Transportation Safety Index Applicable to All Modes

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There are a number of basic classes of transportation safety indices, based on time, event, activity, and population. Each has special utility for certain modes, but they lack a common basis and general applicability. This paper presents a failure index that can be applied to all modes and can allow cross-modal and intramodal comparisons. By using available data, the failure index was calibrated for the case of passenger fatalities. Among the results were that air was found to be less safe than intercity bus or rail for trips of less than 2400 km (1500 miles) and that, for short trips, air is generally less safe than the automobile. The failure index was also used to show how two operators that have the same basic safety performance can appear to differ because of composition of routes (i.e., trip-length distribution).

During the years 1965 to 1975, almost 625 000 people were killed in accidents related to transportation. A breakdown of fatalities by mode for the period shows that about 93 percent of all transportation-related fatalities were highway related. A reasonable conclusion would then appear to be that the improvement of the overall transportation safety record requires that the highway mode receive priority treatment.

Nevertheless, such percentages have little meaning when presented without an accompanying measure of modal exposure (i.e., passenger or vehicle kilometers). For illustration purposes, the trend of fatality rates per passenger kilometer for the period 1955-1974 is shown in Figure 1.

From an analysis of this figure, one would deduce that the most dangerous transportation mode is not highway but general aviation. However, analyses based on various accident-exposure rates may lead to different results, posing a valid question regarding the basis for a comparative ranking of the safety performance of the various transportation modes.

The problem of the evaluation of relative safety is further complicated by the definition of accident severity. The frequency of various types of fatalities and injuries also differs for each mode. Thus, the average severity observed in accidents by each transportation mode is different: Simply counting the number of fatalities and injuries is not sufficient to analyze a transportation-system safety performance. However, to do this systematically on a common basis and to allow for inclusion of all severity levels is a beginning. This paper presents a failure index by which the safety of the various modes can be expressed on such a common basis and illustrates it for the fatalities-only case (due to lack of suitable data for other severities).

CLASSES OF TRANSPORTATION SAFETY INDICES

Safety performance of transportation systems is generally expressed as accident frequencies.

Establishing satisfactory numerical indices to measure the safety of transportation systems requires the use of proper exposure measures (denominators such as distance, time, and number of passengers).

There are four basic types of safety exposure measures (denominators) used in the transportation field:

1. Time-based denominators,
2. Event-based denominators,
3. Activity-based denominators, and
4. Population-based denominators.

Cheaney (1) has given a thorough discussion of safety indices based on these four exposure measures. He investigated modal authorities' motivation for using a particular index and points out that their choice is influenced by the desire to present their facility in the best possible light. Some of the exposure measures frequently used in the field of transportation are summarized below.

Base	Exposure Measure
Time	Vehicle hours, passenger hours, system year
Event	Number of operations, number of takeoffs and landings, number of entries to and exits from harbors
Activity	Vehicle kilometers, passenger kilometers
Population	Number of registered vehicles, number of licensed drivers, residential population, number of vehicles in operation, number of passengers

