Safety Data Needs, Resources, and Issues

RICHARD M. MICHAELS

Two concepts of safety in transportation are presented. One is termed the "system design" definition and the other is the "casualty" definition. A discussion of accident statistics is provided, along with a look at the conceptual structure of safety data systems. Accident mitigation efforts are analyzed, and safety data needs are discussed. It is concluded that safety is an essential criterion of the effectiveness of all transportation modes. A more consistent and coherent safety policy would require more sophisticated data bases than are currently used. However, if they were employed, limited resources could be allocated more effectively and all modes could be measurably improved.

Data are required for safety policy purposes to achieve three objectives:

1. Safety investment decision making,
2. Safety program evaluation, and
3. Rationalization of regulatory policy.

The first objective is concerned with program initiatives necessary to improve the safety performance of the mode. What data are essential for the Office of the Secretary of Transportation (OST) to evaluate proposed initiatives and the resources required to implement cost-effective safety programs?

The second is concerned with the data required to evaluate the performance of the modes and their safety programs. What data, functional and economic, are essential to determine the cost effectiveness of such programs after implementation?

The third is concerned with the role of the U.S. Department of Transportation (DOT) in regulating transportation modes to increase or ensure safe performance. What data are needed to rationalize and justify imposition, relaxation, or extension of the safety design or operational regulations of the various modes?

At present, a wide range of data has been collected by the modal agencies within DOT and other public and private agencies with a stake in transportation safety. Relatively little of the safety data is useful for policy purposes as defined here. This is true because there has been and continues to be a basic confusion of definitions of safety and a basic unwillingness at the policy level to confront the measurement problems inherent in those definitions. Both have led to frequent misallocation of resources and an inability to evaluate the cost effectiveness of safety programs.

The purpose of this paper is to review the definitions of safety and develop an operational framework from which the data required to satisfy the policy goals outlined above may be derived. The paper is divided into three sections. One is devoted to safety constructs. A second is devoted to the operational priorities deriving from those constructs. The third is the information required for policy making and analysis.

ALTERNATIVE CONCEPTS OF SAFETY IN TRANSPORTATION

The concept of safety in transportation has had a long history. It has had two levels of meaning, one reactive and the other rational. The first reflects the response to a real or perceived threat in the interaction between mechanical systems and users or operators. The threat derives in part from the uncertainty about the systems and their potential for harm, in part from their scale relative to users, and in part from direct and vicarious experience with those systems. People thus respond with the same variety of emotions that they exhibit for natural events that are or appear to be beyond their control.

The rational meaning has emerged as a response to system design and its economic consequences. The driving force has been to create mechanical systems that produced wealth for producers and consumers. Engineering, theoretical or empirical, was the vehicle for generating the systems that produced this wealth. The limitations of design engineering, however, produced systems that were frequently unreliable and often poorly adapted to user capabilities and limitations, physical and psychological. Inherent, then, in the design of systems was a willingness to accept a risk of failure, including harm to users and operators.

One of the consequences of this evolutionary engineering was that it led to an externality in which the reactive and rational converged to create a unique definition of safety. This has been tort law and the concept of negligence. In the occurrence of harm to users and operators of mechanical systems, who is responsible and who must recompense a "victim"? This is an issue that has come to be a hallmark of industrial societies. Liability insurance, the legal profession, and the courts have become the subculture responsible for managing the resolution of damages done by transportation engineering.

For this social mechanism to function, it must focus on a specific event that has been the "accident." It must determine the "cause" of accidents as a basis for adjudicating negligence. It has accomplished this through accident investigation, reconstruction, and analysis. It has, as a consequence, defined safety as a casualty event.

Out of this history have arisen two different definitions of safety, which have consistently been confused. One comes from the systems engineering tradition, which defines safety

---

Illinois Universities Transportation Research Consortium and The University of Illinois, Urban Transportation Center, 1033 West Van Buren, Chicago, Ill. 60607-9940.

as the performance accuracy and reliability of the system and its component elements. Its focus is on component and systemic performance and the analyses of their modes of failure.

In this frame of reference, safety is part of a continuum of system behavior. Damage to persons or property is derivative. The accident as casualty is the unpredictable outcome of random failure in the Baysian sense. Knowing the characteristics of the components of a system, it is possible to estimate the probability of failure. It is equally possible to evaluate the random variations inherent in system performance and estimate the probability of deviations from ideal. The system design approach thus deals not with any discrete event (e.g., accident) but with the continuum of system behavior and its performance. Failure analysis is one well-developed method for evaluating system design. Unfortunately, the more complex the system and the more empirical its design, the less reliable is failure analysis.

The second view of safety is that of a casualty event. Its focus is on the damage resulting from "accidents." This approach has developed both a conceptual structure and a methodology for evaluating accidents and developing hypotheses, structural and institutional, for reducing the effects of accidents. It has also used accident analysis as a means of determining causality. In very simple systems or those very rationally designed (e.g., aircraft), investigation of accidents has been useful in identifying component and system failures as a basis of engineering modification. In less rationally designed systems (e.g., highways), the approach has been less successful.

In sum, there are two different definitions of safety. One is the system design definition and the other is the casualty definition. Each leads to radically different analysis, data, and policy requirements. Each also leads to radically different measures for policy purposes. Both safety definitions are essential for determining programmatic effectiveness and conducting policy analysis, but they need to be treated separately for policy purposes.

ACCIDENT STATISTICS

In almost all modes of transportation, the casualty approach has been the dominant, socially acceptable frame of reference for safety. Consequently, all transportation agencies use accidents as the safety criterion. The counting of accidents provides the dominant data of safety. FHWA uses accident rates to measure each state's safety program effectiveness. NHTSA uses accident data as a basis for automotive safety standards.

