I was asked to write this paper on the relationship between speed and safety a few days prior to returning to the United States after a sojourn of a few months in Israel. I was returning to my home, to my car, and to my routine. On the first day back to work I drove on Washington’s crash-prone I-495 beltway and had the comfortable feeling of slipping back into a familiar routine. Then I noticed I was driving at nearly 70 mph (113 km/h), way above my routine speed on the beltway. My previous typical speed on that road was 60 mph (97 km/h). I did not feel any more risk than I had felt before. In fact the feeling was one of “sameness.” What I think had changed in the interim was the perceived enforced speed limit [raised from 55 to 65
mph (89 to 105 km/h)—not to be confused with the posted speed limit that has remained 55 mph] and the traffic-flow speed. What governed my chosen speed—the perceived enforced speed limit? My speed correlated with it. The prevailing speed of traffic? It correlated with that too. My risk-homeostasis level? I felt as safe as ever. My need to conform? Perhaps, since I certainly moved with the herd.

Once I realized what my speed was, my initial reaction was to ease off the gas. But I overcame this tendency (with ease) and decided to continue “with the traffic.” Was I taking a greater risk by traveling at a higher speed? My recollection of the aggregate research in this area supported such a conclusion. But I did not feel that way. And, perhaps most important, I did not slow down. My behavior was consistent with my feeling of safety.

My own response and probably that of most drivers is to balance safety, pleasure, and mobility. This review focuses on safety. However, statistically significant safety benefits are not always of practical significance. What makes a statistically significant effect practically significant is its magnitude relative to the societal value of mobility and the value of the pleasure the individual derives from driving. Speeding is logically related to mobility and subjectively related, for many people at least, to pleasure. Although these issues are outside the scope of this review, they are relevant to the implications of any empirical relationship between speeding and safety.

This paper is therefore as much an attempt to synthesize the information on the relationship between speed and safety as an attempt to understand my own behavior—in the belief that it reflects that of many other motorists.

BACKGROUND

The relationship between speed and crashes is axiomatic for many people in the traffic safety community. That axiom is encapsulated in the slogan “speed kills.” Speed is also listed as one of the manifestations of “aggressive driving” by the National Highway Traffic Safety Administration (NHTSA) (Martinez 1997) and safety interest groups such as Advocates of Highway and Auto Safety (Snyder 1997). Grass roots movements specifically targeting speeding are
emerging (e.g., Citizens Against Speed and Aggressive Driving) (Shiekh 1997). Yet recent drops in U.S. traffic fatalities despite repeal of the National Maximum Speed Limit (NMSL) serve to raise public doubts on the relevance of speed to crashes, as reflected in the national media with front page captions like “Fewer dying despite faster speed limits” (USA TODAY 1997).

In the following analysis this axiom is questioned, and the causal relationship between speeding and crashes is evaluated. In referring to speed as the predictor variable and crashes as the predicted variable, it is assumed that speed is the independent variable of interest and that safety is the dependent variable of interest. Optimally, to demonstrate that speed is the independent variable behind changes in crashes, it should be under the experimenter’s control (and it rarely is). For crashes to be a true dependent variable, a causal relationship has to exist, and it can never be unequivocally justified. Finally, both variables are multidimensional and need to be specifically defined.

DEFINITIONS: SPEED, SAFETY, AND INTERVENING VARIABLES

Safety is typically defined in terms of crashes or crash rates. At least two aspects of crashes should be considered as separate dependent measures of the effects of speed: crash probability (or incidence) and crash severity (given crash occurrence). In studying the effect of speed in particular, these two measures may not be highly correlated, since speed-related crashes are more commonly associated with severe injuries and fatalities and less with mild injuries and property damage. In contrast, the relationship between crash probability and speed is more complex, and speed-related crashes are not necessarily associated with high speeds.

Speed is not a singular concept in this context. First there is a need to distinguish between speed limits (prescribed speed) and travel speeds (drivers’ speed). The two overlap only in the presence of at least one of the following: intense enforcement, environmental constraints (e.g., speed humps, reduced lane width, reduced visibility), or vehicle limitations (e.g., old cars) that force drivers to drive at or
below the speed limit. Second, whereas speed limit is a single value, driving speed can be the speed of a single crash-involved vehicle or a statistic of the prevailing traffic speed distribution. Three such statistics are most often used in the context of safety: average travel speed, 85th percentile of the speed distribution, and some measure of the dispersion in travel speeds. Speed dispersion, in turn, can be quantified by the speed variance (the squared deviations from the mean of the speed distribution), the speed standard deviation (the square root of the variance), and sometimes by the speed range, such as the differential between the 15th and 85th percentile speed (which corresponds to approximately two standard deviations).

All the studies reviewed in this paper use some estimate of speed. In addition to the difficulty of integrating results obtained with the various speed measures mentioned above, there is a problem with the validity of the speed measures themselves. It is nearly impossible to obtain an objective measure of the true precrash speeds of crash-involved vehicles. This is because crashes are not planned, and consequently speeds must be estimated post hoc by various subjective and objective techniques, all having a limited validity. Only one study was found in which actual traffic crashes were videotaped and speed was calculated from the video frame analysis. In this study by Pasanen and Salmivaara (1993), a video camera specifically calibrated to measure speed recorded 18 intersection collisions in Helsinki, 11 of which involved pedestrians. In another study (West and Dunn 1971), precrash speeds for approximately one-fourth of the crash-involved vehicles were determined with a high degree of certainty from data obtained from speed detectors embedded in a section of an Indiana rural state highway with a 55-mph (89-km/h) speed limit. All other studies relied on drivers’ estimates, police officers’ estimates, or crash deformation data for calculating the speed of crash-involved vehicles. The few data that exist suggest that the relationship among the different speed measures is moderate at best (F.A. Haight, unpublished data, 1994). For studies relating traffic-flow speeds to crashes, the actual speed of the traffic stream at the place and time of the crash is usually not known; instead it is extrapolated from traffic-flow measures taken before or after the crash (e.g., Solomon 1964).
The reason drivers drive at different speeds probably affects the relationship between speed and crashes. Driving slowly in congested urban traffic is associated with many fender benders and very few severe crashes, whereas driving fast on expressways is associated with very few fender benders and a small but significant number of severe crashes. On the basis of these two situations, if all crashes are counted, it appears that speed is inversely related to crashes. However, if only severe crashes are examined, the relationship between speed and crashes is direct. In addition, driving slowly in congestion is done for a different reason than driving slowly on an open freeway. The difference may stem from the situation or from individual differences among drivers (a slow driver on a freeway may be a cognitively impaired elderly driver, whereas a slow driver on a congested urban street may be a highly capable driver hampered by traffic). For example, Solomon (1964) found that drivers at precrash speeds significantly above or below the average traffic speed have a greater likelihood of overinvolvement in crashes than do those driving just slightly above the average (Solomon 1964). But that relationship changed when turning vehicles were removed from the total driving population (Fildes and Lee 1993).

In aggregating crash data from different roads and different times to evaluate the effect of speed as a single independent variable, one assumes (at least implicitly) that “all other things remain equal.” This is never the case. In real life, driving speed is highly correlated with at least the following (Bowie and Walz 1994):

1. Other crash-related driver behaviors such as drinking, not using safety belts (Evans 1991), and other types of aggressive driving (in fact, speeding is often considered as a subcategory of aggressive driving);
2. Crash-related individual differences in variables such as age and sex;
3. Road design (e.g., speed-related crashes are overrepresented on curves) and road conditions, traffic conditions, and speed limits; and
4. Vehicular variables such as type of vehicle, engine power, and steering and brake performance.
All of these factors complicate the interpretation of data. In the absence of complete data to evaluate the joint contribution of all variables, the conclusions remain qualified.

Finally, when speed data are not available, a speed management technique is often used to assess the relationship between speed and safety. It is then assumed that speed covaries with the speed assumed by the management technique. The most common management technique is the speed limit. Other techniques are speed enforcement and speed calming through traffic engineering (e.g., sequencing traffic lights) and roadway design (e.g., road humps, traffic circles, and rumble strips). It then remains to be demonstrated that these techniques affect speed.

With these caveats in mind, the literature review will be divided into three major parts: (a) the effect of speed management/control techniques on speed and crashes, (b) the effect of speed on crash incidence, and (c) the effect of speed on crash severity. Finally, on the basis of the literature review, conclusions concerning speed and crashes will be drawn.

SPEED REDUCTION AND SPEED MANAGEMENT TECHNIQUES

An extensive review of the relationship between speed management, especially speed limits, and crashes is outside the scope of this paper. However, since these techniques are also used as surrogate measures of travel speed, a brief review of this relationship is appropriate.

Speed Limits

The impact of speed limits on crash risk is addressed in Appendix C. However, studies measuring both speed changes and crash experience in the context of speed limit changes and enforcement are relevant to this paper. Reviews of studies that evaluated changes in crashes and injuries in conjunction with changes (or the introduction) of speed limits have generally supported the notion that increases in speed limits without other concurrent changes are associated with increases in crashes; decreases or setting of speed limits where none existed
before are associated with crash and injury reductions (NHTSA 1992; Rock 1995; Summala 1985; TRB 1984). However, all of these studies suffer from the shortcomings of poor control of potentially confounding variables such as changes in traffic patterns as a consequence of speed limit changes, spillover effects of crashes to adjacent roads, changes in road service levels, and the concurrent introduction of other safety-related variables including increased enforcement, increased use of safety belts, reduction in drinking and driving, and vehicle-based safety improvements. In the context of the NMSL of 55 mph (89 km/h), a Transportation Research Board (TRB) special report on the enduring effects of this statute concluded, “Nevertheless, as improvements have been made to highways, vehicles, and medical services, the risk associated with higher speed driving has been reduced somewhat” (TRB 1984, 70). This means that comparisons across jurisdictions and over time (especially when the higher speed is the more recent) are flawed. The difficulties are so great as to yield opposite conclusions from the same data, depending on the measure of crash involvement used and the factors other than speed limits that are included in the analyses. Such disagreements have led Lave (1985; 1989; Lave and Elias 1994) to argue that, although raised speed limits increased fatalities on the affected rural roads, they have actually contributed to the observed reduction in statewide fatalities, whereas researchers of the Insurance Institute for Highway Safety (Zador and Lund 1991; Lund and Rauch 1992) have argued that the specific effects measured by Lave can be attributed to multiple other factors that have been previously linked to fatality reductions and that raising the speed limit has cost lives (NHTSA 1992).