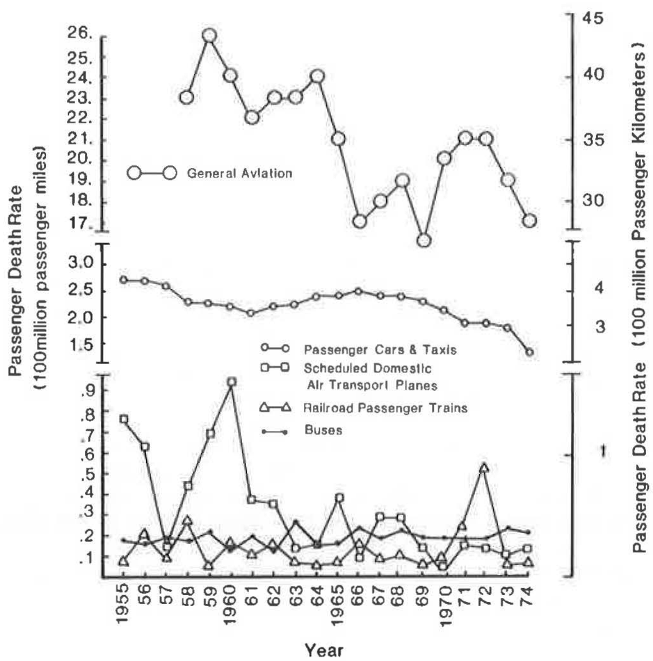
Time-Based Exposure Measures

These measures are important to both system operators and vehicle manufacturers for analyzing vehicle reliability. However, not all time spent in transportation-related activities is of equal risk, which leads to misleading conclusions regarding the safety of a system. Accident rates based on duration of operation or travel tend to neglect those accidents that occur during relatively short time periods, such as landings and takeoffs or entries to or exits from harbors. Aside from this, there are inconsistencies in comparing accident rates within a particular transportation mode. Annual changes in average speed are not directly accounted for and, thus, misinterpretations may arise in the meaning of accident rates. A faster vehicle may have an accident rate that is higher than that of a slower vehicle, without experiencing any increase in accidents, simply because the higher speeds of the faster vehicle will result in fewer hours of exposure, which in turn will reduce the accident rate.

Event-Based Exposure Measures

Not all of the time spent by an operator or a passenger in a given mode is of equal safety or danger. In the case of air transportation, the majority of accidents have more to do with the fact that a flight is made than with its duration or length. Thus, at least to a close approximation, the number of flights can be considered as a fair measure of exposure to accidents.

Figure 1. Comparison of fatalities by mode: death rates per passenger unit distance.



A rate such as "serious accidents per x million flights" is a reasonable technical indicator of safety achievement. This is only so, however, when the distribution of trip distance and landings and takeoffs per flight is invariant and, in actuality, this distribution has changed throughout the years.

Regarding the water mode, in his investigation of differences between U.S. and foreign vessel casualty rates, Tennenbaum (2) has pointed out that vessel years is not an appropriate exposure measure. Because most casualties occur in harbors and the approaches to harbors, he considers the number of harbor entries and exits to be a more satisfactory measure of exposure.

In rail transit, statistics (3) show that 78 percent of all accidents occur mainly in stations and in the immediate vicinity of car doors, indicating that the number of passengers who use the system, rather than the total travel time, may have the more significant impact on the total safety.

Activity-Based Exposure Measures

The most important activity-based exposure measure is annual kilometers of travel per vehicle. This type of measure is widely used for the analysis of both motor-vehicle and aircraft safety performance. Passenger kilometers as an exposure measure seems generally applicable to the evaluation of passenger safety.

This measure of safety becomes distorted when it is applied to aircraft or ships, where the probability of being involved in an accident is greater during takeoff and landing or when entering or exiting a harbor than during normal cruise.

Another major disadvantage of this exposure measure is its inability to account for differences in capacity and loading factors among the various modes. Also, in practice, problems exist in obtaining accurate data on the distances traveled by private automobiles and recreational boats.

Population-Based Exposure Measures

One exposure measure applicable to all modes of transportation is the number of deaths per million of population. Such statistics appear in demographic summaries and are used to compare the relative contributions of various factors (such as disease and accidents) to the population mortality rate.

Large variations in vehicle use among the different modes and on annual bases blur the real issue: human and property exposure to hazards. Modal comparisons are meaningless when there are significant differences in vehicle use and vehicle size. Even within the same mode, comparisons based on this measure may be misleading. Consider, for example, the taxi versus the private automobile. The taxi is exposed to hazards for longer time periods and experiences more accidents per number of licensed drivers or of registered vehicles than does the private automobile. This, however, does not mean that using a taxi is more dangerous than using a private automobile.

A NEWLY DEVELOPED MEASURE: THE FAILURE INDEX

The above analysis leads to the conclusion that only two of the four measures of exposure presented—time and distance—may be useful for the accurate evaluation of the safety of a system.

The most important question is, Is the probability of failure best expressed in terms of an exposure-hour or service-hour figure or in terms of distance traveled?

From the point of view of the transportation-service consumer, the issue is clear: The consumer must travel a distance X to arrive at a specified and desired destination. Therefore, the final issue is total risk or safety while traversing the specified distance.

However, this does not address the basic issues of device failure (e.g., motor or pilot) or exposure (hours in the air or time for conflicts) that are of interest to those doing risk modeling of a specific system. Indeed, the critical issue to some is, Is the risk more dependent on time or distance in this context?

If one turns to the macroscopic aspects and asks whether time or distance is more appropriate on that level, a review of the data renders the point moot. Rather than asking about basic engineering hazards on this level, we are simply asking whether time or distance has better explicatory value. The literature shows that time and distance are rather well correlated on a macroscopic level; however, the use of macroscopic data must be viewed with caution.

To account for the various problems noted to this point, this paper introduces and justifies a novel failure index (FI) that can be used as a measure of safety.