Accidents as the definition of safety and the criterion for system performance leads to a series of measure issues that need to be clearly recognized. These issues are (a) data acquisition, (b) data normalization, (c) interpretation for policy implementation, and (d) evaluation of policy initiatives. Fundamentally, unless the accident measures used are rational, mathematically determinate, and reliable, they are useless for policy purposes.

The first consideration is the accuracy of the definition of accidents in the transportation system. Practically, an accident is defined in every mode of transportation by the magnitude of damage and casualty. For commercial carriers, either all accidents are reported, as in aviation, or all those over a certain dollar amount (e.g., $7,500 in rail transportation, if damage is restricted to railroad property). In all commercial carriers, significant injuries and fatalities are reported and are subject to investigation, hence such accidents are accurately counted whether they involve carrier labor or system users. Such accident data bases also allow a reasonably accurate estimation of the direct costs of the event in terms of repair and replacement. Accuracy of cost estimation drops rapidly when either indirect effects, such as time and administrative costs, or the life cycle costs of victims are considered.

In highway transportation, even the counting of accidents becomes a far more difficult problem. Only a small fraction of all accidents are reported, much less investigated. Those that are investigated are the responsibility of the criminal justice system. (This is in marked contrast to aviation, rail, and transit accidents, for which at least the carrier, and in major accidents the federal government, has technical specialists assigned to investigate and analyze such events.) The level of sophistication in accident analysis is low, as is evident in the accident report forms used. There is no medical evaluation of the victims, little evaluation of the structural damage to the vehicles, and no cost analyses. These evaluations are almost always left to the legal system and the insurance industry. Little of that process becomes part of any accident data base, especially at the federal level. Through its claims process, the insurance industry probably has more data on highway accidents and their costs than any public agency. However, these do not appear to be accessible in any form useful for policy purposes.

In sum, in highway transportation especially, accident data are unreliable and incomplete. More fundamental, however, is the fact that accidents are rare events in all modes of transportation. To describe them statistically requires the use of complex distribution functions, that is, statically as compound Poisson or dynamically as Markov processes. In essence, accident occurrence is rarely the consequence of a single event. In almost all cases, regardless of mode, several factors operating in time and space conjoin to produce the event. In most situations, these factors are unique and cannot be generalized.

Further, the occurrence of a serious injury or fatality may bear little or no relation to the cause of the accident. What happens after the initiation of the sequence that causes a vehicle to become "out of control" may not be predictable. It should be recognized that the process occurring after the event is a different operational regime, the transition describable at best by chaos theory. To use fatalities as a criterion for safety in almost any mode of transportation, either as a measure of safety or as a basis of policy, is largely futile.

Beyond the complexities of accident accounting and the temporal and spatial relations involved in their occurrence, another fundamental issue exists: exposure. In all modes of transportation, accident frequencies need to be normalized to obtain a measure of performance or risk. Three global measures of exposure have been used: (a) vehicle or passenger miles of travel, (b) population, and (c) vehicle volume. The implicit assumption behind exposure is that the probability of an accident is directly related to the amount of time spent on the system. The validity of this assumption has never been proven for any mode of transportation, certainly in the aggregate sense and especially using vehicle or passenger miles of travel. In the case of aviation, 75 percent of all accidents occur on takeoff and landing. Passenger miles of travel clearly are no measure of this class of event. Accidents per flight operation are more relevant but obviously must be weighted by aircraft size and/or passenger load, to say nothing of airport operations and environment. On the basis of passenger miles of travel, general aviation could be expected to have a far greater accident rate than commercial aviation, even if the probability of accidents was the same. This is true simply because the number of passengers per operation is much greater on commercial flights than in general aviation, although the number of operations in general aviation is much greater.

In highway transportation, the issue is even more complicated. If exposure is really defined by time, then the vehicle miles of travel (VMT) will be in error at least by an amount equal to travel speed on any highway segment. If a trip is made using three equal roadway segments—arterial, primary, and freeway—and the travel speeds on each segment are in a ratio of 30, 45, and 60 mph and the likelihood of an accident is simply a function of time, then an accident rate using VMT should be 1.3 on the primary and 2 on the arterial relative to the freeway. This is less than observed fatality rates on the VMT basis, but considering the previous discussion, the difference is not that great.

Even if VMT is considered a legitimate exposure measure for highway and bus transportation, measurement accuracy is a problem. This is not an issue in aviation, because of federal requirements for aircraft maintenance and management. The hours flown by each aircraft are documented, even if passenger load is not. Similar but less precise data are available for railroad and transit. In highway transportation, however, VMT is estimated as an aggregate or by highway system (e.g., volume × gasoline consumption × average miles per gallon per vehicle; in special studies, average daily travel (ADT) is determined for a given highway segment). Each of these are stochastic variables, each with a different distribution function. However, each is a derived value (i.e., an annual average). No variance is defined for the product, so the reliability of the measure is indeterminate. Examining the characteristics of the individual distributions leads to the inescapable conclusion that VMT is unreliable as a measure of exposure in highway transportation. More sophisticated types of statistical analysis can be used to measure accident probabilities in specific design situations reliably. These are complex and are not currently used at the policy level.

From a policy standpoint, aggregate measures of accident rates are arbitrary and inherently unreliable when commonly used. Little evidence suggests that any of the global measures of accident rates are useful for policy purposes. There are vitally important reasons for conducting accident analyses and collecting accident data. However, attempts to measure transportation system safety on an aggregate basis, as is current practice, are highly suspect and unproductive for policy purposes. On the contrary, they may be major deflections from more operational means of improving the safety of transportation.

SAFETY: A CONCEPTUAL STRUCTURE

It was suggested earlier that there are two different domains that must be kept distinct in any discussion of safety. One concerns the engineering performance of the mode. The other concerns accidents. Each requires a different analysis framework and a different policy data base. The objectives of the two domains may be defined as follows:

- The engineering mode (the design and operation of any transportation system) is to minimize the probability of failure in its performance.
- Accident analysis is to minimize the consequences of a failure event to humans and materiel involved.

