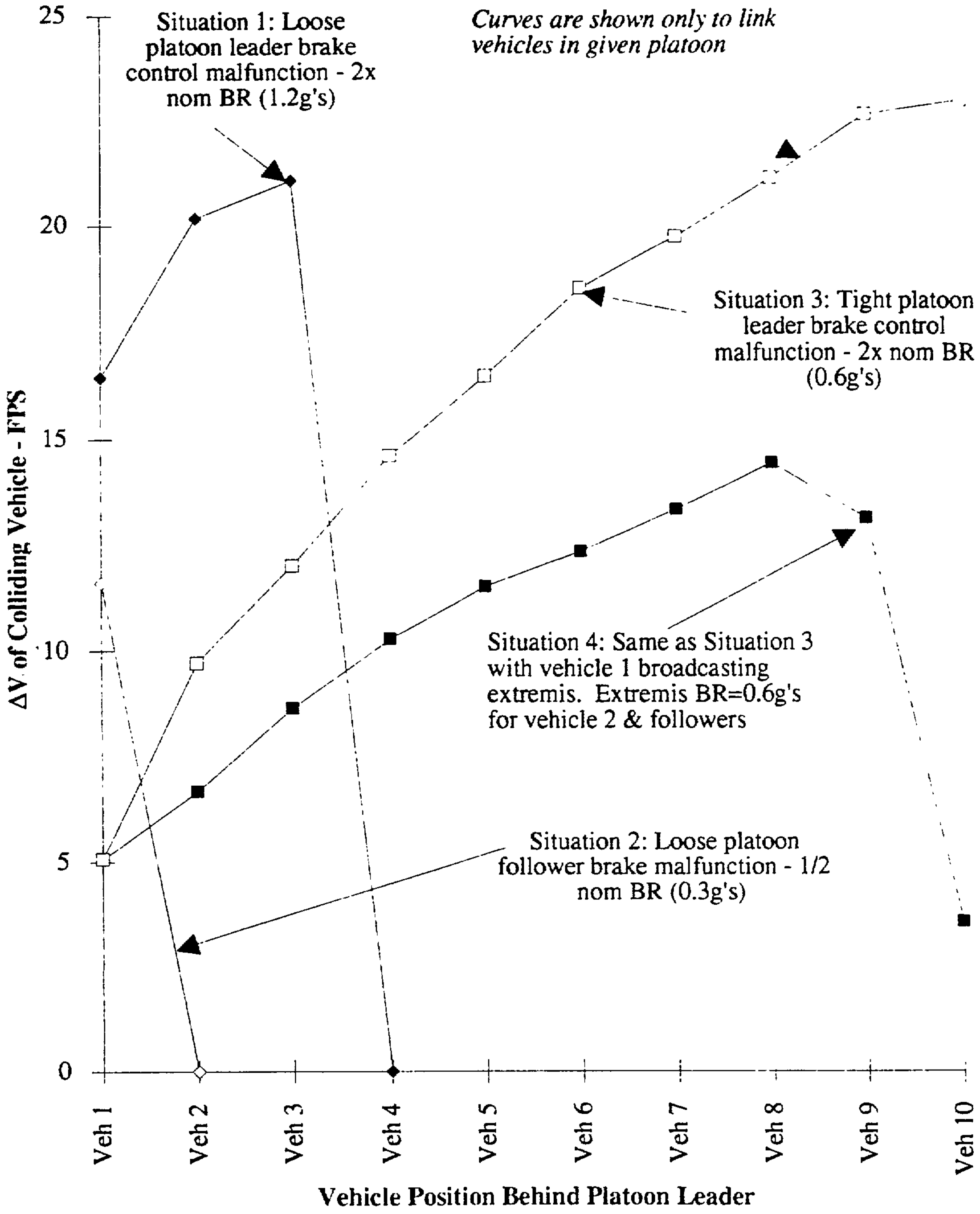

Figure 11. Maximum ΔV for Colliding Vehicle for Selected Malfunction Situations

6.2.3 Sudden Intrusion Collision Transfer Effects

The situations discussed above illustrated the threat transfer effects of an initial collision between two engaged vehicles as a result of a malfunction in one of these vehicles. A more difficult situation to control is the effect of encounters with a sudden intrusion. We analyzed several sudden intrusion situations to examine the susceptibility of platoon engagements to sudden intrusion threats; and provide some insight into extremis action influences. The analysis procedure used was the same as that used above: the same collision characteristics of pack formation and behavior, allowance for vehicle crush, etc.

The specific analyses presented all deal with the same threat situation, characterized as the intrusion into an AHS lane by a rogue vehicle, at line speed, 30 ft ahead of the platoon leader. Immediately upon entry, this vehicle executes a maximum capable stopping maneuver (1.2 g's). Line speed for all situations is 60 mph. Six situations are presented. The first two involve a loose platoon engagement and illustrate the influence of extremis broadcast and coordinated braking. The next two repeat these situation for a tight platoon engagement, with the added enhancement of enabling an extremis braking capability. The last two address a slight variant of these latter situations.

Situation 1 - Loose platoon, No Coordinated Braking

In this situation, a loose platoon, with an intra-platoon spacing of 26.4 ft and a suppressed braking rate of 0.7 g's encounters the intruding threat agent. The platoon does not have coordinated braking capability (all delays are additive). Also, because the nominal suppressed braking rate is the lower bound of vehicle capability, it was assumed that no extremis braking capability was available.

Situation 2 - Loose Platoon, Coordinated Braking

This situation duplicates situation 1 with the addition of extremis broadcasting to enable coordinated braking. Again, no extremis braking rate was assumed to be available. The algorithm for coordinated braking is the same as that used in used above in the malfunction examples: the lead vehicle senses extremis and broadcasts the extremis message to all followers at 0.1 seconds after it senses the situation. All following vehicle brake in unison with a delay relative to the leader of 0.1 seconds.

Situation 3 - Tight Platoon, Extremis Braking, Not Coordinated

This situation duplicates situation 1 for a tight platoon with the added feature of extremis broadcast to enable an extremis braking rate, but not coordinated braking. The nominal intra-platoon spacing is 4.4 ft and the nominal suppressed braking rate of the platoon leader is 0.3 g's. The extremis braking rate is assumed to be 0.7 g's.

Situation 4 - Tight Platoon, Extremis Braking, Coordinated

This situation duplicates situation 3 with the addition of coordinated braking.

Situation 5 - Tight Platoon, Leader Vision Failure

In this variant of situation 4, the leader fails to "see" the intruder and continues at full line velocity to collision. The second vehicle infers extremis from this initial collision and broadcasts to enable coordinated braking at the extremis rate.

Situation 6 - Tight Platoon, Leader Vision Failure, Look-ahead Option

This situation duplicates situation 5 with an added capability of the second vehicle to "look ahead" and see the intruder and act accordingly. This vehicle, independent of the leader vehicle actions. determines the extremis situation and is the source of an extremis broadcast, enabling all of its followers to brake in unison at the extremis rate. An additional enhancement was also used in this situation: all vehicles act in unison with the second vehicle. There is no additional delay.

Severity Summary

The relative severity of the collision situations analyzed above is shown in Figure 12. As in the malfunction induced collision severity discussed above, the severity measure is the maximum AV endured by the colliding vehicle. These data illustrate the following, which are totally consistent with the results of the malfunction induced collision investigation:

1. The rather obvious observation that, facing the same threat conditions, a tight platoon will involve more vehicles in the collision event than looser strategies. Again, this points to distance as our most important weapon for collision avoidance.

2. However, the relatively few vehicles involved with the larger separation strategy are subjected to a more severe collision than their direct counterparts in a small separation system.

3. Subsequent participants in the collision, for small separation systems, see an increasingly severe collision, perhaps exceeding those of the vehicles involved in a larger separation system.

In all cases the influence of extremis actions was dramatic, underscoring our belief that the separation management function must have these types of action options available and calibrated for the current conditions and engagement strategy.

