# The Safety of Older Persons at Intersections

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The aim in this paper is to examine the ways in which the use of intersections by older persons, both as pedestrians and as drivers, could be made safer and easier. The paper is in three main sections. In the first, accident statistics for older persons are examined with a focus on intersections. Next, possible improvements in the design and operation of intersections are investigated. The paper concludes with a summary of the major findings and recommendations.

## OLDER PERSONS AND INTERSECTION ACCIDENTS

The age profile of injuries due to motor vehicle accidents turns out to be very malleable. Its shape depends on what is chosen to serve as the denominator of the injury or accident rate of interest. Thus, when the fatality rate is computed "per licensed driver," noticeable overrepresentation begins around ages 65 to 70; the rate for men is more than twice that of women (Figure 1). However, when the rate is computed on a "per unit of travel" basis, the driver fatality rate has already begun to climb around 50 and the difference between male and female drivers is small (Figure 2).

What one sees in every such graph is a mixture of two phenomena: the frequency with which people are involved in a crash and the chance of injury or death as a result (frailty). Older persons have a greater chance of being fatally injured in a crash of fixed severity. When this effect is accounted for, a very different set of age profiles emerges. Not only does the per-licensed-

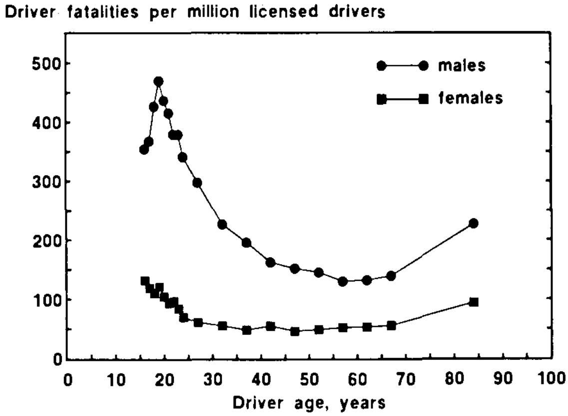



FIGURE 1 Driver fatalities (all motorized vehicles) per million licensed drivers based on FARS and FHWA data for 1983 *(1)*.

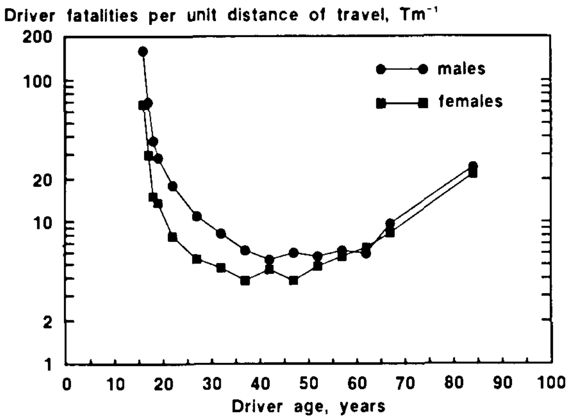



FIGURE 2 Driver fatalities (all motorized vehicles) per terameter (1 Tm = 621 million mi) of travel based on FARS, FHWA, and Nationwide Personal Transportation Study data for 1983 *(1)*.

driver rate show no sign of increasing with advancing age, the rate for older persons is dwarfed by that of young men (Figure 3). Similarly, when the frailty effect is eliminated from the data, the plot of the per-unit-of-travel rate also changes (Figure 4). The rate begins to climb only around age 70, and its ascent is much slower than that in Figure 2.

A look at the corresponding graph for pedestrians (Figure 5), this time on a "per population" basis, shows a sharp upturn in the raw data, again around age 70. As noted before, the solid line mixes involvement with frailty. A

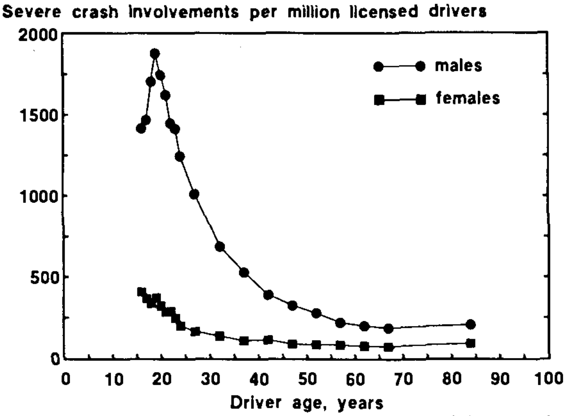



FIGURE 3 Estimated driver involvements (all motorized vehicles) in crashes of sufficient severity to kill 80-year-old male drivers per million licensed drivers *(1)*.