Safety inheres in the design of a transportation system insofar as the behavior of that system is predictable. There are three basic means of determining system predictability. One is through the development and application of verifiable design theory. The second is through failure analysis. The third is through understanding the higher order interactions of the components that make the system operational. In surface transportation especially, and in highway transportation in particular, none of these three requirements for the design of a safe system is met. In many of the attributes of highway transport, the failure modes are well known but cannot be eliminated cost effectively. Contrast, for example, aviation and highways under conditions of ice and snow. Significant decreases in the coefficient of friction will close airport operations, but highways close only in the most extreme situations. Yet reducing frictional contact places the controller (the driver) in the position of having to operate without knowledge of the change in vehicle response. The consequences for system performance and safety are well known.

This, of course, is an obvious example of a well-recognized failure mode. There are much more basic and subtle examples, which are not well understood or even recognized, especially in highway transportation. To a significant degree these relate to vehicular and system control, which in all modes are largely left to human operators. Since the detailed mechanisms of human control of the automobile, train, bus, or aircraft are not understood, the range of reliable performance of these systems is not predictable. This is the case partly because these systems have not been designed to match the capabilities and limitations of the human operator. In commercial aviation, compensatory and redundant mechanisms minimize the uncertainties in pilot performance. This is far less developed in the surface modes.

It is interesting to compare failure mode analysis for the command and control component of transportation systems with that for the structural and mechanical components of the systems. It is inherent in the design of every mechanical element of transportation vehicles that comprehensive failure analysis is undertaken from the design stage through test and evaluation. Airworthiness certification involves detailed failure mode evaluation. All contracts for rail transit vehicles require similar analysis as part of the procurement. Automotive engineering involves comprehensive component and structural evaluation for vehicles of any size and use. It inheres in the engineering.

To determine the safety of any mode of transportation, there must be an identification of how the system does and may fail. This is not usually a discrete event but a continuum of performance under different ranges of operating conditions. What uncertainties occur under what static and dynamic situations? What conflicts arise in the interaction among vehicles (e.g., weaving sections of freeways)? As a basic data set, it would be worthwhile to have each transportation administration define and prioritize the failure modes. This would allow a far more rational basis for safety investment than is currently followed.

If failure analysis were used as a basis of safety policy, it should be recognized that within the current state of knowledge it would be incomplete (as in the failure of the Nimitz freeway structure). On the one hand, none of the modes has sufficient theoretical understanding to identify all the failure modes. On the other, data on system operations are too limited to allow reliable failure analysis. This is one reason that failure investigation is useful. Where system performance is not fully understood, operational failures can identify design problems. Clear air turbulence and wind shear are two examples where unpredicted behavior of the medium as reported by pilots (to a lesser degree through accident investigation) led to the modeling of the phenomena. This, in turn, led to design and operational modifications that sharply reduced the threat to system stability. In highway transportation, the Europeans have been much more active than the Americans in using conflict analysis for identifying potential failure modes. For safety investment and evaluation, for policy purposes, such analyses would provide a policy-sensitive safety data base.

What is increasingly clear is that new technologies holding tremendous promise for reducing operational failure and conflict are emerging in the 1990s. Viewed from this perspective, collision avoidance technology is becoming an important means of reducing failure probabilities in all modes. Automated warning and override control systems are well within the state of the art for surface transportation modes and are, of course, well advanced in aviation. The underlying issue over the next decade will not be the transfer of this technology but rather the determination of the performance dimensions for which that technology will offer the highest safety returns. Without a detailed understanding of the failure modes, it will be impossible to evaluate the return on collision avoidance or safety technology. Equally, without an understanding of the underlying performance mechanisms, it will be impossible to design such safety technologies.

An example of a new technology that reduces one failure mode is antilock brakes. Basically, this system responds to a particular braking system failure caused by drivers who have no way of knowing the relation between brake pedal pressure and brake lock-up. It does not prevent skidding or loss of steering control under very low friction conditions. It does resolve a narrow range of that set of failures in highway transportation, just as it has in aviation for years.

Automated headway control has recently been proposed for highway transportation, not only to reduce rear-end conflicts but also to increase highway capacity. Such control has been an integral part of aviation and rail transport; however, it has developed in both these modes as part of a superordinate control system. The pilot or engineer is given instructions either symbolically or verbally of the "safe" space coordinates and is expected to navigate within those assigned spaces. In the highway transportation proposal, the concept is based on maintaining continuous control over separation of individual vehicles.

There is an implicit assumption in such a proposal that separation of automobiles is a nonrational driver behavior. Yet there is considerable research to indicate that headways are dictated by both desired relative speed control and steering control. Without understanding the driver control modes, superimposed systems may degrade rather than improve system safety performance. Without understanding control dynamics of any transportation system, it is impossible to design technology that will predictably improve system safety.

In the end, technological changes in system design must be based on an understanding of how the system performs. Without that data base, it is not possible to define safe design. In most modes of transportation, aviation perhaps less than surface, the current understanding is not sufficient to ensure development of standards for or design of safety. The issue is not one of technology—mechanical, electronic, or structural—but rather understanding the basis of system failure.

Collision avoidance technology may be viewed as inherent in the design of the transportation mode or superimposed on its current structure and performance characteristics. The former derives from design theory and may be either evolutionary or revolutionary, depending upon the state of engineering knowledge. There is little question that in all modes the evolution of engineering knowledge has led to design, standards, and regulatory changes that have produced safer transportation systems. Similarly, failure mode analysis has been an integral part of aviation system design and in rail transit is a requirement for railcar procurement. The level of sophistication clearly varies for the different modes, but failure mode analysis is a recognizable function in vehicle and structural design, at least. It does, however, need to be integrated into the operational analysis of transportation to a far greater degree than currently practiced. From a policy standpoint, a knowledge of where and under what conditions the system and its components fail would provide a far better safety data base than current practices.