Garber and Gadiraju (1988) suggested that the difference between the design speed and the posted speed limit accounts for differences in driving speeds; widening speed dispersion, in turn, was linked to increases in crash rates. On the Virginia highways they studied, minimum speed dispersion was obtained when the design speed was 5 to 10 mph (8 to 16 km/h) above the posted limit. This could also explain why lower speed limits sometimes increase the incidence of crashes. Parker’s findings (1997) of the inconsistent effects of temporary speed limit changes on short highway sections support this con-
clusion. Other factors, such as traffic conditions, can also affect speed and speed dispersion. Thus, Vaa (1997) found that compliance with enforced speed limits is less during peak periods than during off-peak periods. Also, when speed limits are lowered, they are typically accompanied by increased enforcement and public information campaigns (e.g., Nilsson 1990).

Parker’s analysis is relevant here because it measures the effects of changes in speed limits on driving speeds and the effects of these changes on crash involvement. Parker found small but statistically significant effects of speed limit changes on travel speed. Whereas the speed limits were changed by as much as 20 mph (32 km/h), the changes in travel speed (using either the means or percentile levels) were generally less than 2 mph (3 km/h) and were unrelated to the change in the speed limit. Also, the maximum speed limit never exceeded the 55-mph (89-km/h) NMSL that was in effect at the time of the speed limit manipulation (1985 to 1992). Finally, the relationship between speed limit and crashes in Parker’s study was ambiguous. Comparisons between crashes at sites where the speed limit was changed and crashes at the control sites showed a slight increase in crashes with increases in speed limits, whereas the before–after comparisons yielded a significant decrease in crashes with increases in speed limits. Parker’s study had an acknowledged major shortcoming in the site selection. The sites selected for the speed limit changes were chosen by local agencies on the basis of a predetermined need (e.g., request from the public, high incidence of crashes, compliance with local ordinances, changing land use patterns) rather than randomly. Thus it is likely that in many cases the changes actually reflected existing travel speeds. Given this severe constraint, the small number of sites, and short follow-up, Parker (1997) qualified his conclusions by stating that “the findings may apply to similar sites where the speed limits are changed for similar reasons. Generalizations to other roadways are not appropriate” (p. 85).

Under some circumstances, changes to higher speed limits may have a greater and more consistent effect. Photo-radar surveys conducted by the Insurance Institute for Highway Safety revealed that the percentage of drivers exceeding 70 mph (113 km/h) increased
significantly when speed limits were raised to 65 mph (105 km/h) in California and 70 mph in Texas (Retting and Greene 1997). If speeds in excess of 70 mph are well beyond the average traffic speed on these roads (admittedly an arguable assumption), then—either because of their high speed or because of their contribution to widening the range of traffic speeds—speeding drivers are at a greater crash risk. Their increased risk is consistent with both the “speed” model and the “variance” model because the more the driver exceeds the average traffic speed, the greater the range in traffic speeds and the further the driver’s position from the minimum point of the U-shaped crash involvement curve.

The issue of the role of speed dispersion is further complicated by the ambiguity of the term. Although the statistical definition of variance as a measure of dispersion is clear, the term is often misused. Different researchers have used different statistics to represent speed dispersion. Traffic engineers typically measure speed dispersion from the speeds of free-flowing vehicles over a short period. When measurements of speed dispersion are based on long durations of exposure and many of the vehicles are not free-flowing, it is not clear what the measure reflects. For example, an exposure period that covers both peak- and non-peak-period traffic can yield a wide range of traffic speeds, whereas in a short interval the range of traffic speeds may be narrower.

An intervening variable that may affect both compliance and crash involvement is the “perceived reasonableness” of the speed limit. McCoy et al. (1993) studied road sections in Nebraska and found that sites with “reasonable” speed limits were safer than those with limits 5 to 10 mph (8 to 16 km/h) below the “reasonable” levels. To ensure a good correspondence between this measure and speed choice, a recent evaluation of the relationship among safety, speed, and speed management conducted for Transport Canada suggests that the traditional rule of thumb for determination of speed limits—to use the 85th percentile for existing roads and the design speed for new roads—is still a good one (Knowles et al. 1997). Because actual speed limits are often dictated by other considerations, and given the lack of control of these variables in most studies, the researchers concluded that “changing the posted speed limit does not automatically
mean that speeds and crashes will be affected by the change and that it is not clear under what conditions changing the speed limit is likely to lead to a change in safety” (p. 2-9).

**Speed Enforcement**

Speed enforcement is probably the most common mediator between speed limit and speed choice. There is ample evidence that drivers respond to perceived enforcement by adjusting their behavior, most notably by reducing their speed (Shinar and McKnight 1985). The effect of enforcement is typically maximal at the site of the perceived enforcement, but halo effects relating to both time and place have been demonstrated. Holland and Conner (1996) obtained a time-halo effect lasting up to 9 weeks for speed enforcement coupled with signs stating “Police Speed Check Area,” and Vaa (1997) demonstrated that massive enforcement, with a daily average of police presence of 9 h, yielded speed reductions that lasted up to 8 weeks. This was done in a semirural area with a road section having speed limits of 37 and 50 mph (60 and 80 km/h). Interestingly, speed reductions varied by time of day, and morning peak-period speeders were the most resistant to change. This could have been due to pressure to get to work on time or the drivers’ knowledge that enforcement is more difficult (and therefore perceived as less threatening) in high-density, peak-period traffic. Shinar and Stiebel (1986) showed that compliance was highest near police vehicles and diminished with increasing distance. The distance-halo effect was greater for a moving than a stationary police vehicle, presumably because the moving vehicle could be perceived as more threatening even when it was already out of sight.

The link between enforcement and crash reduction was evaluated by Elvik (1997), who conducted a meta-analysis of studies that evaluated automated speed enforcement in several countries including England, Germany, Sweden, Norway, Australia, and the Netherlands. He concluded that, overall, automated enforcement yielded a 17 percent reduction in injury crashes (16 to 19 percent at a confidence level of 95 percent). The difference in effectiveness at different locations suggests that it is most effective at crash “black
spots” (i.e., high-crash locations). Whether the crashes migrate elsewhere, as has been argued by Lave and Elias (1994), is still an issue.

Other Speed Management Techniques

Perhaps the most cost-effective approach to speed control in the long run is through road design. This has been demonstrated with speed humps and with changes in design that are made to accommodate pedestrians in urban streets with “traffic integration.” This design approach was initiated in the Netherlands (and called “woonerf”) in 1968 and has spread in various forms to Germany, Denmark, England, France, Israel, and Australia (F.A. Haight, unpublished data, 1994). The integration is achieved through making roads narrow or winding or placing obstacles on the travel portion of the road so that vehicular traffic has to slow down to practically walking speeds [e.g., 9 mph (15 km/h)]. Although the effect on safety has not been the focus of evaluations of these changes, the effect on speed has been consistently reported (F.A. Haight, unpublished data, 1994).

SPEED AND CRASH INVOLVEMENT

From a very simplistic point of view it appears that as speed increases, the time to react to emerging dangers is shortened, and the likelihood of successfully coping with the imminent crash situation decreases. Also, even after a driver reacts by braking, the braking distance of the vehicle is proportional to the square of the prebraking speed. Therefore the distance traveled to a complete stop increases with speed, and the likelihood of a collision increases in a corresponding fashion. But reality is much more complicated, both theoretically and empirically. In this section an attempt is made to consider the theoretical issues involved and the empirical data that support and refute the relationship between speed and crash probability.

Some Theoretical Issues—and a Theoretical Quagmire

There are at least three theoretical approaches to relate speed to crashes, each leading to a different conclusion. Each approach views
the driver and the traffic environment from a different perspective, and each has been used as a conceptual framework that relates driver behavior to highway traffic safety. Some empirical validation has been demonstrated for each of them. The three approaches are referred to as the information processing/attentional approach, the risk-homeostasis motivational approach, and the traffic conflict approach.

**Information Processing Approach**

This approach considers the driver as an information processor with a limited capacity. The limit is on the rate of information processing. From a theoretical perspective, if a driver is assumed to be introduced into a fixed roadway/traffic situation, then the faster that driver drives, the greater the required rate of information processing, and the greater the demands of maneuverability of the car in an imminent crash situation. A crash is likely to occur when the information processing demands exceed the attentional or information processing capabilities of the driver (Shinar 1978) or the capabilities of the car. Even if the total amount of information the driver has to process stays constant, the rate at which that information must be processed increases directly with the speed of the driver. Furthermore, even at a constant speed, the rate of information flow is not constant but changes as a function of changes in the environment. Specifically, unexpected events dramatically increase the amount of information that must be processed. Such events include a car weaving in the lane, an obstacle in the travel lane, a curve with short sight distance, merging vehicles, and so forth. Other attention-demanding factors may be unrelated to driving, such as radio broadcasts, cellular phone conversations, or distractions from within the car. Consequently, at some speed, the increase in the information load can make the driver more likely to fail to process and respond fast enough to all the information, resulting in a crash. In lay terms, the driver was surprised and unable to respond to the situation in time. This approach leads to the conclusion that “speed kills.” As more and more drivers increase their speed, the likelihood of an overload increases for more and more motorists, and the probability of a crash—a situation in which the driver cannot respond appropriately in sufficient time—increases as well.
The attention factor is perhaps the most critical aspect of the information processing chain. Without exception all theories of human information processing acknowledge the limited attentional capacity of human beings; although it can vary over time, it cannot be sustained at a high level for any lengthy duration (Lindsay and Norman 1977). Furthermore, the act of paying attention is an effort (Kahneman 1973), as has been demonstrated in the driving context in sign detection and recall (Näätänen and Summala 1976; Shinar and Drory 1983). In-depth investigations of crash causes invariably point to lapses in attention (variably labeled as inattention, distraction, or improper lookout) as the most common human cause of traffic crashes. Such lapses have been implicated as a “cause” in approximately 50 percent of all crashes (Treat et al. 1977; Sabey and Staughton 1975; Shinar 1978; Evans 1991).

The implication for speed is twofold. If attention level remains constant despite increases in speed, then the crash potential due to a lapse in attention for a given duration increases as speed increases because in that duration the distance traveled increases and the safety margin decreases. If, on the other hand, the driver increases the amount of attention with increasing speed (as some drivers claim—the extreme claim being that driving slowly is boring and induces drowsiness), then the driving task becomes very fatiguing, and the heightened attention cannot be sustained for long periods. In either case, the attention factor suggests that increasing speed is tantamount to increasing crash potential. Because some highway design codes are based on assumed speed and reaction times (e.g., reading signs) and assumed sight distance to obstacles (e.g., railroad crossings), information overload and lapses in attention are more critical the faster the driver is going. Finally, as speed increases, each of the driving tasks becomes more difficult—detection of obstacles, recognition of impending danger, decision making, and response selection—and that difficulty contributes to the increase in crash risk (Kallberg and Luoma 1996).