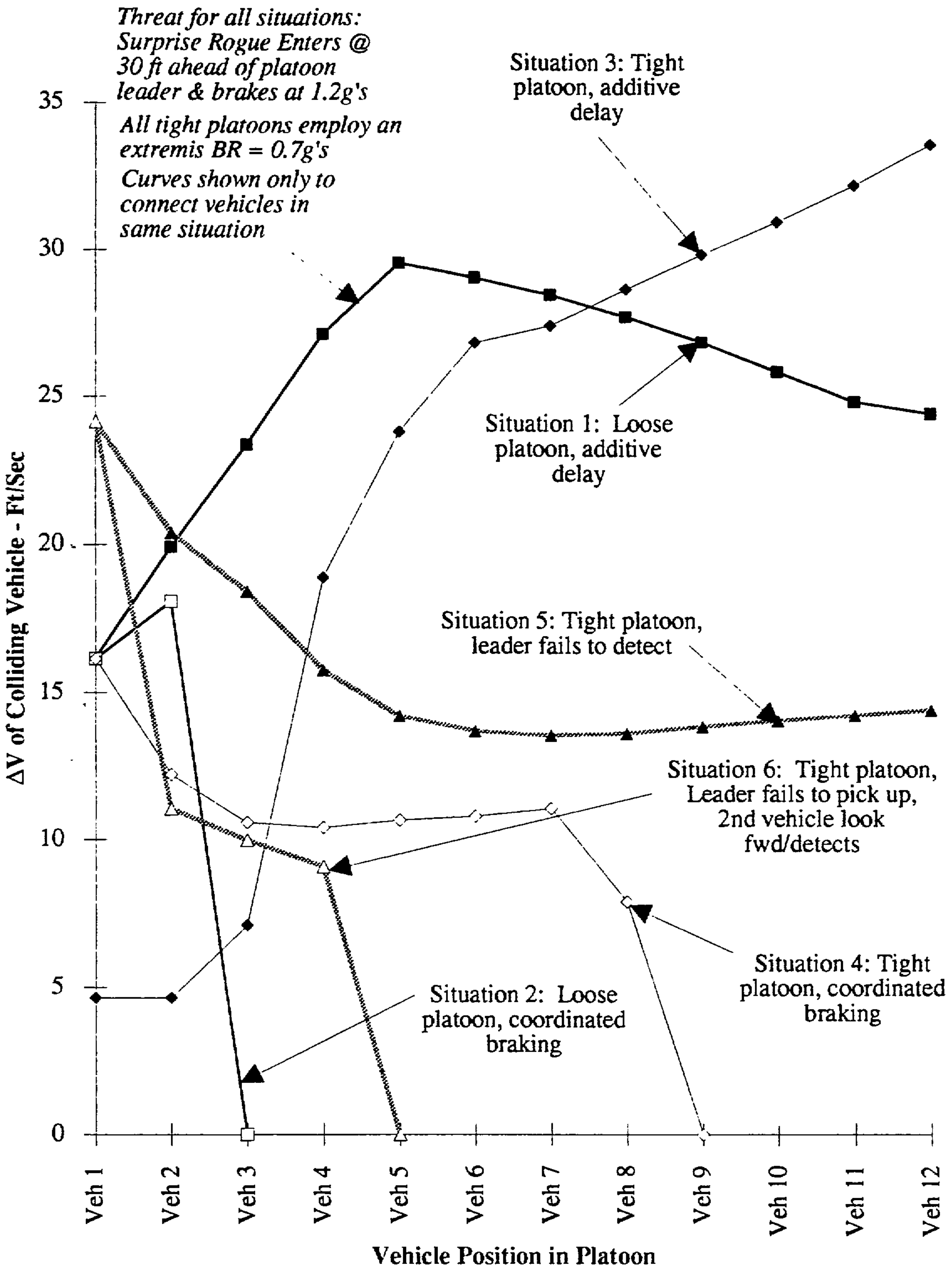

Figure 12 Maximum ΔV for Colliding Vehicle for Selected Sudden Intrusion Situations

7. Separation Manager Implications

Our analysis addressed concerns, implications, and requirements for an adequate separation manager function; periodically imputing capability and responsibility to its definition. These implicit and explicit concerns were generally focused on required capabilities to perform a function --- manage safe separation, under many different conditions.

As implied in previous sections, almost every separation management “problem” increases as we decrease vehicle separation. This is qualitatively illustrated in Figure 13. If there was no demand for a high level of roadway lane capacity, the separation manager would have a strong bias to large separations. The demand for capacity, however, is always seeking small separations. If there was no demand for a high level of safety, this “capacity manager” would have a strong bias toward small values of separation.

These different biases illustrate the classic adversarial relationship between safety demands and capacity demands. Satisfaction of both views requires negotiation. In this negotiation, safety should never be the loser. Further, it would be out of character for the safety manager to initiate a move toward operations with smaller separations. It defers to the capacity manager for this motivation. In return, the safety manager reserves the right and the responsibility to establish the conditions under which this operation can be permitted without compromising the standards of safety. Furthermore, the separation manager reserves the right to seek a more relaxed separation if the demand for capacity is removed.

Throughout this investigation, an image of a concept of operations evolved that provides the functional capabilities we believe are necessary to enable the demand for capacity and the demand for safety to coexist. This section formalizes this image, using elements of operational concepts were borrowed from other transportation modes, such as:

- Concepts of “fail-safe”.
- Concepts of “authority, agreement, and permission” to coordinate vehicle movements relative to one another.
- Concepts of “privilege” and “burden” to establish relative responsibility for collision avoidance.
- Concepts of “restrictive state” management to lessen the possibility that vehicles will establish engagements that are not safe.

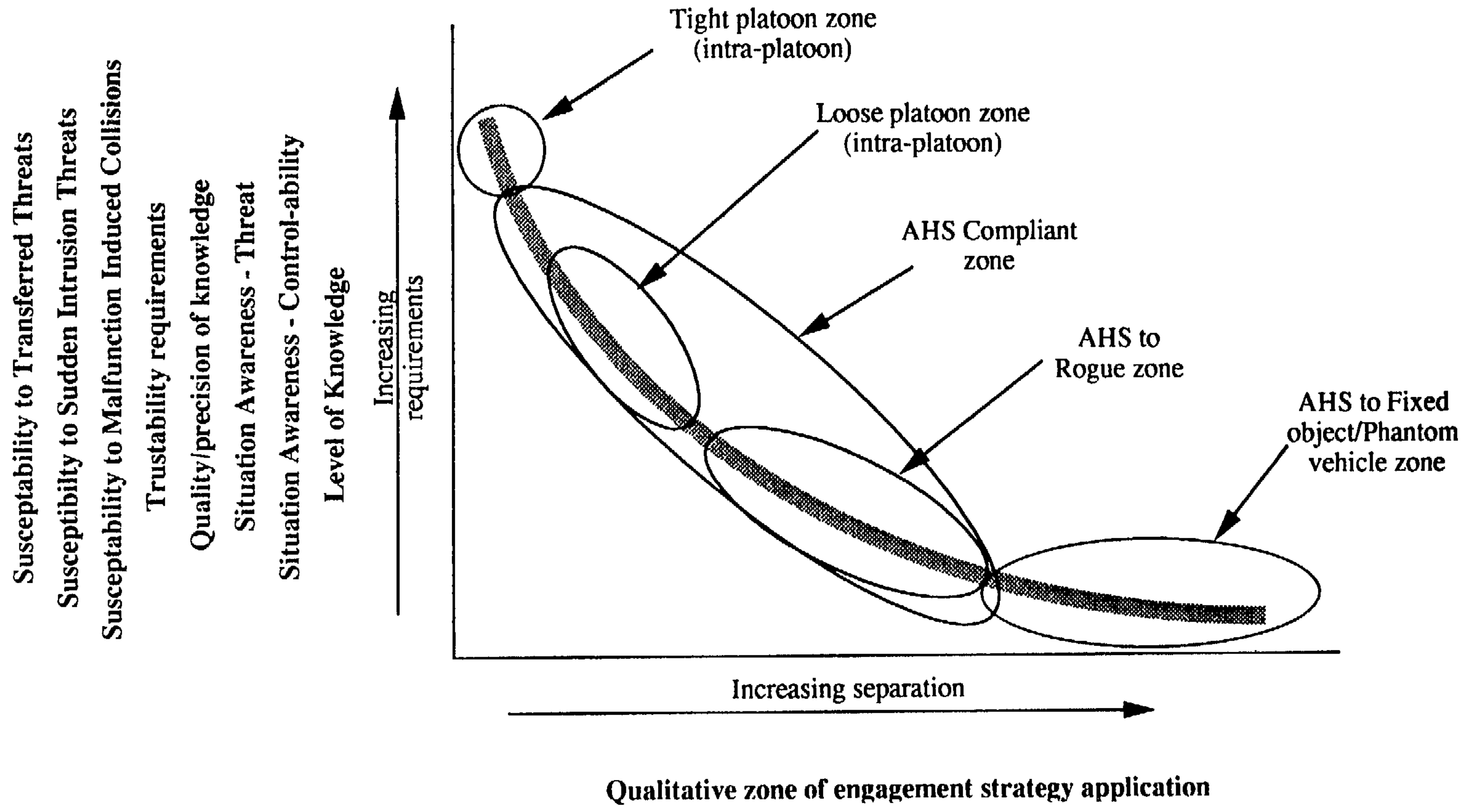

Figure 13. Qualitative relationship between Selected Engagement Strategies and Separation Control Complicating Factors

7.1 Conceptual Basis

As indicated earlier, we adapted a posture that all threat agents that may appear on an AHS lane must be addressed by the AHS. System safety concepts allow three methods of treatment:

(1) Threat engagement: a strategy for maintaining separation between an AHS vehicle and other threat agents on the roadway;

(2) threat exclusion: a strategy for eliminating the need for engagement by controlling access to the AHS lane; and,

(3) threat acceptance: a considered decision that some threats are simply not reasonably controllable by exclusion or engagement (e.g., the bullet, the 747, and the bowling ball). This option is reserved for very low probability threat situations.

This investigation focused on the first two options: engage or exclude. Unfortunately, the relationship between these is circular:

- If a threat cannot be safely engaged, it must be absolutely excluded; and,
- if a threat cannot be absolutely excluded, it must be safely engaged.

A fail-safe perspective resolves this logic: we assume that exclusion techniques will not be 100% effective. Therefore, strategies must be developed to safely engage all threats that approach the boundary of an AHS. This stance does not diminish the desirability and benefits of exclusion; but it does remove the demand for absolute exclusion as a condition of AHS safety.

In addition to this fail-safe consideration, two additional factors influence our position:

(1) Even if the exclusion provisions were 100% effective. conditions can change on-line, by a malfunction (real or perceived) or other means; and

(2) Even if the above line changes did not occur, multiple engagement strategies must exist to manage, for example, transition maneuvers or intra-platoon spacing as opposed to inter-platoon spacing.

As a result, five engagement strategies were developed, based primarily on the characteristics of the threat agent to which an AHS vehicle may be exposed. It is the role of the separation manager to apply these strategies as appropriate. To accomplish this, the separation manager uses the same principles of exclusion used for controlling access to the AHS --- except in this situation, exclusion is used to control access to engagement strategies. Figure 14 is a schematic diagram illustrating this concept. The top illustrates the exclusion applied at the boundary of an AHS. At the entry to each lower level, all vehicles that do not satisfy the conditions required to safely participate in the engagements at the next lower level are restricted from passing to that level.