In the operational domain in all modes, but especially highway transportation, conflict analysis has emerged as a potentially productive tool for evaluating operational safety. The techniques are well developed but lack consistent application in the field. However, FHWA has now produced a manual for the states on making effective use of conflict analysis. Again, a systematic collection of conflict data would be most useful for safety policy objectives.

Data of the type discussed in this paper have been and are collected largely under the rubric of research. Much is known about design and operational failures and conflicts. Much of this knowledge has not been systematized in ways that can be used for policy purposes. It is certain that if the modal agencies were asked to provide such data for policy purposes they could do so. Certainly FAA collects incident data that can, properly analyzed, provide a significant policy data base. Its current program to develop an integrated safety data system is an attempt to do this.

ACCIDENT MITIGATION

It will never be possible to eliminate harm to users or damage to property in any transportation system. As part of the evolutionary engineering design process, the probability of failure will continue to be reduced. However, the underlying design theory will never be sufficient to eliminate all sources of operational failure that directly or indirectly lead to property damage, injury, and fatalities. This will be true, in part, simply because every mode will be used to its structural, organizational, and operational limits to extract the maximum benefit, economic or social.

Given that, the question becomes one of mitigating the consequences of such events. This leads to the separate domain of accident analysis. In essence, regardless of any antecedents in the operation of the system, accidents require analysis with the objective, as previously stated, of minimizing their effects. This whole domain requires both a frame of reference for its analysis and a body of data for setting priorities for modification and regulation of the system. Such data constitute the basis for accident mitigation policy making.

Any accident mitigation effort divides naturally into three component elements:

1. Analysis of crash dynamics,
2. Engineering of damage reducing systems, and
3. Minimization of the consequences of accidents to occupants.

In any mode of transportation, the forces to which the occupants are subjected, the time rate of application of those forces, and the locus of their application to the occupant are major determinants of the extent of damage. Because of their complexity, these processes in real accident events are extremely difficult to analyze and model. In aviation, FAA has been involved in such research for years and has developed an understanding of some of the processes occurring in aircraft accidents. The work in fire propagation is especially noteworthy, as it has led to major design and materials changes. Whether these changes have led to reductions in aviation injuries and fatalities is probably indeterminate, but they do provide a rational basis for accident mitigation.

In highway transportation, accident analyses have led to a recognition that a significant proportion of serious injuries and fatalities are the consequence of ejection from the vehicle. Much of the accident minimization attributed to seatbelts is because they reduce ejection. It becomes much more difficult to evaluate modifications internal to the vehicle. This is due in part to the complex interaction of the motions of a body in an accident and in part to the interactions between the different body structures and the vehicle interior. The biomechanics are inadequately understood to model the consequences for all but the simplest force dynamics. This makes it extremely difficult to reliably specify the elements of the vehicle interior that are the source of the trauma or whether their modification would significantly reduce injury or fatality. Consequently, any regulatory policy must be compromised and it is difficult, if not impossible, to evaluate the cost effectiveness of such proposed regulations.

This issue is most salient in highway transportation, where the numbers of accidents are so large and distributed so randomly. Compounding this difficulty is the way in which accident data are collected. Highway accident investigation is done by police for purposes other than accident mitigation. The nature of the information is largely superficial and cannot be used to evaluate the sources of trauma or damage and certainly not the crash dynamics. Beyond that, there is little coordination and cooperation between the health care system and the accident investigator. For a variety of reasons, it is almost impossible to obtain hospital records of accident victims to precisely identify the locus and severity of injuries or the consequences of treatment on the time of recovery or the enduring effects of the accident. Without such data, it is impossible to evaluate the accident and obtain the knowledge to improve the design of the system. Further, without such cooperative efforts, data on even the direct costs of accidents will remain unreliable.

These limitations are well recognized in the field, and NHTSA has, over the years, supported intensive and expert accident investigation. Although much has been learned from such programs, they have a fundamental limitation: ex post facto analysis cannot reconstruct the dynamics and hence cannot reliably determine the cause of trauma. The result is that, on the operating system level, only the occurrence of the trauma and, at best, its gross source can be reported. Finally, most investigation has focused on fatality accidents, which may provide far less useful understanding of crash dynamics than injury accidents.

These limitations have led to the use of alternative means of analyzing crash dynamics. Some have involved analysis of the force dynamics of vehicles in controlled crashes. Others have involved animal and human cadavers, but most have employed anthropometric dummies in controlled impacts. Dummies, unfortunately, are crude representations of the human body and do not reflect most of the complex interactions of skeletal and soft tissue structures. Although crash dynamics research has developed considerably over the past three or four decades, it is far from precise or scientific. As long as this is the case, accident mitigation policy will be compromised.

It is obvious that the purpose of crash dynamics research and analysis is to provide the basis for design changes in the vehicle. If fatalities are to be reduced to injuries and injuries reduced to structural damage, then vehicle design, structural as well as interior, is the means to achieve that end. Seatbelts and air bags are appurtenances whose cost effectiveness has to be evaluated relative to design changes. Good policy requires data whose accuracy and reliability allow rational choices among these alternatives. At present, such data are far less complete than is needed. As a result, most accident policy making concerning design standards or regulations is at least controversial if not unjustifiable. This is especially true for highway transportation.