**Traffic Conflict Approach**

This approach considers the traffic stream and roadway system as the source of potential conflicts to which a driver responds. The load on
the driver increases as a function of increasing disparities in speed in the traffic stream because of the different behaviors and speeds of the other drivers and vehicles. If all traffic moves in unobstructed lanes on divided highways at the same speed, then there is no uncertainty about the movement of the other vehicles, differences in driving speeds approach zero, and the potential for conflicts among vehicles does not increase with increasing speeds. Unfortunately, this is not the case since most roads are not divided highways, and the traffic flow is best represented by a distribution of speeds. Thus, in reality the number of conflicts between vehicle pairs can be represented by the number of passing maneuvers. The number of passing maneuvers a driver must make increases as the driver’s speed increases, and the number of times a driver is passed by other vehicles decreases as the driver increases speed. It can be shown that the distribution of the total number of overtakings (derived from the distributions of the number of times passing and number of times being passed) has a minimum at the median traffic speed. Therefore, the more the slower and faster drivers deviate from the median speed, the more conflicts they are likely to encounter (Hauer 1971). This logic leads to the conclusion that it is not speed that kills but the deviation from the median or average traffic speed that kills; the more a driver contributes to this deviation (by driving faster or slower than the median or average), the more likely the driver is to be involved in a crash. Therefore, the danger lies in the relationship between each driver and all other drivers. This can lead to the prediction that crash rates will be higher on roads with low median speeds but a wide range of speeds (e.g., two-lane rural roads) than on roads with high median speeds but a narrower range of speeds (e.g., expressways).

**Risk-Homeostasis Motivational Approach**

The first formulation of this approach was probably Taylor’s (1964) “risk-speed compensation model,” which postulated that drivers adjust their speeds in accordance with the perceived risk. Wilde et al. (1985) generalized this model to “risk homeostasis,” which, in the context of driving and crash avoidance, assumes that (a) drivers are not passive information processors who merely react to conflicts but
are active in the sense that they have needs and goals that affect their driving style, and (b) a primary motive of drivers is to maintain a subjectively acceptable level of risk. From this perspective, drivers do not set their speed indiscriminately; they adjust their speed according to the perceived risks. This approach has intuitive appeal since most drivers “feel” that they adjust their speed in response to the changing demands of the highway and the traffic (and thereby moderate the rate of information that must be processed). Thus, most drivers increase headways (the distance they maintain behind the cars ahead of them) at faster speeds to maintain a fixed temporal interval (Taieb and Shinar 1996), and drivers slow down on intersection approaches, on entering construction zones, in areas where the lane width is decreased, in the absence of hard shoulders, and so forth. If this adjustment is appropriate, there should be no correlation between speed and crashes. If the adjustment is insufficient, crashes should increase with speed. By the same token, if the adjustment to a perceived danger is excessive, then crash probability may actually decrease.

The question then becomes not one of the relationship between speed and crashes, but one of the correspondence between actual and perceived risk and between perceived risk and driver actions. This means that increasing speed per se is not a dangerous behavior but that an inappropriate excessive speed—stemming from misperception of the situational demands and lack of appreciation of the car and the driver’s own handling capability—may be dangerous. This approach can lead to different predictions concerning the relationship between speed and crashes, but since most drivers’ perceptions of the road and traffic ahead are fairly accurate, it would predict that under most circumstances the voluntary increase in speed of most drivers would not necessarily increase crash risk.

There is some empirical support for the risk-homeostasis theory. Mackay (1985) found that British drivers of newer and heavier cars drove at higher speeds than drivers of older and lighter cars (except for sports cars, which are fastest), but speeds of belted and unbelted drivers did not differ (this study was conducted in 1982, before the use of safety belts was made mandatory). Rumar et al. (1976) found that drivers with studded tires drove faster than drivers without such
tires on road curves in icy conditions but not in dry conditions, indicating that drivers adjust their speed according to their perceived safety or vehicle-handling capability. On the other hand, O’Day and Flora (1982) in their analysis of National Crash Severity Study (NCSS) data for tow-away crashes found that restrained occupants had lower impact speeds than unrestrained occupants. (This finding is consistent with the notion that it is the same hard-core segment of the driving population that speed, do not use safety belts, and drink and drive.)

With these conflicting theoretical approaches, it is no wonder that the issue of the relationship between speed and safety is hotly debated and one on which the motoring public is divided. Of the three major safety issues—safety belt use, drinking and driving, and speeding—the reported tendency to obey speed limits is the lowest and has decreased over the past decade. In contrast, the reported use of safety belts and the avoidance of drinking before driving have increased continuously (Shinar and Schechtman 1998).

The remaining task is therefore to review the empirical literature to determine whether there are sufficient data to reach definitive conclusions about the nature of the relationship between speed and crashes.

**Review of Empirical Data**

National crash statistics from the Fatal Analysis Reporting System (FARS) indicate that “driving too fast for conditions or in excess of posted speed limit” is a “related factor” for 20.8 percent of the drivers involved in fatal crashes. This statistic is often cited as the basis for concern with speed (Martinez 1997). However, the crash data must be interpreted with caution since they do not include an exposure measure, in this case, a statistic that indicates the percentage of drivers in the traffic stream where these crashes occurred who “exceed the speed limit or drive too fast for conditions.” On the basis of Parker’s (1997) study on the effects of raising and lowering speed limits on selected nonlimited-access roadway sections, the percentage exceeding the posted speed limit is typically greater than 20.8 percent. For this reason, to evaluate accurately the contribution of speed to
crashes, it is important to control for spurious effects through well-designed correlational analyses of crash and travel data or detailed cause-and-effect analyses of individual crashes. Unfortunately, neither type of analysis is common.

**Correlational Studies: Interpreting the Evidence**

Because of lack of controls, the results of the various correlational studies are often inconsistent with each other. Perhaps the best way to demonstrate the difficulty in directly testing the relationship between speed and crashes is to cite three studies that attempted to do that. The first is a comprehensive analysis of the correlation between fatality rates and speeds on various road systems in the United States during the 55-mph (89-km/h) NMSL era. The correlations of fatality rates and percentage of drivers exceeding 65 mph (105 km/h) was .33 for the expressways, .25 for rural arterial roads, and not significantly different from zero for rural collectors, urban arterials, and urban expressways. Furthermore, there were no significant correlations between fatality rates and the percentage exceeding 55 mph or 85th percentile speeds for any of the road types (TRB 1984, 66). The second analysis was detailed and focused on Virginia crashes; it failed to find any significant relationship between average speed and crash rates (Garber and Gadiraju 1988). In the most recent of the three studies, Liu and Popoff (1996) compared average speeds in seven sections of 62-mph (100-km/h) roads in Saskatchewan, Canada, between 1969–1982 and 1983–1995. Their measure of speed dispersion was the speed differential between the 15th and the 85th percentile speeds (which roughly corresponds to two standard deviations). In three sections the average speed decreased, the speed range narrowed, and the crash rate declined. In two sections the average speed remained relatively constant, the speed range narrowed, and the crash rate declined. In one section the average speed increased, the speed range narrowed, and the crash rate declined. In one section both the average speed and the speed range decreased but the crash rate increased. In contrast to these mixed results, on the basis of regressions derived from nine speed surveys on Saskatchewan provincial highways conducted since 1969, Liu and Popoff concluded
that the number of casualties is linearly highly related to the average speed (with $R = 0.90$), whereas the casualty rate (relative to kilometers driven) is linearly related to their measure of speed dispersion ($R = 0.94$). The caveats in this conclusion are that the study suffered from (a) a small range of average speeds studied [62 to 65 mph (100 to 105 km/h)], (b) a small number of observations, and (c) no control over many other time-dependent factors. In summary, the three studies can be used as support for both the existence and the absence of a relationship between speed and crashes depending on the speed measures and conditions used, the study design, and the crash statistics used.

It is therefore best to address the evidence from a loose chronological perspective and attempt to integrate the data on this issue as it accumulated.

The benchmark study of the relationship between speed and crash involvement and between speed and crash severity was conducted by Solomon (1964). A critical component of Solomon's study was the inclusion of the speed of the traffic stream as a potential mediating factor. Because of the care that Solomon took in examining all three aspects of speed—average speed of the traffic stream, speed dispersion, and reported speed of crash-involved vehicles—and because Solomon's study was the first, and to date arguably the most detailed and comprehensive study of this nature, its essential design features are described before its findings and conclusions are reported.

The study analyzed the crash experience of 10,000 driver-vehicles that had been involved in crashes between 1954 and 1958 on 600 mi (1000 km) of rural two- and four-lane highways consisting of 35 sections in 11 states. Roadway characteristics varied widely [with an average of 1.33 intersections per mile (0.83 intersections per kilometer) and 0.67 entrances per mile (0.42 entrances per kilometer)], as did speed limits [45 to 70 mph (73 to 113 km/h) for passenger cars in the daytime] and design speeds [35 to 70 mph (56 to 113 km/h)]. Traffic speed measurements at each of the sites were made during 1957 and 1958. Solomon also calculated the exposure of the vehicles traveling at different speeds by multiplying the number of vehicles measured at each speed in each road section by the length of the section, and then summing the data from all 35 sections. Finally, Solomon defined crash
involvement (his dependent measure) as the number of crashes per 100 million vehicle-mi (161 million vehicle-km).

Looking first at the relationship between travel speed of the crash-involved vehicles and the crash rate [number of crashes per 100 million vehicle-mi (161 million vehicle-km)], Solomon obtained the U-shaped functions reproduced in Figure B-1 for daytime and nighttime crashes. These curves show that the lowest involvement rate was at approximately 60 mph (97 km/h) and that the rate increased for both slower- and faster-moving vehicles. Note that the rate of increase relative to the minimum is plotted on a logarithmic scale. The rise would appear much steeper if the scale were linear. Figure B-1 indicates similar patterns for daytime and nighttime crashes, with overall nighttime crash rates being higher, and the minimum point for daytime crashes being approximately 5 mph (8 km/h) higher than at night. The increase in nighttime crash involvement at speeds greater than 65 mph (105 km/h) is much greater than the increase in daytime crash involvement at these speeds.