This schematic is ordered (top to bottom) to reflect increasing capability requirements. To generalize this concept, each engagement strategy can be thought of as a "restrictive state"; that is a vehicle is restricted from entering unless it possesses all the capabilities required to participate at that level. The term "restriction" can be considered a restriction on ability to closes on another vehicle, or, more generally, on another threat agent. Thus, the phrase "seek a more restrictive state" implies a move to an engagement level that is higher in the hierarchy depicted in Figure 14.

6.1.2 The use of "Authority" to Manage Engagements

The separation manager will not allow an engagement between two vehicles unless all the conditions required for this to be safe are fulfilled. If these conditions exist, the separation manager will "authorize" the maneuver to engage. "Authority" is the approval to move between restrictive states. This final authority actually has three components:

(1) The "as-is, where-is" capability of the vehicle. The real-time capability to adequately execute its responsibilities as a burdened vehicle in a particular engagement. We have termed this "functional" authority. (Functional authority determines how far down we can move in Figure 14, based on our own as-is capability to discharge the responsibilities of a burdened vehicle.)

(2) Authority restrictions imposed by a system-level operations supervisory function. For example, such limits may be imposed because of traffic problems elsewhere in the system or weather conditions that suggest more restrictive states are in order. There may also be conditions for minimum capabilities. For example, during the rush hours, it may be desirable to operate at maximum lane density --- tight platoon engagements. Establishing this requirement would invoke controls at the AHS boundary to exclude all vehicles not capable of participating in this restrictive state. We have termed authority criteria generated by a system function "ruling" authority.

(3) The final, and most important authority component is permission from the privileged vehicle. A burdened vehicle cannot autonomously change the rules under which it and its paired privileged vehicle. The privileged vehicle may have to adjust its relationship to the vehicle ahead of it, because of its obligations as a burdened vehicle in that relationship. Furthermore, platoon engagements may require the privileged vehicle to adjust its capability (e.g., engage brake suppression) before it can allow the engagement Therefore, before a privileged vehicle can grant permission for a follower to close, it has certain housekeeping chores that must be completed prior to allowing the following vehicle to close. We have termed this "conditional" authority.

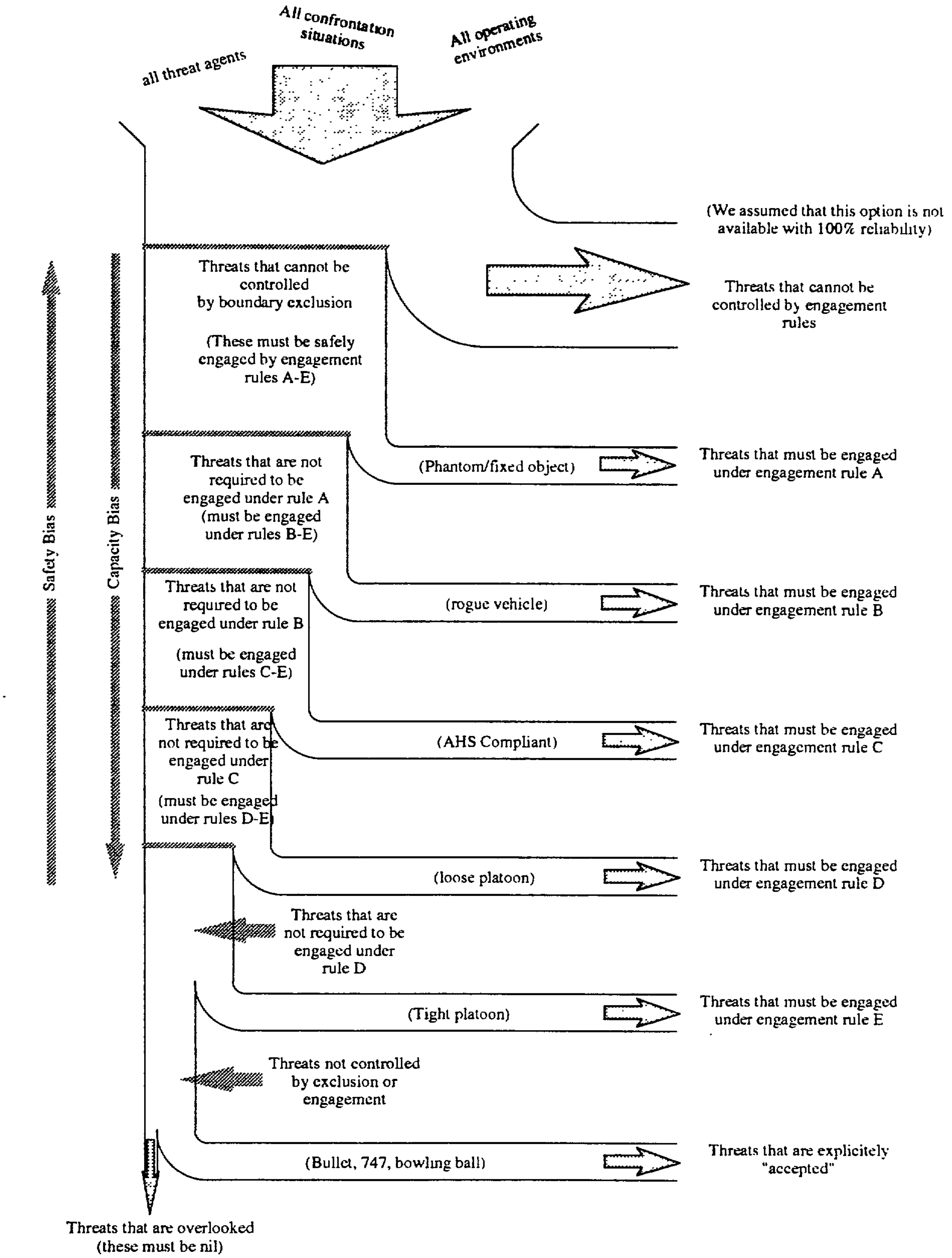

Figure 14. Threat Control Flow Analogy

Authority is granted under exacting conditions that indicate that both vehicles are capable of participation. Furthermore, this authority is granted for a very short period of time, after which the separation manager will seek a more restrictive state --- unless the authority is re-validated. This represents the ‘normally open, held closed” concept of engagement referred to in earlier sections of this report. The “holding force” is authority. If any change in condition results in a non-affirmation of authority, it is assumed it is withdrawn and the trailing vehicle seeks a more restrictive state.

A perhaps subtle implication of the process illustrated in Figure 14 is that functional authority has a “cumulative” attribute: as we move down through the restrictive levels, additional capabilities are required. This means that a vehicle that is capable of operating in a specified restrictive state must also be capable of operating at all more restrictive states. If it is not, it would have been restricted at the level corresponding to this higher restriction. This may not appear significant, but it is fundamental to the concept of operations discussed in the next section.

7.2 Procedural Implications

A concept of operations of the separation manager, for managing the navigation among these various restrictive states is represented by the logic diagram in Figure 15. This figure illustrates a sequential process of engaging threats (underscoring the need for “sequential” capability referred to above). This process is very deliberate; authorizing closures to less restrictive states only when the required conditions are satisfied. This -implies a movement between sequential steady states (no “leapfrogging”). There are a number of reasons why this approach would be desirable, not the least of which is to allow a resolution of one transition maneuver and the establishment of the next before the latter is initiated.

This figure illustrates the feedback loops for maintaining engagement authority, challenging the wisdom of a particular engagement, and invoking disengagement actions. In addition, there is the suggestion that we always begin engagement at the maximum range possible. If there is no threat agent ahead of us, this would be the separation required to engage the “phantom” vehicle (assuming, of course, that at this range we don’t overlook an intermediate threat). When real vehicles enter our view, the process of engaging is initiated --- the final steady state condition is established together with an appropriate transition strategy and the point of initiation. Authority may be granted at this time, however, if the engagement is to far off, this would only be provisional, subject to validation prior to the transition maneuver. It would however, establish communication and notify the lead vehicle that the follower is aware of it presence and what its intentions are. This may be of little consequence in an urban environment because the likelihood of engaging a phantom probably only exist for the first vehicle on the system. In rural application, this forward view must be reset every time an engaged vehicle leaves the lane, in light traffic conditions.