If rational accident mitigation policy is to be developed, far more sophisticated crash dynamics and trauma analyses will be required than are presently available. Two classes of data appear essential. One is on the crash dynamics itself. In aviation, flight recorders have been used to define the forces to which the aircraft have been subjected. They have been most useful in providing critical data on how the system failed and hence providing significant data for design as well as operations and training. No other mode has used this technology. It would appear to be an especially valuable tool in highway crash dynamics analysis, in which it could provide detailed data on the forces to which occupants are subjected. Certainly, such recorders would add significantly to the understanding of the forces occurring in actual collision events. Supplementing the current efforts to model the motion dynamics of vehicles in crashes, they could provide a more effective evaluation of injury and fatality accidents in highway transportation than is currently possible. Such data should lead to more rational policy making on both structural design and restraint technology.

The analysis of crash dynamics without detailed evaluation of trauma experienced in crashes will not provide data for sound policy. Detailed medical analysis of injuries is a parallel activity that must support crash dynamics. Some cooperative efforts between NHTSA and hospitals and doctors, through the Health and Human Services Administration, seem essential. Such a program, which does not now exist, would provide a flow of data that would allow far more rational and cost-effective accident mitigation policy making than is now possible.

The last element of accident mitigation concerns the response of the health care system to trauma events in transportation. It is well recognized that rapid response to and emergency treatment of accident victims have the potential for saving more lives than any other single action. Certainly in surface transportation, where accidents occur unpredictably in time and space and yet most of the traumas suffered are not immediately fatal, medical response within the first 20 min could prevent over half the fatalities now experienced in highway transportation. Most studies on health care response to transportation accidents indicate that the cost of such systems would have a high return on investment, directly through reduced medical costs and indirectly through a reduction in public and private losses (e.g., wages and taxes).

SAFETY DATA NEEDS

The previous discussion reflects an attempt to define the two domains that determine the safety of transportation systems. Essentially, the framework adopted defines safety in terms of system performance. Accident analysis is defined in terms of mitigation of the effects of system performance failure. Such a dichotomization leads to radically different data needs. In this section, the specific classes of data needed for each domain are detailed. The objective is to develop a framework within which existing and new data may be combined to provide a basis for safety policy making.

Transportation System Safety

Failure Mode Analysis

It has been suggested that the basic data required for system safety derives from failure mode analysis and, in interactive systems, conflict analysis. In all modes of transportation there are at least four dimensions of failure analysis that bear on system safety:

1. Medium,
2. Vehicle,
3. Control, and
4. Command.

This is a first-order generic list. It is assumed that a comprehensive analysis would be developed within each mode for each of the dimensions and their interactions, determining, for example, the probability and consequences of failure, the requirements to reduce failure, the cost to reduce the number of accidents, and the return on investment. It is anticipated that this taxonomy would become very detailed.

Estimate Failure Probability

Given the modes of failure (or sources of conflict within systems or groups of vehicles in their operating environment), an estimate of the probability of each failure mode may be made. The objective is to provide a realistic estimate of the frequency of failure. How that probability is measured will vary with the system and the nature of the interactions of its elements. In most transportation systems, it should be possible to estimate both component failure rates and aggregate system failure using classical statistical methods.

Estimate Risk Probability

It is equally important to estimate the significance or risk associated with the failure. A bridge failure may have a low probability of occurrence, but such a failure could have catastrophic consequences (e.g., the Connecticut Turnpike structure or the Nimitz Freeway). Further, the failure probability may be dependent on the location of the element in its life cycle (e.g., fatigue of aircraft structure). Thus, the objective of the data sets is to define the probability of failure or conflict in some priority order of consequence to safe system performance.

What derives from this class of analysis is a "safety" surface. It would define the importance of failure in terms of its effects on system performance. Again, the objective is to allow setting rational priorities for efforts to improve the safety of each mode.

Policy Analysis

If the above analyses are carried out, it should be possible to develop a safety policy analysis. Given both failure mode probabilities and risk assessment, priorities are defined for safety improvements or evaluation. This leads to safety program development: what investments in which elements, structural or operating, would have the highest safety return? That is, what are the technological, operational, organizational, or regulatory requirements for reducing the failure probability to any desired level?

It is assumed that the safety program will define the resource requirements to accomplish the reduction (i.e., the time, manpower, money, and research and development required to achieve the desired reduction in failure or conflict probability). Given the resource requirements, a straightforward rate of return analysis can be performed. Such analysis would allow the Office of the Secretary to determine the short- and long-term gains of alternative safety program proposals and provide a rational basis for selection. Within resource constraints, this process should allow DOT to make allocation decisions that would improve the likelihood of cost-effective safety improvements. It would also provide a rational basis for evaluating proposed safety programs, because they could be located within a common strategic framework. Finally, this process would lead to multiyear budgeting for programs with explicit and measurable safety results.

The general framework for the analysis discussed is shown below:

1. Medium
   a. Designed
   b. Natural
2. Vehicle
   a. Structural stability
   b. Component reliability
   c. Performance stability
   d. System reliability
3. Vehicle control
   a. Data acquisition reliability
   b. Communication reliability
   c. Data processing reliability
   d. Human control reliability
4. Command structure
   a. Data acquisition
   b. System architecture
   c. Communications
   d. Human performance
   e. System management
5. Interactions
   a. Vehicle—medium
   b. Vehicle—vehicle
   c. Operator—vehicle
   d. Operator—medium

Clearly, this framework has been oversimplified. In many modes, the levels of understanding of the dimensions of failure are unknown. The capacity to carry out risk assessment is also limited. This suggests a need for greater investment in technical support in most, if not all, modal administrations to begin to generate the quality and quantity of data that failure mode analysis requires.

Accident Mitigation

The second dimension of safety policy is accident mitigation. Transportation injuries and fatalities are an indirect consequence of system failure. Although such failures are rare in all modes, they are inevitable. The policy objective becomes one of reducing the magnitude of such trauma when these events occur.