Why should speeds of 50 to 60 mph (80 to 97 km/h) yield the lowest crash rates? Solomon hypothesized that the speed with the lowest crash rates should correspond roughly to the average traffic speed. Seven years after Solomon's study was published, Hauer (1971) demonstrated mathematically that the number of vehicle encounters (in terms of passing or being passed) is a U-shaped curve with a minimum for vehicles traveling at the median traffic speed. Speeds greater than the median traffic speed involve more active passing maneuvers, and lower speeds involve more passive (being passed by others) passing maneuvers. Since most of the mileage in Solomon's study consisted of rural two-lane highways, this makes perfect sense. In a detailed analysis of crash involvement on a section-by-section basis, Solomon essentially confirmed this hypothesis. Involvement rates were lowest at speeds 5 to 10 mph (8 to 16 km/h) above the average and increased as the difference between the average and the speed of the crash-involved vehicle increased. His results, summarized for all 35 sections in terms of deviation from the average traffic speed, are presented in Figure B-2. If it is assumed that the speed distribution is not symmetric around the average but is negatively skewed (with a longer tail for slower-moving vehicles), the
average traffic speed is lower than the median, and the 5- to 10-mph minimum point above the average corresponds fairly well to Hauer’s (1971) theoretical derivation.

The pattern presented in Figure B-2 led Solomon to conclude that “regardless of the average speed on a main rural highway, the greater the driver’s deviation from this average speed, the greater his chance of being involved in an accident” (p. 16). In light of the higher rates
at the negative end of the speed axis, he further concluded that “low speed drivers are more likely to be involved in accidents than relatively high speed drivers” (p. 9). Solomon’s findings from the predominantly rural highways of the late 1950s were generalized to Interstate highway crashes by Cirillo (1968). Her data were limited to daytime rear-end and angle collisions and same-direction side-swipe crashes, and they are plotted alongside those of Solomon in Figure B-2.

In a related analysis, Solomon studied crash involvement of pairs of passenger vehicles involved in rear-end collisions. He found that crash-involved pairs were much more likely to travel at larger speed
differences than the likelihood of such differences in the traffic stream. This analysis provided further support for his conclusion that “a reduction in the variability of speeds can be an important element in accident reduction” (p. 17).

Over the years Solomon’s study has been reviewed and critiqued by many researchers (Fildes and Lee 1993; Knowles et al. 1997; Stuster and Coffman 1997). Four of the more critical shortcomings that have been mentioned are as follows:

1. The speed flow measures were not from the same times as the crashes. The speed data were collected in 1957 and 1958, whereas the crash data were distributed over 1954 to 1958.
2. The speed data from turning vehicles were eliminated from the analysis, but turning-related crashes were not.
3. The precrash speeds of the crash-involved vehicles were obtained primarily from self-reports by the drivers. They are most likely to be biased toward low speeds because “drivers tend to explain their traffic accidents by reporting circumstances of lowest culpability compatible with credibility” [“Stannard’s Law” (Aronoff 1971)].
4. The roads, traffic control devices, and vehicles are all from the 1950s and may not be relevant to today’s environment.

Two additional issues appear to have been overlooked in the previous critiques of Solomon’s conclusions and others’ interpretations of his results and should be added to the limitations. First, in arriving at his conclusion, Solomon makes the subtle substitution of a cause-and-effect relationship for the observed association between the speed deviation from the average traffic speed and crash involvement. Not only was speed deviation not manipulated in the study, but the contribution of speed deviation per se to crash involvement was never demonstrated in that study by comparing roads of similar physical geometry with different speed ranges.

Second, speed varies as a function of many factors, an important one being the design speed of the highway. In his analysis Solomon did not control for the design speed of the various road sections. Drivers tend to adjust their speed to design speed, and when different routes with different design speeds (e.g., rural collector roads and
expressways) are entered into the same equation, it can be shown that crash rates decrease with increasing average speed (Garber and Gadiraju 1988). Thus, examining the effects of variability in traffic speeds across different road sections of different types can be misleading.

Munden (1967) studied the relationship between speed and crashes in the United Kingdom. His measure of speed deviation was the ratio derived from dividing the speed of the study vehicles by the speed of the four cars that preceded it and the four cars that followed it. He found that drivers observed only once during the course of the study did not yield the U-shaped curve obtained by Solomon, having little variation in crash rates despite large differences in speed ratios. On the other hand, drivers observed more than once did exhibit the U-shaped curve. Munden's explanation was that the relationship is true only for drivers who habitually drive at deviant—especially slow—speeds. Even if drivers observed more than once drove regularly on that route and the measurement locations were identical, it is still likely that they were involved in turning or entering the road as a part of their regular driving habit.

Still, with Solomon's and Munden's results in mind and with a decade of experience with the 55-mph (89-km/h) NMSL, TRB's Special Report 204 stated that “if the average speed of the traffic stream could be increased without increasing the variance of the speed, then the adverse effects on safety might be comparatively small” (TRB 1984, 68). This statement was evaluated in several studies where, over time (and usually in conjunction with raising the speed limit), speeds increased. Interestingly, TRB's hypothetical scenario of increases in speed without concomitant increases in speed dispersion appears to occur. Unlike many other measures of driver performance in which the variance increases with increases in the mean, increases in speed limits typically result in smaller increases in the average speed and no consistent increases in measures of speed dispersion (Brown et al. 1990; Freedman and Williams 1992 for free-flowing vehicles on expressways; McCarthy 1991) or even a narrowing of speeds (Garber and Gadiraju 1988, who compared road sections of different road classes with different design speeds). Only a few studies reported slight increases in speed dispersion with
increases in average traffic speeds (Levy and Asch 1989, using the difference between the 85th percentile and the average speed as a surrogate measure; Retting and Greene 1997, using speed standard deviation).

To focus directly on the contribution of speed dispersion to crashes, Lave (1985) analyzed the relationship between crash involvement [in the same terms as Solomon—fatalities per 100 million vehicle-mi (161 million vehicle-km)], average speed, and speed dispersion (using a surrogate measure of the speed standard deviation—the 85th percentile speed minus the average speed—which roughly corresponds to the standard deviation when the average is very close to the median speed). Using the data from 48 states as 48 data points, he showed that for most road types, speed dispersion is positively related to crash rates, and when it is held constant (statistically), the correlations of crash involvement with average speed, percentage of vehicles exceeding 55 mph (89 km/h), percentage exceeding 65 mph (105 km/h), and 85th percentile speed are all non-significant. Independent “comments” in reply to Lave’s analysis confirmed the relevance of speed dispersion to crashes (Fowles and Loeb 1989; Levy and Asch 1989; Snyder 1989), although they all claimed that average speed is also a significant contributor. Still, in using the speed of crash-involved vehicles, none of these analyses were able to disaggregate slowing vehicles from slow-moving vehicles. Rodriguez (1990) used data from all 50 states and analyzed the contribution of average speed and speed dispersion to fatality rates [defined as number of fatal crashes per 100 million vehicle-mi (161 million vehicle-km)] separately for each year from 1981 to 1985. He also obtained a significant effect for speed dispersion (for 4 of the 5 years) and no significant effect for average speed.

Further support for the importance of speed dispersion beyond that of the average speed is the negative correlation typically obtained between the two measures: roads with higher average speeds also have narrower speed ranges (Garber and Gadiraju 1988; Lave 1985). In both of the studies that obtained this relationship, speed dispersion was defined in terms of the traffic speed distribution (and not in terms of the deviation of crash-involved vehicles from the average traffic speed). In one study, no relationship was obtained between
average speed and crash involvement (Lave 1985), and in the other study (Garber and Gadiraju 1988), with recorded average speeds ranging from 42 to 59.5 mph (68 to 95.8 km/h), crash rates actually declined with increasing average speed in a logarithmic fashion.

If “variance kills,” then presumably it is because it reflects the potential for intervehicle conflicts. However, accounting for Solomon’s and Lave’s findings and those of all the others in terms of Hauer’s theoretical analysis of the potential for intervehicle conflicts is somewhat problematic. That is because maneuvers that are most likely to be involved in passing and overtaking account for less than 5 percent of all maneuvers for crash-involved vehicles in the United States [merging/changing lanes = 3.0 percent, passing other vehicle = 1.3 percent (NHTSA 1997)]. Furthermore, an analysis of the crash characteristics of speed-related fatal crashes indicates that most (nearly 70 percent based on FARS) involve a single vehicle only (Bowie and Walz 1994), casting more doubt on the role of speed deviation and slow-moving vehicles. Solomon also calculated the percentage of crash involvements for different crash types as a function of speed. He found that whereas the percentage of single-vehicle crashes increased with travel speed, the percentage of rear-end and angle crashes decreased with travel speed, peaking at 15 mph (24 km/h) for angle crashes and 0 mph for rear-end crashes. These findings also point to the likely role that being stopped or entering and leaving the highway plays in low-speed crashes.

Still, ruling out intervehicle conflict as a crash-causing factor is not so simple. Crashes are typically coded as “single vehicle” if the crash-involved vehicle does not come in actual contact with another vehicle. However, often a single-vehicle crash, such as “run off the road,” may be due to an attempt to avoid a collision with another vehicle that enters its path. This information, which is often contained in crash narratives, is based primarily on the driver’s (or occupants’) report and is usually not available in the digitally coded crash data. In Indiana University’s Tri-Level Study of the Causes of Traffic Accidents (Treat et al. 1977), such crashes were coded as involving a “phantom vehicle.” In their representative sample of crashes, such events were relatively rare and were cited as a probable factor in 3.8 percent of all crashes, including multiple-vehicle crashes (Volume I,
p. 53). Their involvement may be greater in single-vehicle fatal crashes, but reports of their involvement would be rarer since most often the involved driver is killed.

Cowley (1987) recalculated Solomon’s involvement rates separately for six types of collisions and replicated the complete U-shaped curves only for nighttime head-on collisions. Predictably, crash rates increased with speed for single-vehicle run-off-the-road crashes and decreased with speed for rear-end crashes. However, angle collisions, “single vehicle struck object” crashes, and daytime-only head-on collisions decreased with increasing speed, suggesting that there is something to the argument that slow or slowing vehicles are overinvolved in crashes without necessarily shedding light on why this is so.

Solomon was aware of the difference between slow-moving vehicles and vehicles that were slowing down to negotiate some maneuver. Conceptually the difference is very significant: the former suggests that slow-moving vehicles are dangerous, whereas the latter suggests that situations requiring slowing down are dangerous. A typical situation that requires slowing down is turning to enter or leave the highway. In Solomon’s sample of roadways, with the exception of one segment of limited-access road, all segments had entrances and intersections. Solomon calculated that even if one-half of the crashes occurred at intersections and the data for these vehicles were eliminated from the analysis, the portion of the curve for low speeds in Figure B-1 would be reduced by a fraction of a log unit. But what if more than one-half of the crashes were at intersections? And what if some of the straight road rear-end crashes were due to vehicles suddenly slowing down in response to an emergency?