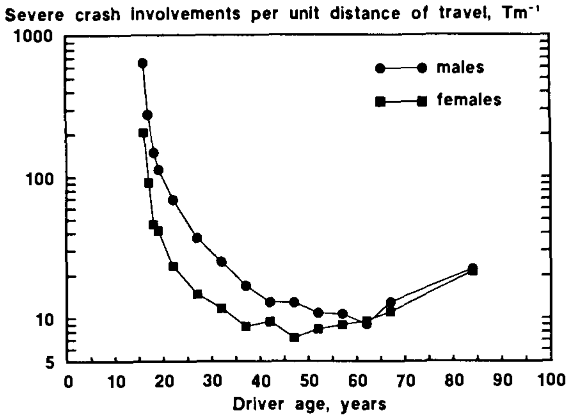



FIGURE 4 Estimated driver involvements (all motorized vehicles) in crashes of sufficient severity to kill 80-year-old male drivers per terameter (1 Tm = 621 million mi) of travel *(1)*.

speculative attempt to separate the two and show involvement alone is represented by the dashed line. The sharp upturn at 70 nearly disappears.

Were one to separate involvement and frailty in foreign data about pedestrian casualty rates per time and distance walked (Figures 6 and 7), one would again find little increase in the accident rate of older pedestrians. One is led to conclude that older pedestrians are not overrepresented in crashes; they are just much more vulnerable. Therefore, we are inclined to believe that the problems of older persons are not so much a matter of degradation in sensory,

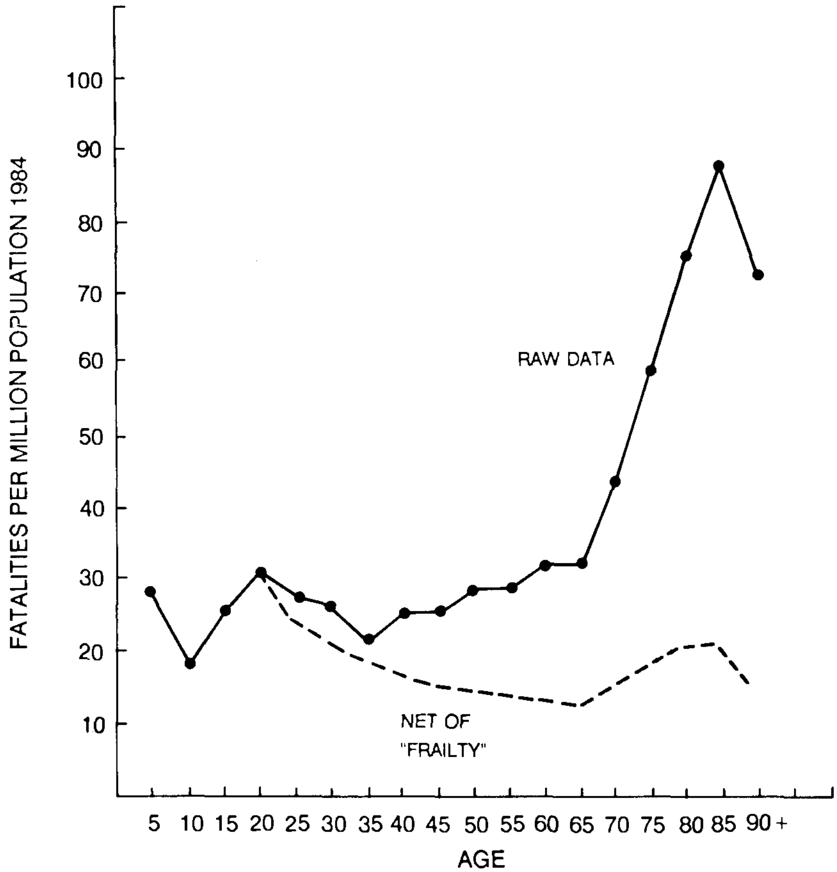



FIGURE 5 Non-occupant (pedestrian and bicycle) fatalities per million population. Note: age shown on horizontal axis refers to first year of 5-year age group.

mental, or psychomotor abilities—for which they may be compensating with success. Their main safety problem is being injured more easily and being able to recover less frequently.