Crash Dynamics Data

A detailed understanding of crash dynamics and the forces to which humans and materials in the vehicle are subjected is required. Out of such an analysis, the nature of the trauma may be defined and its sources within the vehicle determined. Such data should provide a rational basis for vehicle "packaging" design, as well as for restraint and regulatory policy.

Such analyses require not only crash research with surrogate bodies but also more detailed data on crashes in the operational transportation environment. At best, crash research has been cross-sectional rather than longitudinal. Both are essential for a comprehensive analysis of accident effects. One way this can be accomplished is by installing the equivalent of flight recorders in the surface modes of transportation. Installed in, for example, the federal auto and truck fleet, the wealth of basic crash force data would provide an essential flow of information on the whole range of deceleration forces to which occupants are exposed. Such data, added to controlled crash tests, should permit a more precise prediction of trauma risk than is currently possible. Further, these kinds of data may be used to evaluate structural and interior design proposals for accident mitigation.

Trauma Data

A second requirement is to increase the flow of data on the nature of the trauma experienced in transportation accidents. At present, the data are inadequate, which compromises the ability to relate the crash dynamics to their physiological consequences. This is especially significant in injury-producing accidents, which may be significantly more amenable to mitigation efforts than fatalities. Further, the social as well as economic costs of injury accidents are so high that their mitigation would appear to be of highest priority. It is recommended that a joint effort be undertaken with the health care system to provide a comprehensive injury data base, including treatment regimes, practices, and costs. It may also be worthwhile to enlist the insurance industry, which also obtains detailed accident damage and trauma data.

Trauma Recovery

Considerable evidence suggests that the sooner treatment is begun, the higher the prognosis for survival. Most evidence suggests that getting the victim into treatment within 20 min would save upwards of 50 percent of the lives currently lost in highway accidents. The accomplishment of this objective requires a sophisticated effort at the local level involving communications, location, equipment, and manpower. There are varying programs for trauma management among the states, as well as varying investments. Data on such programs would provide a means of evaluating the range of effectiveness of trauma management and provide a basis for resource allocation to states.

Policy Analysis

If the flow of data discussed was available, it would be possible to evaluate investments in accident mitigation programs. The basic process would be the same as that regarding safety programs. It is reasonable in the policy process to ask where investments in the accident mitigation domain would have the highest return. It is certainly reasonable to ask which programs and proposals within program elements will have the highest return. Strategically, this is the only way to make investment decisions for reducing the consequences of accidents with limited resources.

SUMMARY AND CONCLUSIONS

Safety policy is the process of investment in and evaluation of programs designed to reduce the risk of failure in the performance of the transportation function. The ultimate question for policy purposes is, What is the most cost-effective way of reducing the current probability of system failure? From this follows the question, What data must be available to allow resource investment decisions to be made?

It is a major proposition that any of the global measures of safety, especially those defined in terms of accidents or accident rates, are unreliable and in most cases invalid. They may have political, vis-à-vis policy, attractiveness. However, if the objective is to invest in programs that will reduce the risk of system failure and its consequent costs, a more analytic approach is necessary.

Two different paths of analysis appear essential. One is failure analysis directed at the mechanical, electronic, structural, and human elements of the system. In addition, it includes the analysis of the vehicular and superordinate command and control functions, as well as the interactions with the physical and human environment. The purpose of a formal program of this type would be to provide a flow of data that identifies and prioritizes the importance of failure modes and provides a rational risk assessment. This, in turn, would provide the transportation policy maker a means of identifying safety investments that have a high probability of reducing risk to users. Such investments might include operational, structural, and technological changes in the ways transportation systems are designed, operated, and managed.

The second is accident mitigation, which requires analysis of the chaotic regime occurring after failure of the system. Data on how trauma occurs and the dynamics that determine its magnitude are basic to developing cost-effective structural, operational, and organizational programs that will reduce the effects of accidents.

Every modal agency within DOT has a safety responsibility. Every agency has a unit and personnel responsible for collecting, analyzing, and reporting safety data. With the exception of FAA, the focus has been on casualty data rather than safety, as defined in this paper. The safety analysis programs in FHWA and the approach to safety in the Bureau of Motor Carriers are examples. Transit safety has been largely accident oriented, and the data have been embedded in the Section 15 data base. Conversely, the new FAA program to develop a comprehensive safety data base that would provide a method for assessing and identifying aviation safety issues reflects the recognition of the safety as well as accident dimensions. It is well worth review by the other modes.

Finally, although it should be recognized that all modes of transportation are safety systems considering their scale and use, their safety is an essential criterion of their effectiveness. It is unfortunate that poor measures are often used as a basis for policy making at higher levels of safety policy. The result is often superficial and conflicting policy. There is little need for this to be the case. However, moving to a more consistent and coherent safety policy will require more sophisticated and scientific data bases than are currently being used. If they were employed, limited resources could be allocated more effectively and the safety of all modes of transportation could be measurably improved.

ACKNOWLEDGMENTS

The content of this paper derives from a review of the extensive literature on safety in the aviation, highway, and transit fields. More important, the framework and detail were developed with the help of many people. These included staff from NHTSA, FRA, and FHWA directly, as well as staff from the Office of the Secretary, the Library of Congress, and legislative staff. Their insights and material support provided an essential understanding of the federal perspective on safety and its data needs.

A series of workshops were held through TRB, in November 1989. Each covered a different mode; aviation, rail, highway, and transit. The participants were all responsible for safety or safety data analyses in their organizations at the local, state, and private levels. These workshops provided essential insights into safety programs, methods of analysis, and problems in safety planning, programming, and evaluation. Many, if not most, of the issues raised in this paper derived from that expertise. The paper could never have been completed without the continuing support of Richard Pain of TRB. As a liaison officer, he made this work possible.

APPENDIX A
Select Bibliography on Safety Information

Avolio, B. J., K. G. Kroeck, and P. E. Panek. Individual Differences in Information-Processing Ability as a Predictor of Motor Vehicle Accidents. *Human Factors*, Vol. 27, No. 5, 1985, pp. 577–587.