Further compounding this issue is Solomon’s exclusion of vehicles that had to slow down from the traffic speed data. Thus, although turning vehicles were not excluded from the crash data, the comparison data for the traffic speed did exclude these vehicles. A partial answer to these questions was provided by Harkey et al. (1990), who replicated Solomon’s U-shaped curve for nonalcohol, nonintersection, weekday accidents on non-55-mph (non-89-km/h) roads in North Carolina and Colorado. However, in this study too, the accuracy of the speed of both the crash-involved vehicles and the traffic at the time of the crashes remains questionable.
Other research has only added to the confusion about the “variance hypothesis.” The Research Triangle Institute (West and Dunn 1971) collected crash and speed data on rural roads in Indiana. The researchers used the same measures as Solomon for crash involvement and for speed differences (deviation of crash vehicle from the presumed average traffic speed). They conducted separate analyses of the data for all crashes and for crashes that did not involve turning vehicles. This meant removing nearly 45 percent of all crashes. The rationale for excluding these crashes was that turning vehicles should not be considered slow-moving vehicles (since their speed prior to the crash is not typical, but rather a response to a specific situation). The difference between the two data sets is illustrated in Table B-1 and is striking. The effect of removing these vehicles was to significantly flatten the involvement rate U-shaped curve. Since turning vehicles are only a subsample of vehicles slowing (versus moving slowly) ahead, it is likely that Solomon’s estimate of 50 percent of slowing vehicles is very conservative. (Other slowing vehicles are those approaching a blocked intersection, slowing in response to a vehicle ahead that is turning off or onto the road, detecting an obstacle on the road, etc.)

Cirillo (1968) studied the effect of deviations of crash-involved vehicles from the average traffic speed on freeways but also looked at crash involvement as a function of distance from an interchange. Her study was limited to same-direction and sideswipe crashes occurring

<table>
<thead>
<tr>
<th>Speed Deviation from Mean Travel Speed (mph)</th>
<th>Involvement Rate per Million Vehicle Miles</th>
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<tbody>
<tr>
<td></td>
<td>Including Turning Crashes</td>
</tr>
<tr>
<td>More than 15.5 below</td>
<td>42.3</td>
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<tr>
<td>15.5 to 5.5 below</td>
<td>2.3</td>
</tr>
<tr>
<td>5.5 below to 5.5 above</td>
<td>1.6</td>
</tr>
<tr>
<td>5.5 to 15.5 above</td>
<td>1.5</td>
</tr>
<tr>
<td>More than 15.5 above</td>
<td>8.5</td>
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Note: 1 mph = 1.609 km/h.
on weekdays between 9 a.m. and 4 p.m. These crashes were selected as the most likely to reflect the effect of speed differences in the traffic stream. Traffic speeds were also measured on weekdays between 9 a.m. and 4 p.m. As in Solomon’s study, precrash speeds of crash-involved vehicles were based mainly on drivers’ self-reports and therefore were probably biased toward underestimation. Cirillo found that proximity to an interchange substantially increased the crash rate, especially for urban interchanges (where the interchanges are closer to each other and the ramps may be shorter). In urban sections crash rates were highest at the entrance ramp, and in rural sections they were highest at the exit ramps. These findings provide indirect support for the role of vehicles that are forced to slow versus vehicles that move slowly, because in these locations both the traffic patterns and the roadway geometry change as a result of vehicles entering and leaving the highway from entrance and exit lanes.

Fildes et al. (1991) attempted to replicate Solomon’s findings for rural highways and extend them to urban highways. They used drivers’ actual measured speeds on Australian roads consisting of two rural road segments [two-lane undivided highways with a posted speed limit of 62 mph (100 km/h), and design speeds of 75 mph (120 km/h) on one and 47 mph (75 km/h) on the other] and on two urban segments [four-lane undivided arterial roads with posted speed limits of 37 mph (60 km/h)] and related them to self-reports of crash experience. Although self-reports are known to be biased (e.g., for alcohol-related crashes), there is no reason to believe that slow-moving drivers would be less inclined to report their crashes. In their study, the most recent of that kind, Fildes et al. failed to obtain a U-shaped curve at all. Their results are plotted in Figure B-3, which shows a linear rise in crashes as a function of speed, beginning with speeds well below the average. Their sample lacked any speed deviations as extreme (on the low end) as those reported by Solomon. The extreme low-speed deviations in Solomon’s curve and their absence in Fildes et al.’s data further suggest that the vehicles with large deviations were those that were forced to slow down just before being struck or causing a crash.

Interpreted in this light, the U-shaped curve can be explained as follows: in a two-car following situation, slowing vehicles are more likely to be struck than fast vehicles because when they slow down,
drivers behind them are often not immediately aware of the speed change, and thus slowing down reduces the headways of cars behind them. This may create imminent crash situations because of lapses in attention of following drivers, slowed responses of the following drivers, or misperception of the reduced gap by the following drivers. Lapses in attention (variously labeled as inattention, distraction, or improper lookout) are the most common human causes of traffic crashes (Treat et al. 1977; Sabey and Staughton 1975; Shinar 1978; Evans 1991). Thus, the more a driver has to slow down and the more rapid the deceleration, the more likely the driver is to be hit. Conversely, the faster the following driver is going, given momentary inattention, the more likely that driver is to fail to respond in time to the emerging collision situation.
One small study in which both precrash speeds and traffic speeds at the time of the crash were objectively measured has been reported in the literature. Pasanen and Salmivaara (1993) positioned a video camera, specifically calibrated to measure speed, above an intersection in Helsinki for more than 1 year. They recorded 18 intersection collisions, 11 of which involved pedestrians. In eight of the pedestrian crashes, the vehicles had at least a 3-s gap ahead of them (i.e., they were defined as “free-flowing”). In these cases the vehicles were traveling much faster [30 mph (48 km/h)] than the average speed of the traffic [24 mph (39 km/h)] or the speed limit [25 mph (40 km/h)] at that intersection. Thus, at least for urban intersections, there is one study with objective data demonstrating the relationship between a vehicle’s speed and crash probability.

More recently, two other studies focused on the effect of speed on urban crashes, and both obtained a positive power relationship between speed and crash probability. To rule out as many nonspeed factors as possible, both studies used the case control method, in which for every injury crash the speeds of noncrashing control vehicles moving at “free travel speeds” were measured at the same sites, on the same days of the week and at the same times of day, and under the same weather conditions. In addition, drivers with nonzero alcohol or who were involved in illegal maneuvers were excluded from the studies. Although the case control method is a correlational-type study, it is a much more controlled one because every attempt is made to match crash and noncrash vehicles in terms of the driving situation. Both studies were conducted in Adelaide, Australia, in urban 37-mph (60-km/h) zones.

In the first study, Moore et al. (1995) compared the speeds of 45 crash vehicles and 450 control vehicles. With 34 to 40 mph (55 to 64 km/h) used as the reference speed, increased crash involvement was obtained only for drivers exceeding the speed limit and not for those traveling at speeds less than the speed limit. For drivers traveling at 47 to 52 mph (75 to 84 km/h), the relative risk of an injury crash was approximately 8, and at speeds greater than 53 mph (85 km/h), the relative risk was 39 (i.e., the probability of a crash was almost 40 times as high as that of a vehicle traveling at 34 to 40 mph).

The second and more extensive study by Kloeden et al. (1997) compared the speeds of 151 crash vehicles with the speeds of 604
noncrash vehicles and obtained similar results. Casualty crash rates increased exponentially above the 37-mph (60-km/h) speed limit, remaining relatively constant until that speed. For vehicles traveling at 47 mph (75 km/h), the relative risk of an injury crash was 11, for vehicles traveling at 50 mph (80 km/h) it was 32, and for those traveling at 53 mph (85 km/h) it was 57.

In summary, with the exception of one small study mentioned above, none of the observational/correlational studies that have been reviewed were able to measure or empirically or statistically control for all the potential factors that mediate speed and crash probability. Therefore, any conclusion based on these studies must rest on the bulk of the evidence rather than on the results of a single study or series of studies. On the basis of the studies reviewed, it appears that (a) speed is a significant contributing factor to crashes; (b) specific types of crashes, such as “run-off-the-road” crashes, are definitely associated with high speeds; (c) cars with pre-crash speeds that are either significantly above or below the modal or average travel speed are likely to be overinvolved in crashes; and (d) at least part of the overinvolvement of slow vehicles is due to forced slowing down such as for intersections, avoidance of obstacles, and so forth.

**Causal Analyses**

The observational data and correlational studies of the relationship between speed and crashes cannot reveal the underlying causes of this relationship. Older drivers may not be able to respond to all emerging dangers even at low speeds because of age-related and medical impairments, whereas young drivers may be able to respond in time at these speeds. In contrast, mature drivers may have a better appreciation of their limitations and adjust speed accordingly, whereas young drivers may be oblivious to their vehicle-handling limitations as well as the handling limitations of the vehicle and may therefore travel at a speed too high to respond in time to a change in the roadway or the behavior of the traffic ahead. Causal analyses of individual crashes are useful in taking all these factors into consideration. Despite their subjective nature, causal analyses performed by
different investigators at different times and places consistently show that excessive speed is a factor in at least 10 percent of all crashes.

The role of speeding as a crash cause was probably first analyzed in a detailed and comprehensive manner by Treat et al. (1977). In this study, a representative sample of more than 2,000 police-reported crashes were analyzed by crash investigators at the crash sites, and 420 of them were further analyzed by multidisciplinary teams. A cause was defined as an event or action whose absence would have prevented the crash, all other things being equal. Furthermore, a human cause was cited if the causal behavior was a deviation from the normal or expected behavior of the average driver. Thus, speed would not be cited in a crash of a speeding vehicle unless the speed deviated from the speed expected at that site under the conditions that prevailed and the crash would not have occurred had the speed been as expected. With this approach to causation, the study estimated excessive speed to be a definite cause (with a subjective probability of 0.95 or higher) in 7 to 8 percent of the crashes and a probable cause (with a subjective probability of 0.80 to 0.94) in an additional 13 to 16 percent of the crashes. This approach to coding “speeding” as a causal factor is different from the FARS coding, where all causal or related factors are based on police crash reports and thus speeding as a crash cause is likely to include a mix of speeding relative to the posted speed limit and relative to prevailing conditions.

More recently, the role of speed in the causation of fatal crashes was assessed by Viano and Ridella (1996), who analyzed the data from 131 fatal crashes. The most common cause, labeled “nothing to do,” involved 30 crashes. In this type of crash the vehicle driver was unable to do anything to avoid the crash. These crashes were typically caused by “an unusual sequence or recklessness by another driver.” The second most frequently cited cause, responsible for 11 percent of the crashes, was labeled “rocket-ship.” This type of crash involved single-vehicle frontal-impact crashes with the “vehicles leaving the road at a very high speed.” No crashes were attributable to slow driving, although many of the crash scenarios involved maneuvers that presumably required drivers to slow down (e.g., yielding, 6 percent; making left turns, 4 percent; and negotiating curves, 9 percent).