There is a long tradition of motivating need for action on safety by demonstrating the existence of overrepresentation. A review of the connection between overrepresentation and justification of interventions shows little logical linkage between the two. In addition, the debate about overrepresentation tends to be sterile. On one hand, reference to accident statistics does not seem to diminish the diversity in views; on the other, the arguments for action on the basis of overrepresentation seldom seem to be compelling. Perhaps it is

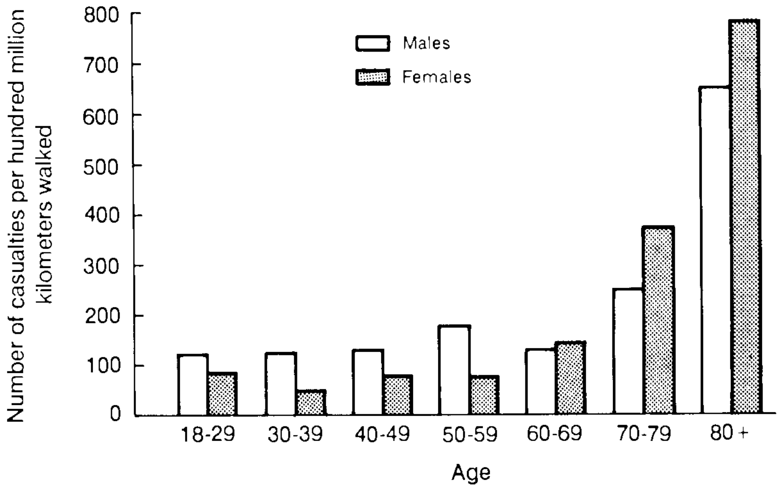



FIGURE 6 Mean number of pedestrian casualties/100 million km walked *(2)*.

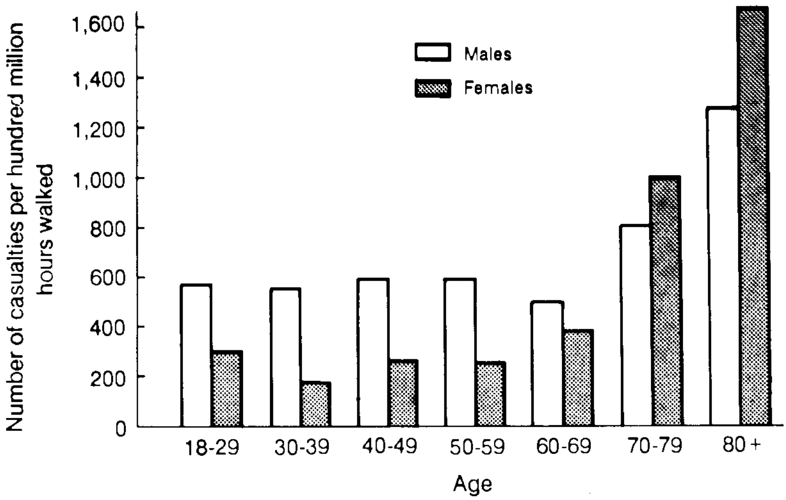



FIGURE 7 Mean number of pedestrian casualties/100 million hr spent walking *(2)*.

better to motivate concern about the safety of older persons with the following argument.

There is little question that as one grows older, it becomes gradually more difficult to cope with the transport system. There is also no disagreement about the importance of mobility for older persons; the more mobile and self-reliant one can be as one gets older, the better for everyone. It follows that if there are opportunities to enhance the mobility and safety of older persons at reasonable cost, such opportunities should be taken. Nothing in this argument depends on the existence of overrepresentation.