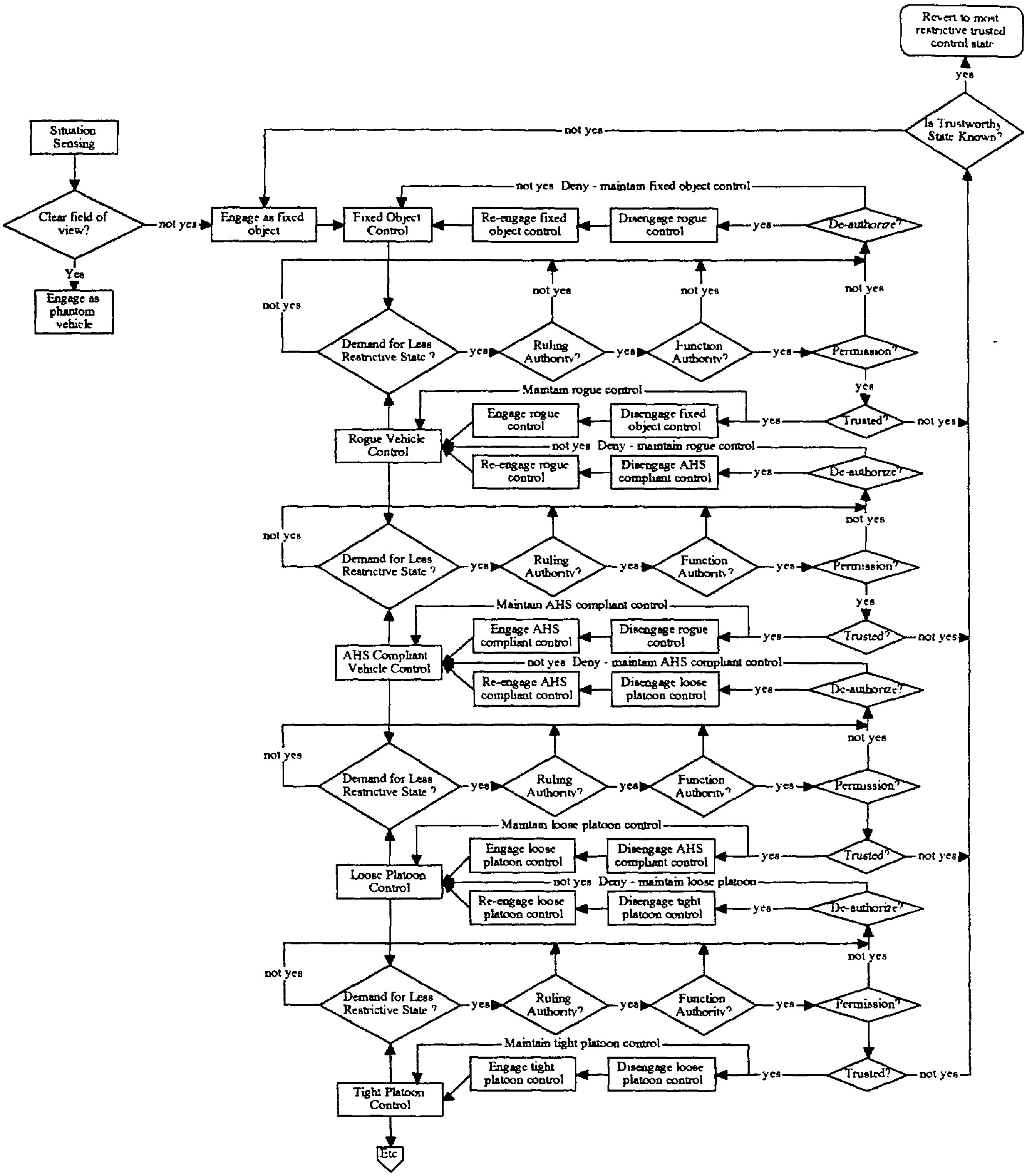

Figure 15. Concept of Operation for Separation Management

With this concept, vehicle check-in takes on additional duties. In addition to determining the health of a vehicle, additional data must be generated to initialize the separation manager:

- The "as-is, where-is" functional authority of the vehicle.
- Factoring in any ruling authority limits that may be in existence at the time.
- Calibrating the control-ability of the vehicle (stopping characteristics) as they exist at that time, factoring in roadway calibration factors if they are used.
- Establishing and calibrating the initial engagement rule to be used to manage the acceleration and merge operations. This process essentially "turns on" the automated capability for that vehicle.

Others exist, but these serve to illustrate the role of check-in as an integral part of separation management. These functions may be performed by the vehicle-based separation manager, but they are still allocated to the check-in process.

7.3 Accommodation of Operator Input

While an AHS must be capable of transporting a vehicle to an absolutely safe state, without any operator intervention, there may be conditions where operator input is desired or necessary. We did not examine the human factors issues associated with operator intervention actions. However, we believe there are at least five situations where it could be effectively utilized within the concepts of authority discussed above:

1. Operator attitude adiustment. There may be some cases where an operator wishes to disengage to a more restrictive state. This may be a result of a perceived malfunction or perhaps simply because small separations between vehicles is no longer comfortable. Some capability to allow the operator to become another signal to the separation manager, tantamount to declaring the existing engagement invalid, could cause the separation manager to seek a more restrictive state. This would utilize all normally functioning separation controls. Therefore, this operation would be accommodated under full control.

2. Conflict resolution. There may be situations where the sensing system may not be definite in identifying threat agents (animals, e.g.). The AHS will assume the absolute worst option (e.g., a fixed object). If there was an ability to involve the driver in this decision, by some query, these conflicts may be resolved to a more appropriate worst case assumption.

3. Threat situation intervention. This is a capability to notify the separation manager of an impending dangerous situation. An operator may see forward situations developing (several vehicles forward, e.g.) and should have the capability to alert the vehicle control

system. This would be handled through the separation manager’s urgent intervention capabilities (which have been established and calibrated, as discussed previously).

4. Extremis alert. This is an extension of (3) above. There should be the capability to initiate a vehicle extremis intervention action if, for some reason, its normal sensing fails to sense the extremis situation. This would activate the normal extremis actions from the current state. This is potentially very problematical because of the possibility of false action or unwarranted panic reactions. An extremis action is itself a likely collision inducing event for following vehicles. This is tolerable if a real extremis situation exists. If not, however, the consequences are clear. We feel strongly that this capability should be present, but are unclear on ways to control it to real extremis situations, in a fail safe design.

5. Extremis takeover. We do not advocate the AHS to ever force a manual takeover as an extremis intervention action. However, we feel it is necessary to allow an extremis takeover. This will probably be demanded. The problem is the same as for extremis alert --- its use when it is not warranted and its potential collision inducing effects.

8. Findings and Conclusions

While this paper has highlighted many concerns regarding the ability of an AHS to achieve a collision free environment, in terms if in-line collisions, in the absence of . malfunctions. While there are significant technical challenges to be met, we do not consider any to be beyond resolution. The following summarize some of the more global concerns that have developed during this investigation:

1. An AHS vehicle must be capable of engaging all forms of threat agents that may appear on an AHS lane. These include other AHS vehicles. rogue vehicles (vehicles not known to under full AHS control), and non vehicles, including dropped loads, animals, people, etc.

2. A separation management function should be developed to handle the decision making function for steady state separations, transition maneuvers, urgent fault intervention maneuvers, and extremis maneuvers.

3. The concepts of managing engagement through authority, fail-safe procedures, and privilege/burden relationships appear to be applicable to AHS operations and should be considered for the separation manager,

4. From our simple dynamic models, it appears that as we move toward small separation operations (tight platoons), the susceptibility to malfunctions and transferred collisions increases. Chain collisions will be difficult to prevent, without prevention of the initial collision.

5. Small separation operations require the maximum capabilities in separation management. We are not fully convinced that separations on the order of a few feet can be supported over the full range of motions and worst case expectations of an AHS. It appears that brake suppression devices, to limit worst case maneuvers, as well as capabilities of coordinated braking and extremely small response time will be required. We suspect that there will be some proof of concept work in these areas. We further feel that extensive simulations will be required to test the validity of small separation concepts over the full duty cycles expected.

6. AHS operations will require a level of situation awareness that far exceeds the implied requirements of current AHS concepts. Threat detection and definition, control-ability in real time, detection of intrinsic threats, merging vehicle awareness, rear visibility --- we suspect that a considerable amount of proof of concept work will be required in the entire arena of sensing and decision processes to adequately assess the situation to be controlled.

7. A corollary to situation awareness is the communications required to adequately establish and maintain a valid engagement. There is one-on-one communications to establish agreement and continually verify validity. How will a vehicle verify that it is talking to the right vehicle. We have had a number of marine casualties because authority and agreement had been reached between the wrong vessels. How can we control this? Similarly, if extremis or malfunction broadcast methods are used to trigger intervention actions, how do we know which vehicles should be notified? How do we limit a broadcast to these vehicles so that we don’t influence the entire system?

8. A number of concerns for the safe exiting of an AHS. We want to underscore our concern in this regard. We believe that this transition may be very difficult to ensure that the AHS does not eject a vehicle into an unmanageable situation.

Approaches to ITS Safety Evaluation: Discussion of Case Studies

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1. INTRODUCTION

Evaluating the safety of emerging technologies presents a number of challenges to the thinking, imagination, and resourcefulness of the safety research community. The four case studies discussed in this paper were presented in the context of an ITS America Workshop on ITS Safety Evaluations (May 1 & 2, 1995, Reston, VA). While these papers by Crompton, Leis, Perez, and Marsh differ in focus, they demonstrate some of the thinking and activity that is critical to increasing our understanding of ITS safety.

Evaluating even a given ITS design challenges our traditional understanding of safety measures and current methodologies used for testing (Dingus, Smiley, Ervin). Yet we need to apply ourselves to developing standards and guidelines for ITS not yet designed -or implemented. Further, some of these technologies are revolutionary and may impact the behavior of users in ways that have not been anticipated. Following are several themes which resonate with the case studies. Following the themes are short discussions of the case studies themselves.

- **Safety research and evaluation should he proactive as well as retrospective.** We cannot afford to "wait for the crash statistics". It is more constructive to continuously create and apply knowledge. It is particularly important to be able to **design for safety.** In order to design for safety, we must understand which design factors can potentially impact safety as well as the mechanisms for these impacts. As this ITS Safety Workshop has established, this is an especially exciting time in the area of driver/system interactions, in understanding how to measure safe driving and assessing the impact of ITS devices. Proactive evaluation, particularly field studies, assists in identifying data needs and identifying institutional barriers. Proactive evaluation is essential for determining the **appropriate scope of claimed safety benefits** for a particular technology.

- **Effective evaluations include critical thinking from the outset and are ongoing.** Critical, flexible thinking is required from the earliest stages of developing a proof of concept for a system and operationalizing research questions, through determining appropriate methodologies, apparatus, and models, and ultimately interpreting, applying, extending results and generating more questions.