One of the central concepts in the development of such an FI is the identification of the functional differences during a trip throughout its various environments where an environment is defined and classified as a function of a specific segment of a trip. For instance, a flight can be divided into three functional environments (see Figure 2):

1. The entire takeoff phase, including terminal activities, taxiing, and actual takeoff to the point of being headed to the en-route controllers;
2. The normal cruise, from the vicinity of its origin to the vicinity of its destination; and
3. The landing phase, including any required holding patterns and related clearances.

Figure 2. Division of a flight into three functional environments.

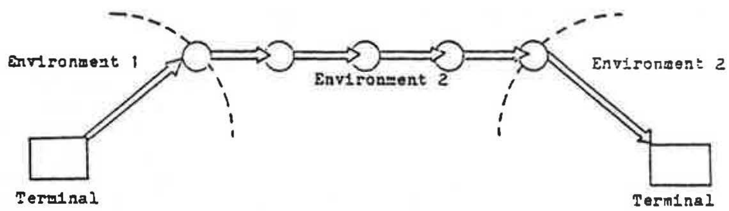
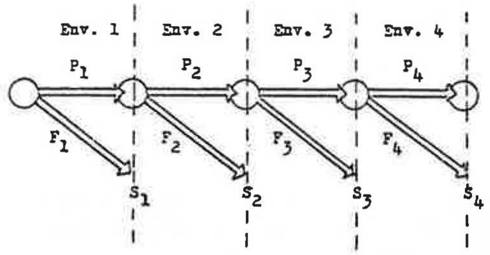


Figure 3. Generalized mathematical presentation of a trip.



It is important to recognize that each environment can be distinguished in the following ways:

1. Its physical description;
2. Its accident probability or risk, due to changes in its function or complexity, compared with that of the previous trip phase; and
3. Its severity, or the consequences of an accident, in terms of differing likelihoods of death, serious injury, and other effects on each of the environments.

For instance, 75 percent of all air-carrier accidents involving passenger fatalities occur during takeoff or landing. However, this does not tell the complete story: 90 percent of all passenger fatalities occur in those takeoff and landing accidents that involve fatalities. Therefore, one must distinguish between accidents involving fatalities (which are commonly called fatal accidents) and the actual distribution of the numbers of fatalities.

There is some value in standardizing the extent of those environments that could be rather open-ended or vary over wide-ranging values.

Among other effects, this definition of individual, consecutive environments that have the same time span allows for various probabilities of accident or severity due to such factors as weather or traveling over water.

It is also possible to aggregate environments when they can be paired logically, such as a takeoff and a landing.

Generalizing on this concept, Figure 3 illustrates a case of traveling through several environments, where the notation used is defined below:

Notation	Definition
P_i	Probability of successfully (i.e., safely) traversing environment i
F_i	Probability of unsuccessfully traversing environment i (i.e., an incident occurs)
S_i	Expected, average, or weighted severity given that an incident worthy of note occurs in environment i

Thus, $F_i + P_i = 1$. In addition, Figure 3 assumes that an incident occurring in any environment terminates the trip. The probability of successfully completing the trip is then

$$\prod_{i=1}^{N} P_i \tag{1}$$

where N = total number of environments.

Because different failure paths can occur, each with its own possible resulting severity, an equation that expresses the expected severity is not a simple one. In the illustration shown in Figure 3, the probability of an incident occurring in environment 3 is $(P_1 \times P_2 \times F_3)$ because environments 1 and 2 must be traversed successfully in order to reach environment 3.

Based on this approach, an FI can be formulated in the following way:

$$FI = \sum_{i=1}^{N} S_i F_i \left(\prod_{k=1}^{i-1} P_k \right) \tag{2}$$

That is, the FI is the expected severity (the weighted average of all the possible severities).

For the simple case in which the severity is equal across all environments (S_i = S for any i), Equation 2 can be rewritten as

$$FI = S \left(1 - \prod_{i=1}^{N} P_i \right) \tag{3}$$

which is based on expressing the probability of failure as one minus the probability of success.

Table 1 defines the environments as they can currently be divided for the data commonly available.

The use of Equation 3 is justified only if the severity does not vary from environment to environment or if the only accidents being considered are those that have a certain specified severity. Thus, this equation can be used in only two cases: (a) where any incidents that naturally occur happen to have comparable severities and (b) when only a certain class of accidents or incidents are considered, such that they all have comparable severities. In the latter case, the probabilities used would be those specific to that class of incident.

In practice, there is no commonly accepted, well-defined severity scale. At present, it is generally not possible to identify S_is for different environments. Therefore, the illustrations of this concept are based on the severity value of fatality only.