Barksdale, R. D., S. F. Brown, and F. Chan. *NCHRP Report 315: Potential Benefits of Geosynthetics in Flexible Pavement Systems.* TRB, National Research Council, Washington, D.C., 1989.

Bose, R. K. *Safety Life Cycle Methodology Development/AEM-7 Assessment.* DOT-AR-74316. FRA, U.S. Department of Transportation, 1982.

Briggs, D. W., and B. V. Chatfield. *NCHRP Synthesis of Highway Practice 133: Integrated Highway Information Systems.* TRB, National Research Council, Washington, D.C., 1987.

Burger, W. J., R. L. Smith, J. E. Queen, and G. B. Slack. *Systems Analysis of the Visibility Requirements of Passenger Car Drivers.* Report HS-802-290. NHTSA, U.S. Department of Transportation, 1977.

Burke, M. P., Jr. *NCHRP Synthesis of Highway Practice 141.* TRB, National Research Council, Washington, D.C., 1989.

Churchman, C. W. *Suggestive, Predictive, Decisive and Systemic Measurements.* Vol. 2, No. 3, September 1970.

Cirillo, J. A. *Limitations of the Current Mass System as Related to FHWA Accident Research.* TRB, National Research Council, Washington, D.C., 1983.

Council, F. M., J. R. Stewart, and E. A. Rodgman. *Development of Exposure Measurers for Highway Safety Analysis.* Report FHWA-RD-87-093. FHWA, U.S. Department of Transportation, 1987.

Council, F. M. Evaluation of Severity of Collisions With Roadside Features: Data Needs. *Transportation Research Circular*, Washington, D.C., 1983, pp. 20–21.

Crashing Cars by Computer. *New Scientist*, 1977.

Davis, S., E. King, D. Robertson, R. Mingo, and J. Washington. *Measuring Pedestrian Volumes and Conflicts.* Vol. II, Accident Prediction Model, Report FHWA-RD-88037. FHWA, U.S. Department of Transportation, 1987.

Delucia, R. A., and J. T. Salvino. *Statistics on Aircraft Gas Turbine Engine Rotor Failures That Occurred in U.S. Commercial Aviation During 1982.* Report DOT-FAA-CT-88-23. FAA, U.S. Department of Transportation, 1988, p. 42.

Edwards, M. L. *An Investigation of Selected Vehicle Design Characteristics Using the Crash Avoidance Research Data File.* NHTSA, U.S. Department of Transportation, 1987.

Evans, L. Driver Age, Car Mass and Accident Exposure—A Synthesis of Available Data. *Accident Analysis and Prevention*, Vol. 17, No. 6, 1985, pp. 439–448.

Faulkner, D., and J. A. Sadden. *Toward a Unified Approach to Ship Structural Safety.* Royal Institute of Naval Architects, London, England, 1978, p. 15.

Federal Highway Administration. *The Commercial Driver's License Information System (CDLIS).* FHWA, U.S. Department of Transportation, 1988.

Federal Highway Administration. *Fatal and Injury Accident Rates on Public Roads in the United States, Highway Safety Performance—1987.* FHWA, U.S. Department of Transportation, 1988.

Federal Highway Administration. *Motor Carrier Activities of the Federal Highway Administration.* Report FHWA-MC-89-045 HPS-1/4-89(4M)QE. FHWA, U.S. Department of Transportation, 1989.

Federal Highway Administration. *The Motor Carrier Lap Top Microcomputer Project.* FHWA, U.S. Department of Transportation, 1989.

Federal Highway Administration. *The Motor Carrier Management Information System (CMIS).* FHWA, U.S. Department of Transportation, 1989.

Federal Highway Administration. *The Motor Carrier Safety Information Network (SAFETYNET).* Report HLA-10. FHWA, U.S. Department of Transportation, 1989.

Federal Highway Administration. *A Program for the Advancement of Intelligent Vehicle/Highway Systems (IVHS).* FHWA, U.S. Department of Transportation, 1989.

Federal Railroad Administration. *Accident/Incident Bulletin No. 157, Calendar Year 1988.* FRA, U.S. Department of Transportation, 1989.

Federal Railroad Administration. Rail-Highway Crossing Accident/Incident and Inventory. *Bulletin 10, Calendar Year 1987.* FRA, U.S. Department of Transportation, 1988.

Federal Railroad Administration. *Summary of Accidents Investigated by the Federal Railroad Administration, Calendar Year 1986.* FRA, U.S. Department of Transportation, 1988.

Fontaine, H. *Risk Evaluation—Traffic Safety and Research Methods*, 1988, p. 14.

Francher, P. S., C. Mallikarjunarao, and R. L. Nisonger. *Simulation of the Directional Response Characteristics of Tractor-Semitrailer Vehicles.* University of Michigan Transportation Research Institute, Ann Arbor, 1979, p. 84.

Guastello, S. J. Catastrophe Modeling of the Accident Process: Evaluation of an Accident Reduction Program Using the Occupational Hazards Survey. *Accident Analysis and Prevention*, Vol. 1, 1989, pp. 61–77.

Hodge, G. A., and A. J. Richardson. Role of Accident Exposure in Transport System Safety Evaluations II: Group Exposure and Induced Exposure. *Journal of Advanced Transportation,* Vol. 19, No. 2, New York, 1985, pp. 201–213.

Joscelyn, K. B., and A. C. Donelson. *Drug Research Methodology: The Detection and Quantitation of Drugs of Interest in Body Fluids from Drivers.* NHTSA, U.S. Department of Transportation, 1990, p. 78.