As the case studies illustrate, the safety of emerging technologies can be evaluated conceptually, empirically, and analytically. Whatever the approach, it is necessary to understand how a specific system specifically works to achieve a particular potential safety benefit or disbenefit. Safety benefits may be achieved directly through technologies such as occupant protection (air bags) and collision avoidance (e.g. obstacle detection, ABS). Safety benefits may also be achieved indirectly by reducing exposure (e.g. navigation, congestion avoidance). If a technology is designed with no specific direct or indirect goal of improving safety (e.g. cellular phones), is there a disposition to safety in its design with the goal of no negative safety impacts? What are the ramifications of system failure? Will driving performance change? What are the societal/cultural contexts in which ITS technology will be deployed? There is, without doubt, greater complexity with more tradeoffs and unexpected effects than envisioned in the initial exuberance which accompanies the promise of emerging technologies and new applications. However, the evaluation process itself can deepen technical understanding .

- **ITS should be framed as person/machine systems.** It is particularly important in the safety arena to understand what role the human user or system operator plays; even when “the system will be completely automated”. The human is an actor in achieving the current level of transportation safety and is also at the heart of many safety errors. So, we need to understand safe driving as well as unsafe driving. ITS takes the current state as a point of comparison.

2. CASE STUDIES

1. “Collision Avoidance Systems: A European Perspective on Some Reliability Issues”, Michael J. Crompton

The focus of Michael Crompton’s paper is collision avoidance technology; his approach is safety assurance. Designers of collision avoidance systems (CAS) hope to directly achieve safety benefits by intervening in the driver’s control of a vehicle in order avoid crashes. Safety concerns are in the areas of vehicle control and system failure. In Europe, the safety evaluation of CAS has played a continuing role in the PROMETHEUS program. Crompton and his European colleagues have thought extensively about liability as well as technical issues. Of particular interest is role of technology development Guidelines in assuring reliable collision avoidance systems. This approach begins with a set of safety principles and recommends that a safety verification and validation plan be defined at the *outset* of a project. Safety is considered though the lifecycle of a CAS and a supporting safety analysis concept is offered for our consideration. Safety is conceptually integrated with the specification of requirements, design and implementation of the system and its subsystems, its testing, and operation, maintenance, and support. As such, this is an fine example of designing for safety and of the evaluation process supporting the design process.

While concentrating on the software reliability domain, Crompton acknowledges the importance of human factors engineering and recognizes that there are driver/vehicle interaction and performance questions. He also perceives that “real life” driving is complex and that current concepts of collision avoidance may be limited.

However, driver/vehicle interaction and performance evaluation should begin at the outset and continue throughout a system lifecycle. It requires the thought, effort, and resources given to software and hardware design, but is often more of an afterthought. CAS ought to be viewed as person/machine systems even if control shifts from the driver to the vehicle from time to time.

2. “Case Study: Precursor Safety Analysis of an Automated Highway System (AHS)“, Richard. D. Leis

Dick Leis has presented a dynamic conceptual model of an automated highway system (AHS). The benefit of automated highway systems, as defined by Leis, is increased traffic capacity without decreased convenience. There are no direct or indirect safety benefits proposed, rather there are a number of safety concerns. These include potential vulnerability to chain and transition collisions, system malfunction concerns and control issues. This paper is an example of modeling safety prior to design. Leis’s approach is the development of general system requirements based on a specified safety target. It is a detailed analysis with the assumptions clear and the scope delineated (in-line collisions only, no system malfunctions). Leis has identified issues and risks, particularly the threats vehicles might encounter. A specific design application is the management of separations between platooning vehicles. A result of the analysis is that preventing chain collisions rests on preventing the initial collisions. Leis proposes proof of concept work and simulations in technical areas such as sensing, decision and communications.

Although this undertaking is primarily an engineering analysis, Leis acknowledges that there are human factors issues associated with operator inputs. However, automatic highway systems need to be generally framed as person/machine systems which include drivers as well as system operators. It is apparent that the empirical evaluation of safety was outside of the scope of this particular work. It is essential that that empirical research and evaluation of driver/AHS system performance, safety, and acceptability be undertaken as early as possible as simulations and in controlled over-the-road studies. In many ways, the scenario presented by Leis is a best case scenario (in-line collisions only, no system malfunctions). The sooner AHS system concepts are evaluated in at least approximations to more realistic contexts, the sooner designers can address the safety challenges presented.

3. *"Case Study: The Safety Evaluation of TravTek"*,
William A. Perez

An Advanced Traveler Information System (ATIS) was the object of Bill Perez's safety evaluation (as well as two other workshop papers). ATIS technology such as the navigation, traffic information, and communication technology included in the TravTek system provide indirect rather than direct safety benefits. Safety concerns are centered on the potential for distraction and interference with driving. However, ATIS can have a disposition to safety through a design for safety approach in the driver system interface design. TravTek demonstrated what can be accomplished in utilizing an operational field test as a real world laboratory. TravTek was conceived as a person/machine system. As such, the the driver/system interface was designed to minimize attentional demands on the driver.

Safety was conceptualized at different levels of analysis and multiple field studies and analytical methods were used to evaluate the both the safety of the design and potential safety impacts in a fully deployed ATIS system. Perez describes several studies which were designed to collect a variety data which may pertain to safety. At the network level, incidents, crashes, traffic volume, road facility type data were collected. At the vehicle/driver level, numerous attention and driving performance measures allowed the comparison of information display types as well as the development of a taxonomy of safety-related measures such as near misses (Dingus). It was a goal of the TravTek evaluation program to increase understanding of the relationship between traditional crash metrics and measures of driving performance and attention. In addition. the INTEGRATION traffic model was extended to safety in order to extrapolate safety impacts at different levels of market penetration (Van Aerde): The model used data collected in the TravTek studies in an exploratory fashion to investigate the effects of road facility type and traffic volume as well as the in-vehicle device.

Perez has provided a number of concerns and recommendations for future directions. My voice is added to his in the following areas. There is a need for more baseline data; data of interest is often not in the standard databases. Methodological challenges also include small sample sizes and selection bias. Crashes can be rare; counts and simple descriptions of near misses or close calls may not be detailed enough to evaluate the design factors associated with in-vehicle devices. Continuing effort to integrate a variety of measures and to understand their relationship is needed. In addition, in my opinion, it would be useful to put risk in some meaningful perspective. Presenting a technology/device/display as "twice/half as safe" is difficult to evaluate and can lead to misconceptions. How much exposure would be required to experience a given increase or decrease? For example, would differences be observed if I drove normally every day for a year? Or would differences be observed if I drove normally every day for 100 years or drove around the world seven times? This would assist in pondering, along with the general public, meaningful risk.

4. " Case Study: Evaluation of Revolutionary Technology: Air Bags - Lessons Learned for ITS,

Joseph C. Marsh

Joe Marsh presents lessons learned from Ford's field evaluation of supplementary air bags and has illustrated his points with numerous examples from this project. Air bag technology is an example of providing direct safety benefits through occupant protection. Safety concerns are in the areas of occupant positioning, gas, and user misconceptions. Marsh emphasized the value of field evaluations in "real world" settings. Ford employed a variety of methods, some planned; some discovered. It is particularly important to conduct evaluations on trial fleets so that knowledge gained can be applied before the full deployment of a technology. A system should be evaluated comprehensively throughout the lifecycle and with an an eye to possible "side effects". These side effects or unexpected outcomes can be in the operation of the physical system and its components and/or in the user' behaviors. Of particular interest are two lessons learned: 1) misunder-standings about safety or safety technology can have effects and 2) A technology can be an engineering success, yet fail or human/social reasons. Users need to understand that air bags are supplementary to safety belts, not designed to be used alone.

Some of the challenges mentioned by Marsh were case investigations of air bag deployments which can be incomplete and difficult to interpret. There is also a need to overcome institutional barriers to data acquisition and the need to obtain supplemental crash data. Apparently, even though air bag technology has been deployed in growing market penetration, data concerning actual air bag deployment are very scarce. A challenge for the future, inspired by some of Marsh's examples, is the need to develop and/or utilize methods of capturing user concepts and studying ITS safety in a societal context.

3. FINAL DISCUSSION

All of the case studies are examples of proactive evaluation which can increase the ability to design these technologies for safety. Both Perez and Marsh emphasized the usefulness of real world field testing and phased deployment. Both of their projects used multiple methods and grew in resourcefulness to meet the challenges of complexity and unexpected effects presented by the "real world". Leis and Crompton have shown how careful thinking can aid in the identification of safety concerns and contribute to the eventual assurance of safety. These analyses were prior to the deployment of a specific design. Several of the papers mentioned the need to identify and overcome institutional barriers through cooperation. All of the papers at least acknowledged the need for human factors work.

Developing Intelligent Transportation Systems (ITS) which are both effective *and* safe depends on planning and research from the beginning of the system design process through its implementation. This process would be aided by progress in several methodological areas. The crash databases do not include data of interest such as the presence of in-vehicle devices, air bag deployments, etc. Including additional data in standard safety databases would facilitate the evaluation of deployed ITS technology. However, crashes in conjunction with ITS technology might be relatively rare. Therefore, increasing understanding of the relationship between behavioral measures and the probability of crashes or increased risk would be especially useful to designers of ITS. Continued identification of potential crash situations and hazard analysis will also make a contribution to this effort. There is a need for ongoing development of models, aided by useful data for calibration and validation. In addition, consideration of the scope of application and generalizability of models is needed. While this is true of all research, models are used most extravagantly to predict future impacts. Finally, there is a need to better understand users' mental models of safety and safety technology in order effectively educate. Overall, understanding the societal aspects of safety would be a useful addition to the traffic network and technical facets of ITS safety.