For each environment, it is necessary to identify a P_i of successfully traversing the environment. It is useful to define this in the form of

$$P_i = \exp(-\alpha_i) \tag{4}$$

For the case of the air-transport illustration, one might define

$$P_1 = \exp(-\alpha) \tag{4a}$$

$$P_2 = \exp(-\beta) \tag{4b}$$

$$P_3 = \exp(-\gamma) \tag{4c}$$

Table 1. Definition of environments for various transportation modes.

Mode(s)	Environments	Factors Affecting Safety
Air carrier and general aviation	Takeoff and landing and normal cruise	Weather, sophistication of air traffic control system, character of area overflown, total number of operations, type of airport, and maintenance
Highway	Rural freeway, rural arterial, urban freeway, urban arterial, and local street	Weather, traffic volume, lighting, geometrics, speed, and maintenance
Rail	Yard switching, normal cruise, station operation, and railroad crossings	Weather, number of passengers, geometrics, speed, conflicts with other modes, and maintenance
Rail rapid transit	Normal cruise, station operation, and yard operation	Weather, number of passengers, speed, and maintenance
Vessel	Harbor operation, ocean cruise, lake cruise, river cruise, and docking operation	Weather, traffic volume, harbor location and configuration, speed, and maintenance
Recreational boat	Ocean cruise, lake cruise, river cruise, stream cruise, and docking operation	Weather, traffic volume, speed, and type of craft

where the environments 1, 2, and 3 are as defined in Figure 2 [i.e., takeoff, normal cruise of 80 km (50 miles) standard distance, and landing] and α stands for environment 1, β stands for environment 2, and γ stands for environment 3. In the course of normal flight, N_1 takeoffs are encountered; N_2 cruise segments, each 80 km long, are encountered; and N_3 landings are encountered. Of course, $N_3 = N_1$. Thus, by using Equation 3,

$$FI = S\left(1 - \prod_{k=1}^{N} P_k\right)$$

$$= S\,[1 - \exp(-N_1\alpha)\exp(-N_2\beta)\exp(-N_3\gamma)] \quad (5)$$

where the product of the exponential terms gives

$$FI = S\left\{1 - \exp\,[-(N_1\alpha + N_2\beta + N_3\gamma)]\right\} \quad (6)$$

The use of Equation 3 is justified only if the severity does not vary from environment to environment or if the only accidents being considered are those that have a certain specified severity. For example, we may wish to consider fatality as the only severity worthy of note. In that case, the probability terms α, β, and γ (or, more generally, α_i) would be those associated with a fatal event.

The exponential term in Equation 6 can be expressed as a power series and approximated for small θ as

$$\exp(-\theta) = \sum_{i=0}^{\infty} (-)^i\theta^i/i! \simeq 1 - \theta \quad (7)$$

Because any accident is a relatively rare event, the values of θ are indeed small. Thus, Equation 6 can be approximated as

$$FI \simeq = S[N_1(\alpha + \gamma) + N_2\beta] \qquad (N_1 = N_3) \quad (8)$$

which is a convenient linear form. A similar useful approximation can be derived for each mode; generally resulting in

$$FI \simeq A + B(\text{distance}) \quad (9)$$

where A and B are constants related to the α_i.

CALIBRATION OF THE FAILURE INDEX

Because of the lack of a uniform severity ranking for the various environments and modes, attention in this section is restricted to fatalities. That is, the only severity considered explicitly will be a totality and probabilities will be developed for such events only.

This section describes

1. The development of the coefficients (α_is) involved in the probability P_i in the failure index and
2. The comparison of modal safety as a function of trip distance.

For each mode, the data that are typically available include (a) the number of fatalities, (b) descriptive statistics such as vehicle kilometers of travel and number of terminal operations, and (c) trip characteristics such as average distance traveled.

It is important to recognize that most statistics [which are expressed in terms of fatalities over some operating statistic (e.g., millions of vehicle kilometers)], are in fact fatalities per typical trip. This is shown graphically in Figure 4, as a single point where the two coordinates are "fatalities" and "typical trip". A typical trip by U.S. air carrier might be represented as one takeoff, one landing, and 960 km (600 miles) of normal cruise. For a local bus, it might typically be represented by one boarding, one alighting, and 16 km (10 miles) of on-board travel. The conventional statistics are in some sense a weighted average of the FI.

To the maximum extent possible, existing data were used to estimate the α_is for the various environments. The results are tabulated below (1 km = 0.6 mile).