Clinical post hoc causal analysis becomes much more difficult and expensive for large data files. However, it is possible to integrate
several files to obtain more reliable estimates of the role of speed in crash causation. This was done by Bowie and Walz (1994), who used several independent data files. They combined (a) the comprehensive census of all fatal crashes in FARS, (b) 1 year of data from all police-reported crashes from six states that are in the Crash Avoidance Research Data file (CARDfile), and (c) the 420 crashes analyzed in depth by Treat et al. (1977). Although they were based on different data sets and methodologies, the three sources yielded similar estimates, with “excessive speed” being involved in approximately 12 percent of all crashes and more than 30 percent of fatal crashes.

Liu (1997) studied the Saskatchewan, Canada, crash data files for the years 1990 through 1995. He defined a speed-related crash as one in which the police crash report noted that the driver was both “exceeding the speed limit and driving too fast for conditions.” Although this definition may appear conservative, it is appropriate since police reports are not as reliable as professional in-depth crash investigations. Liu found that speed was a causal factor in 9.2 to 10.5 percent of all crashes and in 11.9 to 15.2 percent of all casualty crashes.

In summary, in contrast to the conclusions that can be drawn from correlational analyses, studies using clinical causal assessment are unanimous in their conclusions about the contribution of speed to crashes: excessive speed (not necessarily in relation to the speed limit) definitely contributes to a small but significant percentage of all crashes and to a higher percentage of severe crashes. The various studies suggest that at least 10 percent of all crashes are speed related. However, these analyses have shortcomings: (a) their assessment methodology is “soft,” being based on post hoc clinical judgments, and (b) they have no adjustment for exposure. (If the percentage of drivers speeding in the traffic stream—in the clinical sense, not relative to the speed limit—is greater than the percentage of speeders in crashes, it could be argued that speeding may be a mitigating factor in crash involvement.)

**Importance of Road Type**

People drive differently in different environments—on different road types, on roads with different design speeds, and [to a lesser extent
Garber and Gadiraju (1988)] on roads with different speed limits. Consequently, it is important to consider the relevance of speed to these situations. A factorial combination of the various levels of each of the preceding three dimensions would yield many empty cells [e.g., rural expressways with a design speed of 25 mph (40 km/h) and a speed limit of 40 mph (64 km/h)]. Since average speed is closely related to design speed, and the latter is often redundant with road type, it may be best to disaggregate the findings of the studies reviewed above for specific road types. This is particularly important in light of the problem pointed out earlier concerning the validity of aggregating data across different road types. Road types that have different design speeds and different average traffic speeds, and thus for which different policy implications can be drawn, include the following:

- Limited-access highways (Interstate highways, freeways, and toll roads),
- Rural nonlimited-access arterial highways,
- Rural collector roads, and
- Urban streets.

Garber and Gadiraju (1988) analyzed the effects of road type and design speed on speed and crashes and found a strong relationship between road type and design speed and between these two variables and crash rates. Their data consisted of the average traffic speed, speed variance, and number of crashes at 36 road sections consisting of different road types with different design speeds. Limited-access highways had the highest design speeds, the highest average speeds, and the lowest crash rates. However, because of the very high correlation between design speed and driving speed (\( R^2 = 0.79 \)), one cannot conclude that high speeds are associated with low crash rates any more than that high design speeds (i.e., good and forgiving highway design) are responsible for low crash rates. From the risk-homeostasis hypothesis, it appears that good design provides a greater safety margin than the driver compensates for. From the traffic conflict and information processing model approaches, limited-access highways minimize conflicts and information overload, enabling drivers to increase their speed without incurring the risks of information overload.
Unfortunately, few studies have limited themselves to one type of road or disaggregated their results by road type. Therefore, the following observations rest on few data. The problem is further aggravated by the fact that the studies span a period of four decades in which the density of traffic, the design of highways and control systems, and the dynamics and crashworthiness of cars changed dramatically. Nonetheless, in this section the results discussed above have been reevaluated as they apply to the specific road types. For ease of presentation, there are some redundancies with preceding reviews of the studies.

**Limited-Access Highways**

Only one study focused specifically on limited-access highways. Cirillo (1968) demonstrated that Solomon’s U-shaped function between crash involvement and speed deviation applies to limited-access roads as well, as can be seen in Figure B–3. The main difference between Solomon’s daytime crash involvement rates for rural nonlimited-access highways and Cirillo’s Interstate highways is in the absolute lower level of crash rates on the latter. Otherwise, the two curves are very similar, indicating that the minimum crash involvement rate is at approximately 10 mph (16 km/h) above the average traffic speed; the rates rise above and below that point. Cirillo also found that crash involvement rates are significantly higher in the vicinity of interchanges than in straight highway segments, though an analysis by speed differences was not conducted. It is important to keep in mind that Cirillo’s study suffered from the same shortcomings as Solomon’s study, as mentioned earlier.

Garber and Gadiraju (1988) conducted a separate analysis on Interstate highways (rural and urban) and found a significant, positive relationship between crash involvement and speed variance. Crash rates increased as speed variance increased ($R^2 = 0.55$ in a linear regression model). Since the speeds of crash-involved vehicles were not available (unlike Solomon’s and Cirillo’s studies), the effect of the speed of crash-involved vehicles on crash probability could not be directly tested. Models of linear regression of the average traffic speeds on different road sections against their crash rates yielded no significant correlations.
Lave (1985) analyzed the contribution of both average speed and speed dispersion (using the difference between the 85th percentile and the average speed as a surrogate measure) separately for six road types and 2 years (1981 and 1982) using the 48 contiguous states as individual data points. For rural Interstates, he found a significant relationship between fatality rate [fatalities per 1 million vehicle-mi (1.61 million vehicle-km)] and speed dispersion, and essentially no contribution of the average traffic speed. In regression equations using both variables, \( R^2 = 0.63 \) for 1981, and \( R^2 = 0.52 \) for 1982. For all other road types (except arterial roads in 1981 as discussed later), the correlations between both variables and crash rates were statistically nonsignificant. Thus, no significant effects of average speed or speed dispersion were found for urban Interstates in either year.

*Rural Nonlimited-Access Arterial Highways*

Most of the road sections (27 out of 35) studied by Solomon (1964) were two-lane nonlimited-access rural roads. The remaining eight sections were four-lane divided rural highways of which only one had full access control. Thus, Solomon’s data previously reviewed in detail (and shown in Figures B-1, B-2, B-4, B-5, and B-7) indicate that it is not the absolute speed of the crash-involved vehicle that is related to crash probability, but its deviation from the average traffic speed (with all the caveats listed in the section on correlational studies).

The other studies that attempted to assess the importance of speed deviation to crash involvement on nonlimited-access rural highways were less conclusive than Solomon’s study. West and Dunn (1971) attempted to improve the validity of the crash-involved vehicle speed data and assess the contribution of turning maneuvers to the U-shaped curve. As can be seen in Table B-1, once turning vehicles were eliminated from the data, the U-shaped curve was greatly flattened and manifest only at very low and high speeds [i.e., 15 mph (24 km/h) above and below the average speed].

Fildes et al. (1991) conducted a speed and crash involvement study on two major rural arterial roads in Australia and were unable to replicate Solomon’s (1964) findings. Their results, plotted in Figure B-3, show that there was only a simple linear association between
crash rate and speed deviations of crash-involved vehicles. However, even that relationship was based on a very low correlation [as estimated from their scatterplot (p. 61)]. Furthermore, in their study the crash data were all based on self-reports, and the total number of data points was much smaller than in Solomon’s study. Finally, the range of speed deviations (also noticeable from Figure B-3) was much smaller than in Solomon’s study.

Garber and Gadiraju (1988) and Lave (1985) attempted to relate measures of speed dispersion to crash rates. Garber and Gadiraju obtained a significant and very high correlation ($R^2 = 0.79$) between speed variance and crash rates for all arterial highway sections combined. Since 12 out of the 14 arterial sections in their study were rural, it is safe to attribute the finding to rural arterial highways. Lave obtained a weak but statistically significant relationship between crash rates and a measure of traffic speed dispersion (85th percentile minus average traffic speed) on rural arterial highways for 1981 data ($R^2 = 0.25$ approximately), but not for 1982 data. Neither Garber and Gadiraju nor Lave obtained any significant relationships between average traffic speeds and crash rates. Speeds of the crash-involved vehicles were not available in their studies.

**Rural Collector Roads**

Rural collector roads form a large portion of the highway system. Their crash rates [per 100 million vehicle-mi (161 million vehicle-km)] are relatively high, but their fatality rates are lower. For example, in Virginia crash rates on rural collector roads were more than three times those of rural Interstates [169 versus 52 per 100 million vehicle-mi (105 versus 32 per 100 million vehicle-km)] but the fatality rate was the same [2.0 per 100 million vehicle-mi (1.2 per 100 million vehicle-km)] (Garber and Gadiraju 1988). Although Garber and Gadiraju collected data on seven segments of major rural collectors, they did not provide any information on the relationship between speed-related measures and crashes separately for these sections. Solomon probably also included rural collector road segments in his data, but they were not analyzed separately. Lave (1985) conducted a separate analysis of crash rates on rural collector roads, but average speed, 85th percentile speed, and his measure of speed dis-
persion (85th percentile speed minus the average speed) were not significantly related to crash rates.

**Urban Streets**

Urban streets account for the highest percentage (39 percent on “local roadway/streets and collectors”) of speed-related fatal crashes among all road types (Bowie and Walz 1994). Yet only one of the studies reviewed provided data specific to these types of roads in the United States. Fildes et al. (1991), in their attempted replication and extension of Solomon’s data, only obtained a positive linear relationship between crash rates and speed deviation, indicating that the higher the speed the greater the probability of crash involvement (Figure B-3). However, although the relationship appears strong, Fildes et al.’s data are based on only two sites consisting of undivided urban streets posted at 37 mph (60 km/h). More rigorous case-control studies (Kloeden et al. 1997; Moore et al. 1995) also obtained a positive power relationship between speed and crash probability. A similar conclusion, also based on a small data set, can be reached from the study of urban pedestrian crashes at a signalized intersection in Helsinki by Pasanen and Salmivaara (1993). Lave (1985) found a low correlation between his measure of speed dispersion and crash rates on U.S. urban arterial roads \((R^2 = 0.15\) approximately), but even that correlation was significant for 1982 and not for 1981.