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Section IV

Breakout Session Reports

This section contains a description of the breakout sessions and a summary of the discussions. The breakout groups were organized around three ITS Areas (Advanced Traveler Information System, Automated Highway System, and crash avoidance), with two subgroups for each topic, The session leaders for each of these topic areas were:

Tonic	**Session Leaders**	
ATIS	Gene Farber	John Hitz
AHS	Rick Pain	Dick Bishop
Crash Avoidance	Bob Clarke	Mark Freedman

The Workshop committee developed a list of four general questions for each breakout group to address. These questions were molded to the specific topic at hand by breakout session leaders. Time allowing, participants were encouraged to pose and perhaps address additional questions they felt were appropriate. The basic questions were:

1) What are the critical safety issues associated with ATIS (AHS, or CAS) in terms of hardware/software and human factors?

2) What is an idealized sequence of safety evaluations (objectives, methods, units of observation, analysis) appropriate for ATIS (AHS or CAS), from concept to post-deployment?

3) What “decision criteria” might be applied in safety evaluations, i.e., indicators that a system should (or should not) move from one phase of evaluation to another?

4) What are the fundamental issues or difficulties associated with conducting safety research on the ATIS (AHS or CAS) safety issues and how might these difficulties be addressed or resolved?

All participants took part in the discussion of each of the questions for a single breakout session topic. At the end of the breakout session, small teams were assigned to write a brief synopsis of the discussion surrounding a single question, and any conclusions and recommendations offered by the group. These written responses, edited only for clarity, follow.

ADVANCED TRAVELER INFORMATION SYSTEMS

Question 1

What are the critical safety issues associated with ATIS, in terms of hardware and software, as well as human factors?

Hardware Issues

A major hardware concern centers on the potential hazards associated with safe mounting of devices. Devices should not become unsafe projectiles in rapid acceleration or deceleration environments. They should not interfere with safety system deployments (seat belts and airbags).

Hardware should be designed to meet user requirements for information timelines. For example, user shouldn't have to wait five minutes for system warm-up. Congestion information and accident information should be processed fast enough to enable drivers to make effective route diversions. Unreliable hardware or hardware not equipped to meet users' needs can cause users to act unsafely in order to work around system limitations.

Software Issues

Software safety issues include the responsibility of insuring that all related data bases are accurate. The types of databases include locations of services and attractions, location of roads, and directionality of one-way streets.

Data processing protocols can impose limitations on the amount of information that can be conveyed to the user such that inadequate levels of information can be provided. Software must be designed to provide user-friendly representations of information from multiple databases. Software designers must ensure that, even if data bases are accurate, route diversion algorithms do not provide inaccurate guidance.

Another more global software issue is concern over variance across the country with regard to database coverage and consequence variance in operability of ATIS systems. Such variances could violate user expectations and cause unsafe user responses.

Software designers must also consider safety impacts of routing traffic through residential areas. Perhaps software standards are needed to avoid increasing safety problems for local communities.

Human Factors Issues

In the area of human factors, the major issues center on the possibility of information over-load and distraction. The addition of multiple after market ITS systems without considering the interactive effects of the products represent a threat to safety. Factors such as type of display, modality (auditory or visual), and user interface placement (HUD vs. head-down) have potential impacts on safety. On a more global level, designers must consider the effects of varying levels of ATIS market penetration, and the behavior of drivers with and without the system.

Integration Issues

Although critical safety issues associated with ATIS can be categorized in terms of hardware, software, and human factors, as outlined above; one of the major safety issues is the integration of hardware, software and human factors considerations into ATIS systems. ATIS should not pose significant risk to the user and should, preferably, enhance the efficiency and safety of travel. The table below shows the relationship between the four components of ATIS and the critical safety issues identified by the breakout group.

	ATIS Components			
Safety Issues	In-Vehicle Service Information System (IMIS) *Yellow Pages*	In-Vehicle Routing and Navigation System (IRANS) *Navigation*	In-Vehicle Information System (IVIS) *Signing*	In-Vehicle Signal and Warning Systems (IVSAWS) *Warning*
Attention Demand	X	X	X	X
Risk Exposure		X		
Distraction	X	X	X	X
System Errors	X	X	X	X
Maneuvers		X	X	X
Security		X		
Information Timing		X	X	X

Attention Demand, deemed the key issue, refers to the requirements that the ATIS places on the attention of the driver. The higher the requirement the more detrimental the effect upon the driving task.

Risk Exposure was identified as a critical safety issue because reduced exposure should reduce accidents.

Distraction, distinct from attentional demand, is an unintended effect of ATIS implementation and is directly related to safety. Information presented to drivers must be presented in a comprehensible form, without ambiguity, and in an acceptable manner. Particular emphasis should be devoted to guard against information overload.

System Errors impact safety whether they originate from hardware, software, or databases. The "best case" for system error is to be "safety neutral."

Maneuvers arise as an ATIS safety issue because one intent of ATIS to aid in the planning of maneuvers through effective route planning and through the presentation of appropriate aids at the time maneuvers are to be executed by the driver.

Security refers to the personal security of the vehicle occupants. The use of ATIS should not create personal safety concerns.

Information Timing impacts both driver attention and distraction but is important enough to be listed separately. The timing with which route guidance instruction, presenting of in-vehicle signing, and in-vehicle warnings will have a substantial effect on the safety of the driving task.

Question 2

What is an idealized sequence of safety evaluations (objectives, methods, units of observation, analysis) appropriate for ATIS, from concept to post-deployment?

Proper safety evaluation is not an after thought in system development; it should be tied to the system development life-cycle, beginning in the early stages. These stages are:

- Requirements definition
- Prototype testing-human factors lab
- Field testing - limited
- Limited deployment, and
- Full deployment

The general objective is to collect the most accurate, valid, reliable ATIS safety data possible. This objective is limited by the methods available, which are, in turn, constrained by the stage of concept/design/evaluation and other limits of practicality. The idealized sequence from the earliest concept through post deployment is:

- Development of Modeling and Analysis Frameworks
- Conduct of Laboratory Simulations
- Evaluation and Testing of Prototypes
- Establishment of Baseline Performance Measures/Databases
- Conduct of Closed Track Testing
- Performance of Controlled On-the-Road Studies
- Conduct of Fleet and Pilot Testing
- Performance of Post-Deployment Testing
  -> Mass accident data files
  -> Targeted studies

In general, measures of attentional demand and the related construct of driver distraction are of primary interest and importance to the evaluation of ATIS. In the later evaluation stages, macro analysis of near-crashes and crashes presumably reflect the earlier, micro-measures of attentional demand/distraction. As part of the evaluation of attentional demand, the development of standardized measurement protocols and metrics would substantially aid the process of early system safety evaluation.

The evaluation objectives, which are general in nature, are broken down into specific questions or hypotheses. These hypotheses are used as the basis for specifying measures of effectiveness and performance, which are used to develop experimental designs, data requirements, and analysis methodologies. The results of the experiments are then synthesized to address the evaluation questions. Some examples of methods for ATIS systems include:

- Interviews and questionnaires
- Individual performance tests
- Incremented system performance.

This process is iterative and supports each phase of system development and deployment, as listed above.

Question 3

What "decision criteria" might be applied in safety evaluations, i.e., what are indicators that a system should (or should not) move from one phase of evaluation to another?

Whenever decision criteria are developed or applied, the customer must be known. Government, manufacturers, and consumers will each weigh costs vs. benefits at various stages of the design process, from concept to production models in the market place.

The process of evaluating the safety of ATIS progresses from gross, high-level criteria to more esoteric measures by consumers of component cost and utility versus perceived safety benefit/cost. The higher level criterion address such issues as whether the product is inherently dangerous; does it take too much attention away from the more basic driving tasks, perhaps resulting in accidents/near misses. In the middle ground are measures and criteria that aim to objectively measure "how much" safety, benefit, or risk results from use of the system.

The general criteria used in safety evaluations of ATIS should be "no harm, no societal cost". The Safety effects of ATIS may be difficult to identify and measure and may require policy evaluations. Small safety disbenefits may be accepted due to large improvements in mobility. Clearly, systems which are obviously unsafe will be discarded early, based on state-of-the-art considerations or from negative simulation results.

The performance of safety evaluations will require acceptable baseline information as a basis of comparison. Safety evaluations should be conducted at each phase of development and implementation. The operational criteria used at each phase must be defined before evaluations are conducted. The most significant criteria for these quantitative analyses relative to ATIS seems to be attentional demand, as a surrogate measure of safety. On the opposite front, failure to provide significance with respect to a control group baseline may also represent grounds for skepticism or closer evaluation on other measures.

The potential for adverse interactions with other systems, especially safety related systems, must be considered. For example, ATIS systems that conflict with air bag deployment due to their location in front of air bags will be unacceptable.

Question 4

What are the fundamental issues or difficulties associated with conducting safety research on the ATIS safety issues and how might these difficulties be addressed or resolved?

Safety Issues/Difficulties

Safety evaluation of ATIS should be comprehensive and should take place throughout the entire system development cycle (e.g. from concept development through full deployment). This evaluation approach requires different procedures and measures to be used at different stages of development and deployment. The research issues and difficulties associated with conducing safety research track with the idealized sequence for safety evaluations.

> **Initial Concept Stage** . During the concept phase, it is important to identify a baseline for comparison. The complexity of the system makes’it difficult to conduct valid modeling and simulation. Proprietary information and federal impediments can inhibit cooperative evaluation programs.
>
> **Prototype Testing Stage.** As the system matures to the prototype test stage, numerous test issues arise such as sample size, fidelity and robustness of early testing. The use of human test subjects and their protection must be addressed. The metrics must accurately represent the criteria tested. An example is the use of counting eye blinks to measure work load.