Environment	$\alpha_1 + \alpha_3$	α_2 (fatalities/ 15 000 km)
U.S. air carrier	0.80×10^{-6}	0.0034×10^{-4}
Local roads and streets (rural)		2.31×10^{-4}
Federal-aid primary roads (rural)		1.47×10^{-4}
Local roads and streets (urban)		0.72×10^{-4}
Federal-aid primary roads (urban)		0.60×10^{-4}
Passenger automobiles and taxis		0.96×10^{-4}
Passenger automobiles on turnpikes		0.65×10^{-4}
Buses (city)		0.20×10^{-4}
Intercity buses		0.06×10^{-4}
Railroad passenger trains		0.07×10^{-4}

Where the data to obtain the α_is for the major phases were not available—takeoff and landing versus normal cruise—estimates were made according to the following logic:

1. Terminal activities (boarding and alighting) for local buses are assigned an A-value of 0.1 $\overline{FI}$; this is

somewhat arbitrary but necessary because of lack of data.

2. Personal transportation by automobile is assigned an A-value of 0.0; a driver and his or her automobile immediately enters the normal-cruise activity and has negligible landing-takeoff risk.

3. Rail rapid transit and passenger railroad are assigned A-values of 0.1 $\overline{FI}$ on a basis similar to local buses.

4. Intercity buses are assigned an A-value of 0.0, not because of negligible terminal activity, but rather because the nature of intercity buses is that they have some terminal risk, travel x kilometers on the road, encounter another terminal situation (e.g., a rest stop), continue for another x kilometers on the road, enter another terminal situation, and so on. The assumption of A = 0.0 is the approximation to this situation.

5. Airline data are available from which to estimate A and B independently, and this is done. Because A is so significant, the graphical presentation will show distinctly different results, depending on the number of stops during a journey.

Figure 4. Failure index for a typical trip.

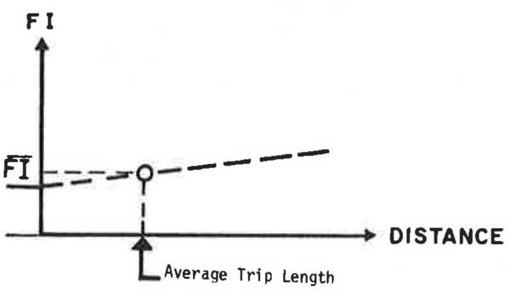


Figure 5. Detailed safety comparison among modes.

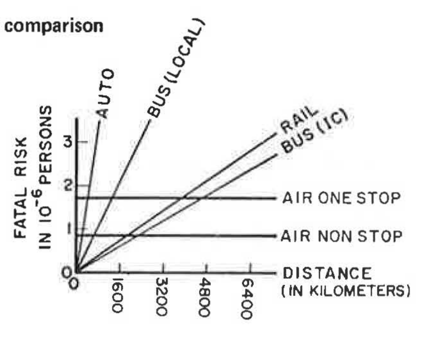
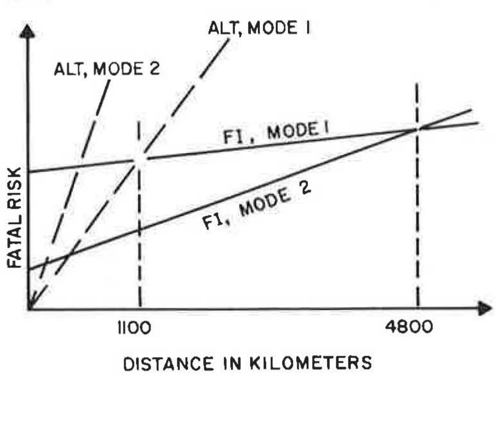


Figure 6. Comparison between two modes: which is safer?



KEY RESULTS OF FAILURE-INDEX FORMULATION

Figure 5 summarizes the key results for the failure index, given consideration of only fatal accidents from the point of view of the individual consumer—the passenger. With the exception of the air carrier estimate, these results are based on 1974 data; because of the inherent variability of that estimate (due to the rare-event nature of such accidents), the average for 1974-1976 is used. The use of only 1974 data would have led to an estimate almost twice that indicated.

The use of the failure index, as defined in this paper, shows that, as concerns the passenger interest and solely from the point of view of passenger fatality,

1. Travel by passenger automobile tends to be the worst choice of all modes, except when the only available modes are automobile or air—in this case, private automobile has a clear and distinct advantage for trips less than 240 km (150 miles) long.