In summary, there appears to be a limited amount of data—and with many methodological shortcomings mentioned in the preceding section—that suggest that on Interstate highways, increases in the range of traffic speeds are associated with increased crash rates; the more a vehicle deviates from the average traffic speed (or from slightly above the average traffic speed), the more likely it is to be involved in a crash. The underlying cause of the crashes of vehicles deviating from the average speed appears to be related to entering and exiting the highway, indicating that the low speed is situationally forced and not due to vehicles moving at a consistently low speed. On nonlimited-access rural arterial highways and collector roads there are more data, but they are conflicting. Consequently, it is difficult to draw any conclusions. On urban streets there appears to be a strong relationship between crash rates and the absolute speed of the crash-
involved vehicles (which correlates with their deviations above average travel speeds). Although that relationship has been observed in several independent studies, with one exception (Kloeden et al. 1997), the conclusion is based on small data sets, and the majority of the studies have been conducted outside the United States.

**SPEED AND CRASH SEVERITY**

When his son got a driver’s license, a Carnegie-Mellon University physics professor glued this reminder on the car’s dashboard: \( E = \frac{1}{2}mv^2 \). The son got the message and remembers it to this day, 13 years later.

Crash severity can be defined in at least two ways: (a) the physical severity of the impact speed or Delta-V (the velocity change in the crash) and (b) the severity of injuries to the vehicle occupants. Over the years, the measure of physical severity has changed from the speed (or relative speed in the case of two or more vehicles) at impact to Delta-V. Injury severity is still described in various ways, such as the worst injury sustained in a crash (e.g., fatal, injury, or property-damage-only crash) or the more graduated Abbreviated Injury Scale (AIS) in which injury levels range from 1 for a minor injury to 6 for an unsurvivable one.

The relationship between speed and Delta-V is intuitively obvious. The faster a vehicle is moving prior to contact with another vehicle or a stationary object, the greater the Delta-V. Furthermore, the expected effect on injury should not be linear, because the at-crash deceleration is proportional to the square of the impact speed. Nonetheless, the actual effect on injury should be demonstrated empirically. This is because the power of the impact may be mitigated by various shock-absorbing behaviors that occupants may adopt (e.g., use of safety belts) and the various shock-absorbing design features of the various car makes and models.

In his 1964 report Solomon also studied the relationship between speed and severity using two measures of crash severity: (a) injury rates expressed as the number of people injured relative to the number of crash-involved vehicles and (b) property damage cost per crash-involved vehicle. The results of these analyses are presented in
Figures B-4 and B-5, respectively. The relationship is clear-cut: the higher the speed, the greater the cost, in both injuries and property damage. Solomon calculated fatality rates in a similar manner. With a total of 253 fatalities, Solomon found that the odds of a fatality given a crash accelerated with speed from a low of approximately 1 to 2 fatalities for every 100 crashes at speeds less than 55 mph (89 km/h) to a high of more than 20 fatalities for speeds of 70 mph (113 km/h) and above.

In an analysis of the National Analysis Sampling System (NASS) data, Joksch (1993) found a consistent relationship between the fatality risk for a driver in car-car collisions and Delta-V. On the basis of his analysis, risk is closely related to Delta-V^4 (i.e., to the fourth power). By fitting curves to crash data with known and estimated

![Figure B-4 Persons injured per 100 involvements versus travel speed for daytime crashes (Solomon 1964). 1 mph = 1.609 km/h.](image-url)
Delta-Vs and by using different assumptions for the estimated Delta-V, Joksch obtained similar functions with exponents ranging from 3.9 to 4.1 for all types of crashes (and not just car-car). This led Joksch to conclude that “the findings are somewhat robust against changes in the assumptions” and that “the exponent 4 may reasonably reflect the relation between the fatality risk and Delta-V. Even if not precise it may be useful as a rule of thumb” (p. 104). The relationship obtained by Joksch using different assumptions about Delta-V is presented in Figure B-6. A relationship where the dependent variable is a function of the independent variable taken to some power is known as a power function. In the present analyses of the relationship between severity (the dependent variable) and speed (the independent variable), the power was always greater than 1.0, indicating not only that severity increases with speed but also that the rate of severity increases with speed. A similar power function was obtained in an earlier analysis of 10,000 crashes documented in the NCSS from
1970 to 1979 by O’Day and Flora (1982). Their function showed that at speeds of 50 mph (80 km/h), the fatality rate—mostly for unbelted occupants—was slightly above 50 percent. Interestingly, Mackay (1988), apparently using the same U.S. NCSS data, estimated that the risk of fatality exceeded 90 percent when Delta-V exceeded 50 mph. It is next to impossible to examine the original data that both used, but it appears that O’Day and Flora’s estimates are more appropriate, because 1995 NASS data (with national safety belt use rates exceeding 60 percent) indicate a fatality rate of 33 percent for Delta-Vs above 45 mph (72 km/h) (NASS 1998).

The effect of speed on pedestrian fatalities follows the same trend. The European Transport Safety Council (1995) concluded that in a 20-mph (32-km/h) collision between a vehicle and a pedestrian, the probability of pedestrian death is 0.05; at 30 mph (48 km/h) it rises...
to 0.45; and at 40 mph (64 km/h) it is 0.85. Pasanen and Salmivaara’s (1993) data are in close agreement with these findings.

The power relationship also holds well for nonfatal injuries. Bowie and Walz (1994) calculated the relationship between Delta-V and injury rates for AIS Level 2+ injuries and AIS Level 3+ injuries and obtained the results reproduced in Table B-2. Injury rate was defined as the number of occupants injured at the Delta-V level divided by the total number of occupants involved in crashes at that Delta-V times 100. Thus the AIS 3+ injury rate increased from a range of 0.7 to 1.0 for crashes with Delta-Vs of 1 to 10 mph (1.6 to 16 km/h), to a range of 54 to 57 for Delta-Vs greater than 50 mph (80 km/h). Combining measures from FARS, CARDfile, and the General Estimates System, Bowie and Walz also showed that the percentage of speed-related crashes increases with increasing injury level: from 10.2 percent in no-injury crashes, to 17.1 percent for incapacitating-injury crashes, to 34.2 for fatal crashes.

Using an econometrics approach, O’Donnell and Connor (1996) applied models of ordered multiple choice (logit and probit) to all New South Wales 1991 crash records (totaling 28,747). They found that, relative to a benchmark crash with a 33-year old driver, a 1 percent increase in speed yielded a 0.44 to 0.56 percent increase in the probability of death. Although they mention that in econometrics models such a change of less than 1 percent is labeled “inelastic,” it is a practically and statistically significant change.

In conclusion, all of the studies that have investigated the relationship between vehicle speed and crash severity have found a consistent relationship showing that as the speed increases, Delta-V and injury severity both increase.

THE COST OF SPEED: COMBINED EFFECTS OF INCIDENCE AND SEVERITY

The determination of an optimal or desirable speed is not a scientific issue but a political one. Between maximum mobility at infinite speed and maximum safety at zero speed, there is a huge range for compromise.

An appreciation of the societal costs of crashes of various severity levels is possible when crash rates are disaggregated and their inci-
Table B-2 Injury Rates by Crash Severity; Comparisons of NCSS and NASS (1982–1989) (Bowie and Walz 1994)

<table>
<thead>
<tr>
<th>Total Delta-V (mph)</th>
<th>AIS 2+</th>
<th>AIS 3+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCSS</td>
<td>NASS</td>
</tr>
<tr>
<td>1-10</td>
<td>2.4</td>
<td>4.5</td>
</tr>
<tr>
<td>11-20</td>
<td>9.5</td>
<td>10.6</td>
</tr>
<tr>
<td>21-30</td>
<td>25.3</td>
<td>29.2</td>
</tr>
<tr>
<td>31-40</td>
<td>51.8</td>
<td>53.4</td>
</tr>
<tr>
<td>41-50</td>
<td>70.3</td>
<td>67.2</td>
</tr>
<tr>
<td>Over 50</td>
<td>64.7</td>
<td>69.3</td>
</tr>
</tbody>
</table>

Note: Rate equals the number of occupants at a certain Delta-V level (in 10-mph increments) injured at specific AIS levels (AIS 2+ or AIS 3+) divided by the total number of occupants involved in crashes at that level of Delta-V times 100. Rate does not include cases in which either the Delta-V level or the AIS level was unknown. AIS = Abbreviated Injury Scale; NASS = National Analysis Sampling System; NCSS = National Crash Severity Study; CDS = Crashworthiness Data System; 1 mph = 1.609 km/h.

Sources: NASS, 1982–1986 and 1988–1989 (CDS). Includes only tow-away cases. There was no statistically representative NASS file in 1987. NCSS, 1979. Data are limited to tow-away crashes involving passenger cars and light trucks. Data are not nationally representative.

dence examined separately by severity level. Speeding is typically a more common crash-related factor in the more severe crashes. In contrast, the overall crash data are heavily weighted by property-damage-only crashes, which constitute the majority of crashes. This is illustrated in Table B-3 using CARDfile data of police-reported crashes from six states (Bowie and Walz 1994, Table 5). The table indicates that, of the total crashes in the file, the percentage of speed-related crashes increases with increasing injury severity levels: from 10 percent for no-injury crashes to 34 percent for fatal-injury crashes.

A similar effect can be observed in Solomon’s data. The injury rates [number of people injured per 100 million vehicle-mi (161 million vehicle-km)] in Solomon’s study are shown in Figure B-7. The daytime and nighttime curves in this figure are similar to the crash rates in Figure B-1 but (a) have their minimum at a lower speed level [approximately 55 mph (89 km/h)] and (b) show a much greater rate
of involvement at higher speeds (relative to lower speeds) than was observed for all crashes in Figure B-1. An even sharper trend (above the average speed) was noted for fatality rates. During the day, the fatality rate was relatively constant at 2 fatalities per 100 million vehicle-mi (1 fatality per 100 million vehicle-km) for speeds up to 50 mph (80 km/h), increasing to 31 fatalities per 100 million vehicle-mi (19 per 100 million vehicle-km) (i.e., by a factor of 15) for speeds higher than 72 mph (116 km/h). At night, the rate was generally higher. The rate remained under 20 per 100 million vehicle-mi (12 per 100 million vehicle-km) for speeds up to 62 mph (100 km/h). At higher speeds the fatality rate increased sharply—up to 294 per 100 million vehicle-mi (183 per 100 million vehicle-km) (also by a factor of approximately 15) for speeds higher than 72 mph.