Operational Testing Stage. In the operational testing stage, human factors issues must be addressed such as novelty, motivation, and risk. The safety consequences of various design choices (e.g. type or location of visual display for route guidance) may be difficult to measure. Furthermore, for well designed systems safety benefits of the in-vehicle design may not be detectable. Operational effects may frequently mask the safety benefits or costs associated with specific ATIS designs. For example, features of a specific traffic network (e.g. Van Aerde) may produce safety effects that overwhelm effects due to the driver/system interface.

Solutions/Recommendations

Solutions to these difficulties can be found in a consensus building process. A national workshop is recommended to identify subject protection guidelines, standardize methods for unobtrusive testing, standardized protocols (e.g. attention demand), and identify needs and uses for tools.

One way to minimize the problems associated with propriety products is to fund more public-private cooperative research. Post deployment validation is suggested as a solution to problems of inadequate sample sizes and novelty effects found in limited time controlled studies. Caution should be exercised with regard to unintentional outcomes from ATIS user interactions and unrealistic safety expectation of the designers.

Well established baselines of safety performance measures for ATIS are not yet available for evaluating alternative designs. These baseline measures are needed for use with safety "surrogates" and as near-misses, driving performance measures, and workload. Baselines for crash data (with exposure) are also needed. The above classes of measures - crashes versus surrogates- present different challenges.

- Surrogates
    - theoretical relationship to safety
    - ability to predict crashes
    - requires a driver model
- Crash Data
    - large samples needed
    - large levels of exposure required per condition. Complex operational tests may require in excess of 10 million vehicle miles of exposure.

ATIS will be part of an ITS infrastructure with multiple functions. These different functions (e.g. a TOC providing travel time estimates and incident information) my produce safety impacts. It will be difficult to determine and segregate the specific functions or combinations of functions that have safety impacts.

AUTOMATED HIGHWAY SYSTEM

Question 1

What are the critical safety issues associated with AHS, in terms of hardware and software, as well as human factors?

The AHS will be a large distributed system operating in a real world environment. Key issues that must be addressed prior to deployment include ensuring that the system is not so complex that it is impossible to determine failure modes. Appropriate decision making skills must be incorporated into it's design, it must be robust in its operating domain, and it must have sufficient redundancy to mitigate failure modes. Fundamental questions which need to be addressed include:

> ***What is it?*** The lack of a system definition for the AHS is a constraining factor for safety analysis. Existing knowledge is derived from a weak systems engineering approach to fragmented product development. The AHS must evolve from today's system.
>
> How ***reliable is it?*** Presently we do not know the reliability of AHS systems and subsystems. The design criteria must call for high reliability and graceful degradation; designers must consider which failures will have the most impact on the driver and passengers, and make them more robust.
>
> ***To what extent is the driver included?*** This is not clear. The system definition needs to distinguish between hardware and software failures and the unique human impacts of each. In a major system failure the human must act as backup to remove the vehicle from the AHS. Again the lack of a clear mission definition limits evaluation. This should be revisited after AHS mission is defined. Transitions to and from AHS are the most critical from a human factors stand point.

The system must evolve from today's technology into AHS. This evolution will require the capability for AHS vehicles to operate in mixed mode lanes. The mix of vehicles could include AHS, AI-IS ready, semi automatic and today's vehicles. Thus, the AHS could require the ability to accept (duck-in) and release (check-out) vehicles on the fly.

Human Factors Issues

Several key human factors and safety issues were identified in the breakout session. The **driver's perception** that AHS is operating safely and the driver's sense of well-being regarding AHS operation must be considered. The **driver's capabilities** must be realistically evaluated in highway/infrastructure contexts. While these contexts constrain driver abilities, it is inappropriate to assume, at the outset, that drivers have limited processing and control abilities. There are serious questions of the impact of increased automation and the ability to maintain these complex system. This dictates built-in test and automatic fault indicators. The goal should be to address capabilities specifically.

Another group of issues address the **role of the driver** on the AHS. These include:

- driver readiness to assume or relinquish vehicle control,
- driver roles during lane transition from AHS lanes to non-AHS traffic; driver response and acceptance of the system; and demonstration by driver of his or her ability to resume control from AHS,
- the need for interfaces to provide system and vehicle status information to the driver, and
- whether or not a "driver panic button" is needed to allow the driver to exit AHS when he or she desires.

System complexity can also be viewed as a human factors issue. A system that is too complex can be unpredictable (to drivers), which may impact driver acceptance.

Question 2

What is an idealized sequence of safety evaluations (objectives, methods, units of observation, analysis) appropriate for AHS, from concept to post-deployment?

A comprehensive systems engineering approach to safety is required for AHS development and deployment. Safety evaluation should be an integral part of the design, development, and deployment life cycle of AHS. This life cycle was generally defined in five stages:

1. Pre-AHS systems and devices
2. Concept development research and development
3. Prototypes, test bed and operational tests
4. Transition to AHS, mixed traffic issues
5. Full AHS deployment

A formal and disciplined development approach is required, particularly for complex systems like AHS. Planning should proceed using a total system perspective, focusing on functional requirements (i.e., what the system or device should do), before generating system designs (i.e. how to do it). Flexibility must be maintained throughout this process in order to accommodate advances in technology and ideas for AHS. Safety goals must be used as a driver to the development process and allocated to systems and sub-system in demonstrable terms.

Ensuring Compliance to Safety Requirements

Overall system requirements, together with demonstrated measures and tests that can prove compliance with requirements at each level are important as the implementation process evolves. A compliance matrix can be used to test compliance with safety requirements throughout subsystem development and all stages of total system development. This approach can help provide measurable safety assurance throughout the five stages of the AHS life cycle.

This disciplined procedure provides the basic steps to follow, and documents the process of validation and verification. Existing procedures must be tailored to the AHS application. At each level of the development process, it will be necessary to define criteria and verification procedures based on safety requirements for:

- Functional adequacy
- Fail-safe adequacy
- Reliability
- Verification standards and test procedures (including stress testing).

Other methods or approaches include simulation because nothing like this has been attempted before. MANPRINT (from the DOD) is another approach for identifying human factors and safety issues and ensuring that they are addressed throughout this process.

The AHS consortium is generally seen as the managing authority from today through concept development and prototype. A key question is how the total systems approach will be managed or implemented and who will manage it after the AHS consortium completes their task.

Unfortunately, all of the above can be done in an engineering sense, but success will not hinge solely on technical adequacy. The problem of relating functional performance to significant safety goals remains. It will, perhaps, be minimized by the appropriate definition of safety requirements throughout the process. We still need to bridge the gap between engineering considerations and public confidence.

Question 3

What decision criteria might be applied in safety evaluations, i.e., indicators that a system should (or should not) move from one phase of evaluation or development to another?

We should refrain from the use of strict design criteria to prove that safety goals are met; instead the use of guidelines are recommended as a preferred approach to safety evaluations. Session members felt that the Joint Program Office has a key role in integrating FHWA & NHTSA safety goals along with those of the NAHSC. JPO can also be instrumental in integrating the separate guidelines and evaluations from FHWA, NHTSA, and NAHSC.

The key decision criteria to be applied to AHS safety evaluations was to periodically test for safety goals and their re-evaluation using the AHS demonstration site following the completion of the demonstration. During this evaluation phase, attempts would be made to measure the absence of crashes and malfunctions, delays, injuries and accidents.

Other decision criteria suggested include:

- Criteria for demarcation of vehicle control via infrastructure; specifically the aspect of how control is relegated back and forth between the infrastructure and the vehicle.
- Criteria for evaluating the user acceptability of early control systems (termed "partial control systems" by the session attendees) needs to be measured.
- Decisions regarding when a particular AHS device is to be allowed. There were questions regarding when should such AHS devices or systems get safety approvals and by whom should they be approved; were there to be any industrial approvals to be obtained?
- Use of in-situ diagnostics built into AHS devices and systems to predict and detect malfunctions and their expedient repair, while traffic flow is accordingly re-channeled, re-routed, or temporarily halted.

Measures of Effectiveness/Performance

In general, criteria for assessing system safety need to map back to a comprehensive decision model, that is, the decisions to be made and the weak ordering of the criteria. The decision criteria should reflect the overall AHS safety goals and associated Measures Of Effectiveness (MOEs) and Measures of Performance (MOPs), verify and support the tasks of convincing various stakeholders that safety goals are satisfiable or satisfied.

Individual safety decision criteria must be delineated. It is important to note, however, that the overall goal of determining the level of safety improvement or safety degradation must be assessed by surrogate measure of effectiveness or performance. As safety is not in all cases, a binary state or condition, one can address the question more simply as a cost-benefit issue. In any AHS design, there is a cost or risk threshold which must be identified, or at least bounded in some meaningful way. The boundary of these safety decision criteria necessarily include tradeoffs. Examples of candidate decision criteria include:

System wide performance (macro)

- Is the number of catastrophic failures per million vehicle kilometers acceptable for nominal operations? for degraded modes?
- Is the cost of meeting the safety goals in line with the priority of safety goals?

Subsystem specific (micro)

- Is the lateral control system testable and verifiable?
- What level of fidelity do the test or verification results have?
- Does the protocol or its implementation of mode transition for hand off of control during entry or exit meet user expectations?