2. For private automobile travel, as is commonly accepted, the preferred order of roadway systems with regard to safety is (a) federal-aid primary (urban), (b) turnpikes (toll roads), (c) local roads and streets (urban), (d) federal-aid primary (rural), and (e) local roads and streets (rural).

3. Intercity bus travel appears to have a slight advantage over passenger rail travel.

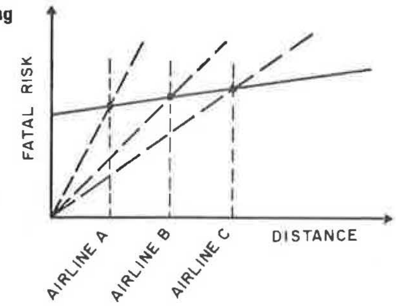
4. Both intercity bus and passenger rail travel have a distinct advantage over air carrier travel for all trips of less than 2400 km (1500 miles) and, if the flight makes even one stop en route, will have the advantage up to approximately 4800 km (3000 miles) [thus, air carrier travel has a safety advantage (as regards fatalities) within the continental United States only for nonstop trips of more than 2400 km, although indirectness of route on the intercity bus may somewhat offset this].

INSIGHTS INTO COMPARATIVE ANALYSIS OF MODES

Some of the above conclusions are quite different from what conventional statistics would lead one to believe. Safety statistics are sometimes used in public relations for a variety of modes, and they are sometimes abused when a mode is comparing its records with those of other modes, for public relations or other purposes. Figure 6 illustrates an interesting condition. Based on the failure index as described in this paper, mode 2 has a clear advantage over mode 1 up to a distance of approximately 4800 km. However, the average trip distance on the two modes may be distinctly different. Indeed, when one considers the arithmetic average of all trips by intercity bus versus the arithmetic average of all trips by air, this is not at all unexpected. Thus, conventional statistics would indicate that mode 1 is the safer of the two because its simple slope (through the origin) is lower (line "alt, mode 1" versus line "alt, mode 2"). That is, its number of fatalities per unit distance for the average trip distribution is smaller.

Even within a given mode, such comparisons can be made. Consider three airlines—A, B, and C—which have identical failure indices. However, for the purposes of simplicity, assume that airline A specializes in 800-km (500-mile) trips only, airline B specializes in 1600-km (1000-mile) trips only, and airline C specializes in 2400-km trips only (see Figure 7). Because all three have the same failure index, one could say that they have the same safety capability. However, one expects that, in terms of fatalities per unit distance, airline C will be shown to be the best.

Figure 7. Comparisons among three airlines that have identical failure indices.



Clearly, then, when any two carriers within an individual mode are compared, one must consider not their basic or even conventional statistics, but rather their α_is as defined in the failure-index concept.

CONCLUSIONS

The failure index can be used to make clear and unambiguous modal cost comparisons. The actual case described in this paper was that of the individual passenger and fatalities only. If sufficient data were available, it would be possible to develop comparable graphs to illustrate fatality risks from the point of view of the operator and of society. These graphs would include deaths of crew members, bystanders, and others. If severity scales were assigned in some systematic way, one could then use future data to ascertain the relative merits of the several modes from the point of view of total severity and not just of fatality. One could then address the critical questions of allocating funds for improvement to the various modes on the basis of equalizing the risk of the individual passenger or assigning priorities to the modes on the basis of minimizing total severity. In actual fact, one would then deal not just with modal priorities but also with the priorities of treatment among all possibilities, irrespective of mode.

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Changing Baseline in Transportation Safety: An Assessment of Some Key Factors

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Transportation accident experience depends on many factors, some very subtle. Although many countermeasures are introduced to enhance safety, it is also true that the accident experience can vary systematically over time even if no countermeasures are introduced. This variation in the baseline is investigated in this paper. How can the average condition vary if no new changes are introduced? Simply put, there are variations built into the total system—operators, roadway, and vehicles. Four major forces are considered in this paper: the changing age distribution of the automobile-driving population; the changing urban-rural balance; changes in modal trip lengths or vehicle types; and modal shifts induced by transportation system management actions. Each of these is found to have a significant effect (5-10 percent on the baseline), and other such forces can also exist. Clearly, it is not valid to explicitly or implicitly assume that the baseline does not change.

The development of a failure index (1) that can serve as a basis for comparing the relative safety of different modes is described in the previous paper in this Record. This paper uses that failure index and general indicators to study the apparent safety-record improvements that are induced by societal and other forces.

A number of forces are working in our society that