The increased incidence of speeding with increasing injury levels was also reported by Liu (1997) on the basis of Saskatchewan crash data for 1990 through 1995. His analysis showed that excessive speed—when it was both above the speed limit and high relative to conditions—constituted:

<table>
<thead>
<tr>
<th>Injury Severity Level</th>
<th>Number&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Speed-Related&lt;sup&gt;b&lt;/sup&gt; (percent)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No injury&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12,610,000</td>
<td>10.2</td>
<td>1,286,220</td>
</tr>
<tr>
<td>Possible injury</td>
<td>1,719,000</td>
<td>10.9</td>
<td>187,371</td>
</tr>
<tr>
<td>Nonincapacitating injury</td>
<td>943,000</td>
<td>14.6</td>
<td>137,678</td>
</tr>
<tr>
<td>Incapacitating injury</td>
<td>481,000</td>
<td>17.1</td>
<td>82,251</td>
</tr>
<tr>
<td>Fatal injury&lt;sup&gt;d&lt;/sup&gt;</td>
<td>45,500</td>
<td>34.2</td>
<td>15,558</td>
</tr>
</tbody>
</table>

Note: GES = General Estimates System; CARDfile = Crash Avoidance Research Data File; FARS = Fatal Analysis Reporting System; 1 mph = 1.609 km/h.

<sup>a</sup>National totals are from 1989 GES.

<sup>b</sup>Speed-related percentage derived from CARDfile (1984–1986).

<sup>c</sup>The estimate for noninjured people is considered to be low because some states only list injured persons.

<sup>d</sup>Fatal crash statistics are from FARS, 1989.
Figure B-7 Injury (above) and property damage (below) rates by travel speed, day and night (Solomon 1964). 1 mph = 1.609 km/h.
• 18 to 25 percent of all human errors in property damage crashes,
• 20 to 29 percent of all human errors in personal injury crashes, and
• 24 to 40 percent of all human errors in fatal crashes.

The most compelling demonstration of the combined effects of crash probability and crash cost as they relate to speed was recently provided in an analysis of crash data from 16 European countries. In that analysis Kallberg (unpublished data, 1997) demonstrated that disregarding the effects of speed on crash severity leads to serious underestimation of the effects of speed on crash costs. On the basis of a Swedish model of the relationship between crash probability and crash cost as a function of precrash speed, Kallberg’s more conservative estimate is that an “increase from 47 to 50 km/h increases accident costs (and the number of injury accidents) by 13.2 percent, speed increases from 80 to 85 km/h by 12.9 percent, and speed increases from 90 to 100 km/h by 23.5 percent, and the effect is the same in all countries” (p. 9).

In summary, these findings indicate that because speeding is a more prominent factor in more severe crashes and because severity increases as a power function of speed, it is difficult to sustain a view that excessive speed—at least relative to the median of the prevailing traffic—is not a crash risk factor with significant societal costs in terms of injuries and fatalities as well as money.

CONCLUDING REMARKS

There is sufficient evidence to indicate that a driver’s absolute speed is a correlate of crash involvement. The indications for the positive relationship between speed and crashes are derived from empirical data of single-vehicle crashes, causal crash analysis, and theoretical frameworks related to the effects of speed on information overload and reduced vehicle-handling capacity. In addition, empirical data show unequivocally that injuries and fatality rates increase as a power function of impact speed or Delta-V.

There is also ample evidence to indicate the contribution of wide disparities in speed of the traffic stream, as well as the deviation of
crash-involved vehicles from the average traffic speed, to crash involvement. However, the support for these findings comes from correlational studies, and the argument for causality rests on the theoretical support for this finding. The theoretical support is not sufficient. To suggest that speed disparities in the traffic stream contribute to potential intervehicle conflicts is not sufficient, since such conflicts appear to constitute a small portion of crashes in general and an even smaller portion of the more severe crashes. So what is the source of that relationship? Liu and Popoff (1996) suggest that the “variance effect” reflects a greater vehicle mix or a greater mix of drivers with different styles and capabilities. If that is the case, the variance effect may be a spurious finding. As long as data on driver and vehicle types (both in crash samples and traffic samples) are unavailable, this remains an interesting speculation.

In a situation in which speed selection is totally at the driver’s discretion, the range of speeds in the traffic stream is a function of the risk levels that different drivers are willing to tolerate, different perceptions of a “safe speed” that drivers have for a given risk level, and the handling capabilities of different cars and drivers. All of the studies reporting narrowing of speed disparities with increasing speed were conducted in the presence of speed limits, and, consequently, a threshold level of speed may have been responsible for the reduction in speed dispersion (i.e., higher speeds were due to higher speed limits on roads with higher design speeds). This is because as the speed limit is raised, fewer and fewer drivers are likely to exceed it by much, and more and more drivers tend to drive close to the limit. This also means that it is highly probable that if speed limits were strictly controlled in low-speed zones, then drivers who would otherwise exceed the limit significantly (and therefore contribute to widening speed dispersion) would refrain from doing so, and both speed dispersion and crash risk would be reduced.

The tendency of speed differences to narrow as average speed increases probably reflects drivers’ tendencies to violate low speed limits (e.g., near schools) more than high speed limits [e.g., on Interstate highways with limits of 65 to 70 mph (105 to 113 km/h)]. The critical issue then is how speed limits are set. If they are realistic (e.g., 85th percentile or design speed), speed dispersion may be low,
constant, and independent of average speed. Since the speed limit, the design speed, and prevailing conditions all contribute to speed choice, separating average speed from speed limits and enforcement is artificial. If speed limits are set at low levels and they are enforced, then speed dispersion would probably not decrease with increasing speed but rather would increase with it, in a manner similar to most measures of human psychomotor behaviors (where variance is positively correlated with the mean). Then what would the relationship between speed dispersion and crashes be? That is an open question. Perhaps what is needed is systematic research into the relationships between measures of speed and speed dispersion under conditions of speed control.

The importance of theory to the role of speed dispersion can be illustrated with older drivers. Older drivers are a good group to pick because the elderly are the fastest-growing age group in the population in general and on the roads in particular (Eberhard 1996). Now, if slow driving (rather than slowing down) increases crash risk, should slow drivers be advised to increase their speed? Older drivers, who tend to drive slow, do so to maintain or reduce their risk level, not to increase it. Given their slowed information processing capabilities, it would be foolhardy to recommend that these people drive faster so as to reduce speed disparities in the traffic stream. Also, removing them from high-speed roads may actually be detrimental to safety since (a) they already restrict their driving to safer roads and times and (b) their crash involvement may actually increase on other roads with lower design speeds (placing greater information processing demands on the driver) that are already associated with higher crash risks.

Given the multiple factors that coexist in the real driving environment, it is interesting to speculate if it is even possible to find or create a situation in which only speed changes. The answer is probably not. Even in a simulator study, if all that is changed is the driver’s speed while the traffic speed and likelihood of emergencies stay the same, then crashes will most likely increase—but so will speed differences. If the speed of all the traffic is changed and an emergency arises, then multiple-vehicle chain crashes are likely. Chain crashes on highways with restricted view (e.g., in fog)
are suggestive of the process: the faster a vehicle travels, the greater the probability of a crash—but only in the event of an obstacle ahead. However, this situation is very artificial, because drivers adjust their speed in accordance with their expectations of obstacles ahead. Thus, it is hard to think of a realistic situation, even in a simulator study, that would disaggregate the effects of the speed of a crash-involved vehicle from the disparities in speed of the traffic.

In summary, the ultimate question is not whether increasing speed increases crash probability and crash severity. Instead, there are three questions: What are the mediating factors involved? What are acceptable societal costs for increased mobility? Who should decide the levels of acceptability—elected officials, safety experts, or the motoring public through their opinion or behavior (such as the 85th percentile speed)?

With respect to mediating factors, it is impossible to hold all “other things equal” while varying speed. This is because the basis for speed choice—roadway design, traffic controls, enforcement, traffic flow, and perceived risk and comfort levels—all affect the relationship between speed and crash probability. With respect to the acceptable risk level, there is willingness at both the individual and the societal levels to accept some degree of risk to improve mobility. Thus, speed management, speed choice, crash risk, and crash severity are all intertwined and linked to the value placed on mobility.

**CONCLUSIONS**

1. There is ample, but not unequivocal, evidence to indicate that, on a given road, crash involvement rates of individual vehicles rise with their speed of travel.

2. There are no convincing data to demonstrate that, across all roads, crash involvement rates rise with the average speed of traffic (i.e., that roads with higher average traffic speeds have higher crash rates than roads with lower average traffic speeds). This is probably because the average traffic speed is highly correlated with the design speed of different road classes (and other conditions).

3. The absolute speed deviation of crash-involved vehicles from the average traffic speed appears to be positively related to crash
probability, especially for rural arterial highways and Interstate highways. There are insufficient data to demonstrate such a relationship for rural collector roads and urban streets.

4. The principal factor that accounts for the effects of speed deviation is the requirement to slow down to make turns and to enter and exit high-speed roads. Still, even when the effects of turning vehicles are removed from the data, some effects of speed deviation, especially at the extreme ends, remain.

5. The disparities in speed of the traffic stream may be positively related to crash probability, especially on Interstate highways. However, the data are not very consistent, and more data are needed.

6. On urban streets there appears to be a strong relationship between crash rates and the absolute speed of crash-involved vehicles. However, this conclusion is based mainly on small data sets from non-U.S. studies.

7. The data demonstrating the relevance of speed dispersion in the traffic stream and speed deviations of crash-involved vehicles are based on correlational effects and therefore cannot be used to indicate that if slow-moving drivers were to increase their speed, their crash probability would be reduced.

8. There are unequivocal data to indicate that the risk of injuries and fatalities increases as a function of precrash speed or Delta-V. This is true for all road types.

9. The overall cost of speed-related crashes is much greater than the relationship between speed and crash probability indicates. This is because high-speed crashes are associated with greater injury levels than are low-speed crashes.

ACKNOWLEDGMENTS

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I was especially assisted by the subcommittee chairperson, Forrest Council, who provided the first impetus and guidelines for this report, and by Nancy Humphrey, the TRB program manager, who provided me with most of the needed source material, acted as an intermediary between me and the committee members, spent hours on the phone with me discussing key issues, and made excellent editorial comments on the previous drafts. Finally, I would like to acknowledge the help of Richard Compton, who acted as a challenging sounding board and spent as much time as I needed to discuss the principal speed issues.

REFERENCES

ABBREVIATIONS
NASS National Analysis Sampling System
NHTSA National Highway Traffic Safety Administration
TRB Transportation Research Board


Liu, G.X., and A. Popoff. 1996. *Provincial Wide Travel Speed and Traffic Safety Study in Saskatchewan*. Faculty of Engineering, University of Regina, Regina, Saskatchewan, Canada.