Error Attributions

'The safety evaluation also needs to separate error due to AHS systems malfunctions from errors due to human misuse or inappropriate use of the AHS system. A decision criteria for "do no harm" or "improve safety" was sought in the light of a need for a trade-off with the risk-mobility factors, in an effort to lower risk. Some level of decision on safety and at what cost was also sought by the session members. It was suggested that crash minimization to the level of 'bumper cars' (magnetic repulsion to achieve retardation during impending longitudinal crashes or some planned controlled impact) should be resorted to, instead of absolute elimination of crashes. These suggestions implied a "5 mile per hour" type of scenario.

Question 4

What are the fundamental issues or difficulties associated with conducting safety research on the AHS safety issues and how might these difficulties be addressed or resolved?

One of the most difficult issues or difficulties associated with performing a safety evaluation of AI-IS is the present lack of a selected system concept or a short list of potential system concepts. Instead, a continuum of potential concepts are being discussed, which in some respects, precludes a tangible system analysis. There is movement towards the early deployment of various subsystem functions prior to the deployment or design of a fully integrated system. While this piece-wise progress permits component testing, it makes the design of the components in view of the overall system much more difficult.

Second, a suitable fault tree structure must be designed and a corresponding fault tree input data must be developed prior to the final concept for the development of most system components. There is also a risk that if fault tree development involves too many parties, it may result in the complete omission of entire fault three branches.

Third, simulation models must be built and validated in the absence of a final selected system concept. This makes it difficult to build a simulation model that is either sufficiently general to accommodate all potential designs or sufficiently specific to provide answers with sufficient confidence. Insufficient lead time for the development of such models may mean that sub-system functions are deployed before sufficiently reliable models are available.

Additional issues and concerns in conducting AHS research raised by the groups include:

- Competition between AHS Safety and Efficiency. The safety aspect often competes with the efficiency aspect of ITS for funding.
- Legal and Liability Issues. Legal and liability concerns can limit the type and amount of research. These concerns also serve as a roadblock to even conducting research and increasing the cost.
- Perceived Versus Actual Safety. Safety perception by the public versus the actual safety is an issue that could be a roadblock to implementation (e.g. it could impact funding).
- Identification of Safety Goals. The proper identification of safety goals is critical to the measuring of safety effectiveness; but the agreement of the goals is difficult. (For AHS crash reduction may be a better measure of effectiveness.)
- Transition between Testing and Application. Testing versus application is an issue because when “testing” is finished is a matter of opinion.

COLLISION AVOIDANCE SYSTEMS (CAS)

Question 1

What are the critical safety issues associated with CAS, in terms of hardware/software and human factors?

Hardware/Software Issues

Well specified hardware and software design parameters for detection probabilities and false alarm rates associated with collision avoidance systems are essential to system safety. Critical safety issues include:

- Hardware reliability,
- Driver understanding of system performance,
- Incidence of false/nuisance/inappropriate alarms, and
- Development of baseline driving performance and behavior data (crashes as very rare, outlier conditions make their study difficult).

Questions we need to answer include:

- Should systems take control from the driver or provide drivers with better information, leaving control with the driver? and
- How might CAS systems and other ITS systems be integrated? The traffic conditions that a system is designed for (i.e. urban, rural, volume, speed) must be defined.

Human Factors Issues

Crash patterns and driver performance must also be better understood. A human performance baseline is needed for specific driving situations. Performance includes short-term micro performance and longer term adaptive behavior. Methods must be established to describe the levels of risk that drivers normally take. Risk compensation and behavior adaptation must be considered. ITS systems should not instill overconfidence in drivers. In terms of the consumer or user:

- The user must understand the system; it must be explainable.
- The system must be acceptable to the user; avoid misinformation and false alarms.
- CAS must be marketable.
- We must understand how well drivers respond to messages/inputs from the system.
- The system should not produce excessive driver workload.

Integration solutions to the CAS problem are needed. CAS may not be the solution to the collision problem. We must not, for example, overlook the effects of training, or enforcement. Systems must not exacerbate the situation by putting the driver into a hazardous situation. We must also understand how vehicles with CAS equipment will impact vehicles not similarly equipped.

Question 2

What is an idealized sequence of safety evaluations appropriate for CAS from concept to deployment?

The breakout groups identified the following framework for sequencing CAS safety evaluations:

1. Define the accident type to be addressed (e.g. rear end, off-the-road)
    - Define normal Driving
    - Define the subsets of accident types to be addressed. Be specific in definitions (crash characteristics)

2. Identify points of intervention for the defined accident type.
    - Get better information on pre-crash environment.
    - Utilize existing knowledge base to target objectives of the intervention (e.g. FARS, NASS, insurance data)
    - Define data expansion needs

3. Identify tools and technologies available for intervention of the identified accident type.
    - Address privacy of information and data.

4. Examine the technical feasibility (fail safe, zero defects); marketability (cost, market penetration, perceived value); usability (human factors engineering, system safety evaluation); and liability (the impact on the manufacturer).

5. Provide proof of concept of evaluated system
    - Prepare prototypes
    - Perform baseline data collection in real environments
    - Conduct data acquisition in test-track environment
    - Assess MMI by public
    - Re-evaluate consumer acceptance
    - Conduct supervised real-world usage studies by consumers.

6. Identify units of observation, performance, and effectiveness
    - Conduct environment testing
    - Assess device performance and effect
    - Examine user performance and effect

7. Perform analysis of baseline data, test track data, and limited (supervised) real-world use by general public.
    - Determine how to integrate all the studies and results.

8. Execute deployment in fleet (controlled)
    - Employ a control group
    - Examine the effectiveness of the deployment with test fleet
    - Re-evaluate based on the observed benefits of the intervention.

9. Conduct post deployment evaluation (Did limited deployment provide the anticipated benefits?)
    - Re-evaluate technical feasibility, marketability, usability, and liability issues.
    - Make appropriate changes

In essence, participants felt that the evaluation process should parallel the systems development and deployment phases (concept/prototype test/ field test/ post production monitoring). Although these steps should in theory be performed in logical sequence, the group acknowledged that reality is dynamic, and often, in practice, these stages are performed simultaneously. The process is market driven, competition is pushing the pace.

Question 3

What decision criteria might be applied in safety evaluations, i.e., indicators that a system should (or should not) move from one phase to another?

Decision criteria need to be developed relative to the specific system function in question. The primary decision criteria are effectiveness of a given system as a countermeasure against the defined threat scenario, and safety relative to secondary effects, which may have been unforeseen in the original CAS concept.

Each phase of the evaluation process is focused on expanding the knowledge/database relative to these parametrics, through increasing levels of human interaction and exposure. At each of these levels, investigation must re-evaluate the effectiveness and safety in light of new data collected , and reassess the overall safety merit of the collision avoidance system.

The following general criteria might be used:

- Reliance upon the judgment of expert panels
- Assessment of whether the system will do more good than harm
- Convergence of quantitative data such as when statistical confidence is high and result variance is low.

Question 4

What are the fundamental issues or difficulties associated with conducing research on CAS safety issues and how might these difficulties be addressed or resolved?

Numerous fundamental issues and limitations applying to CAS research were discussed. The categories of areas where problems exist include, among others, legal, data, and methodology and tools.

Legal Issues

Legal issues represent a substantial constraint in resolving many of the issues relating to CAS systems. With the introduction of technology and systems that may themselves, create safety concerns under certain conditions and segments of the population, the importance of legal issues can become paramount in determining whether we can, in fact, properly evaluate countermeasures under real world conditions. Specific issues concerning privacy and confidentiality include: 1) what mechanisms can be developed to insure privacy and confidentiality in data collection, and 2) how can the subject population be convinced that the data will be kept private and confidential.

Possible solutions include destroying data in black boxes on impact if the purpose of collecting data collection is gathering baseline data (self-destruct mechanism). Another example is to put noise in black box recorder data so it won’t be admissible on court proceedings. We don’t know how to convince the public of adequate privacy and confidentiality.

A second legal area is the use of human subjects in evaluating CAS. Since evaluation of CAS requires investigation of extreme and dangerous conditions, how do you test CAS in realistic conditions without putting drivers in jeopardy? One potential solution is to use simulators and test tracks as much as possible. However, it is important to recognize that results obtained via these methods may not generalize to realistic environments.

A third issue legal issue is where liability resides in the event of a crash during evaluation of these systems. How does the research community protect itself? Insurance is obviously important.

Data Issues

A number of difficulties are associated with conducting safety research on collision avoidance systems. These include:

- Obtaining adequate exposure data. Black boxes should be part of field operational tests.
- Obtaining samples that are representative of target populations and of sufficient size.
- Human use and subject safety.
- Defining appropriate demographic characteristics of subjects used in experimentation
- Generalizability. Subjects may behave differently than ordinary drivers in real world driving environments. Further, findings based on short term research may not be applicable to long term performance.
- Safety effects on non-equipped vehicles may result.
- Maintaining Accurate and Representative Databases. Changes occur over time in crash rates, and crash patterns in the general population

Crash surrogate measures, such as traffic conflicts must be validated and a correlation developed between events (crash surrogates) and the relatively rare crash events.

Methodology & Tools

In general this areas suffers from a lack of uniform evaluation tools and realistic test situations. The significant lack of uniformity-in methodologies adapted for the evaluation of CAS devices, including parameters, measures, analysis techniques and tools, has created a major roadblock to establishing consistent and repeatable evaluations. There is a need to establish a consensus in the research community on what should be measured, how it is should be measured, what tools should be used, and how the data should be analyzed for the variety of scenarios that are to be addressed. Methodologies are needed for characterizing near misses and critical events, as well as for using surrogate measures of safety.

Societal and behavioral trends can have a significant impact on our ability to evaluate CAS devices by masking device effectiveness or by providing misleading results. We need to better understand those effects by documenting trends through analysis of historical data.

Workshop on ITS Safety Evaluations
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