Jovanis, P. P., J. L. Schofer, P. Prevedouros, and K. Tsunokowa. *Analysis of Bus Transit Accidents: Empirical, Methodological and Policy Issues.* UMTA, U.S. Department of Transportation, 1989.

Kroll, C. V., and R. D. Roland. *A Preview Predictor Model of Driver Behavior in Emergency Situations.* Report CAL-VJ-2251-V-6, Buffalo, N.Y., 1970, p. 105.

Lederer, J. Major Contributions to Aviation Safety. *Air World*, Vol. 31, No. 1, New York, 1979, pp. 12–17.

Mak, K. K., and L. I. Griffin. *Assessment of Existing Databases for Highway Safety Analysis.* Report FHWA-RD-85-117. FHWA, U.S. Department of Transportation, 1985.

McGean, T. J. *Special Report 170: Evolving a Rational Transit Safety Program.* TRB, National Research Council, Washington, D.C., 1976.

McGee, H. W. *Development of a Large Truck Safety Data Needs Study Plan.* Report FHWA-84-C-00058. FHWA, U.S. Department of Transportation, 1985.

McRuer, D. T. Measurement of Driver-Vehicle Multiloop Response Properties with a Single Disturbance Input. *IEEE Transactions of Systems, Man and Cybernetics*, Vol. 5, New York, 1975, pp. 490–497.

Mead, K. M., and V. S. Rezendes. *Railroad Safety FRA Needs To Correct Deficiencies in Reporting Injuries and Accidents.* FRA, U.S. Department of Transportation, 1989.

Mela, D. *Exposure Data Needs.* Report HS-019512. NHTSA, U.S. Department of Transportation, 1976.

Millette, R. E., and P. A. Joseph. *Drug and Alcohol in Transit.* UMTA, U.S. Department of Transportation, 1989.

Missouri Pacific Railroad. *Locomotive Component Performance System.* St. Louis, 1987.

National Highway Traffic Safety Administration. *Study Report of Methods to Improve the Application of State Traffic Records Systems.* Phase 2 Report. NHTSA, U.S. Department of Transportation, 1987.

National Highway Traffic Safety Administration. The Transportation Research Board's 403 Program Recommendations Contained in Highway Safety Research, Development and Demonstration. *Proc., NHTSA Conference*, Washington, D.C., 1980.

Office of Technology Assessment. *Safe Skies for Tomorrow.* Report OTA-SET-381, U.S. Department of Transportation, 1988.

Pugh, W. M., J. M. Erickson, and A. P. Jones. *Workers' Predictions of Safety as Predictor of Injury.* Report NAVHLTHRSC-HC-76-67. Washington, D.C., 1976.

Reidelbach, W., and F. Zeidler. *What is a Realistic Lateral Impact Test.* Report 830460. SAE, Detroit, Mich., 1983.

Rillings, S. K. *An Advanced Driver Information System for North America: A Strawman Proposal.* Report 891682. SAE, Detroit, Mich., 1989.

Rillings, J. H. *The Engineering Society for Advancing Mobility: Land, Sea, Air, and Space.* SAE, Detroit, Mich., 1989.

Road Safety; A Review of Research and Practice. 242 Praeger, East Sussex, England, 1981.

Ross, H. E. *Transportation Research Circular 256: Baseline Data Needs.* TRB, National Research Council, Washington, D.C., 1983.

Rugenstein, E. E., and C. DeAngelis. *Safety-Related Information Needs.* U.S. Department of Transportation, 1979.

Sabra, Z. A., E. C. Noel, B. V. Chatfield, and R. W. Eck. *Trends in Highway Information.* Report FHWA-RD-88-055. FHWA, U.S. Department of Transportation, 1988, p. 69.

Saccomanno, F. F., and C. Buyco. Generalized Nonlinear Models of Truck Accident Rates. In *Transportation Research Record 1172*, TRB, National Research Council, Washington, D.C., 1988, pp. 23–31.

Singh, C., and M. D. Kankam. *Reliability Data and Analysis for Transit Vehicles.* Ontario Ministry of Transportation and Communication, Toronto, Can., 1977, p. 73.

Sivak, M. Society's Aggression Level as a Predictor of Traffic Fatality Rate. *Journal of Safety Research*, Vol. 14, No. 3, Chicago, Ill., 1983, pp. 93–97.

Smith, R. A. *Use of Measurement Data.* Report HS-019528. NHTSA, U.S. Department of Transportation, 1976.

Squires, M. L., et al. *Accident Causation Methodology Development for the National Sampling System.* Report HS-805-102. NHSTA, U.S. Department of Transportation, 1979, p. 213.

Transportation Research Board. *Introduction to Comprehensive Computerized Safety Record Keeping Systems.* TRB, National Research Council, Washington, D.C., 1985.

Transportation Systems Center. Safety Information Reporting and Analysis System (SIRAS). *Heavy Rail Transit Safety Annual.* U.S. Department of Transportation, Cambridge, Mass., 1988.

Uher, R. A. *Transportation System Assurance: Terminology, Performance Indices, Failure Assessment, and Maintenance Management.* Report RMUTRI-TP-75-22. UMTA, U.S. Department of Transportation, 1975.

University College. Recent conference papers on traffic safety. London, England, 1979.

Urban Mass Transportation Administration. *Computerized Safety Information and Data Analysis System.* UMTA Office of Safety, U.S. Department of Transportation, 1988.

U.S. Department of Transportation. *The National Highway Safety Needs Report*, 1976.

Weir, D. *Evaluation and Correlation of Driver/Vehicle Data.* Report HS-5-01200. NHTSA, U.S. Department of Transportation, 1977.

Wojcik, L. A. *Probabilistic Risk Assessment and Aviation System Safety*, 1989.

Wolf, R. A. Mathematical Modeling Approach Suggested to Assimilate Data From Vehicle Safety Research. *SAE Journal Monograph*, Detroit, Mich.