In the section that follows, intersection accidents are studied in relation to age. A wealth of information is given, much of it apparently not available from other sources. Accidents involving pedestrians are discussed separately from those involving drivers. Data are given about fatalities, nonfatal injuries (by severity), and accidents involving property damage only.

## Pedestrians

More than 500 pedestrians in the 64+ age group are killed each year at intersections. The number of pedestrians killed yearly at intersections in all other age groups is approximately 800 (Table 1). Nearly 6,000 pedestrians of the 64+ age group are injured at intersections; the number of injured pedestrians in all other age groups is approximately 60,000 (Table 2).

TABLE 1 U.S. PEDESTRIAN FATALITIES, 1985

| | Intersection and Intersection-Related | | | |
|---|---|---|---|---|
| Age | No. | Percent of Total | Other[a] | Total |
| 0–14 | 172 | 16.5 | 869 | 1,041 |
| 15–25 | 121 | 9.6 | 1,133 | 1,254 |
| 26–64 | 523 | 17.8 | 2,408 | 2,931 |
| 64+ | 524 | 33.1 | 1,058 | 1,582 |
| Total | 1,340 | | 5,468 | 6,808 |

[a]Includes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

Some 33 percent of fatalities and 50 percent of injuries to pedestrians in the 64+ age group occur at intersections (Tables 1 and 2). Most pedestrian fatalities (at intersections) in the 64+ group occur during daylight. In comparison, more pedestrian fatalities in the 26 to 64 age group occur during darkness (Table 3). Although not shown, a similar pattern holds for injuries.

TABLE 2 U.S. PEDESTRIAN INJURIES FOR ONE YEAR OF THE PERIOD 1983–1985

| Age | Intersection and Intersection-Related | | Other | Total |
|---|---|---|---|---|
| | No. | Percent of Total | | |
| 0–14 | 22,658 | 32.7 | 46,691 | 69,349 |
| 15–25 | 20,913 | 39.2 | 32,381 | 53,294 |
| 26–64 | 19,202 | 26.2 | 33,763 | 52,965 |
| 64+ | 5,877 | 51.2 | 5,596 | 11,474 |
| Total | | | | 187,082 |

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale).

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 3 U.S. PEDESTRIAN FATALITIES, 1985: DAYLIGHT VERSUS DARKNESS

| Age | Intersection and Intersection-Related | | | Other[a] | | |
|---|---|---|---|---|---|---|
| | Daylight | Darkness | Total[b] | Daylight | Darkness | Total[b] |
| 0–14 | 309 | 205 | 172 | 632 | 236 | 869 |
| 15–25 | 33 | 88 | 121 | 171 | 961 | 1,133 |
| 26–64 | 151 | 371 | 523 | 461 | 1,937 | 2,408 |
| 64+ | 309 | 215 | 524 | 414 | 643 | 1,058 |

[a]Includes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

[b]Slight discrepancies are due to the omission of the "unknown" category.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 4 U.S. PEDESTRIAN FATALITIES, 1985: INTERSECTION TRAFFIC CONTROL

| Age | No Traffic Control | Signs, Signals, etc. | Unknown | Total |
|---|---|---|---|---|
| 0–14 | 94 | 77 | 1 | 172 |
| 15–25 | 62 | 58 | 1 | 121 |
| 26–64 | 250 | 266 | 7 | 523 |
| 64+ | 247 | 273 | 4 | 524 |
| Total | 653 | 674 | 13 | 1,340 |

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

Surprisingly, about half of the pedestrian fatalities at intersections (in every age group) occur where traffic is not controlled by either signs or signals (Table 4). For injuries, the situation is different. In the 64+ age group, 2,000 pedestrians are injured at intersections where no signs or signals exist and 4,000 at intersections where some traffic control is provided (Table 5).

TABLE 5 U.S. PEDESTRIAN INJURIES FOR ONE YEAR OF THE PERIOD 1983–1985: INTERSECTION TRAFFIC CONTROL

| Age | No Traffic Control | Signs, Signals, etc. |
|---|---|---|
| 0–14 | 10,949 | 11,709 |
| 15–25 | 6,284 | 14,630 |
| 26–64 | 5,273 | 13,929 |
| 64+ | 1,725 | 4,152 |
| Total | 24,231 | 44,420 |

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale).

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

## Drivers

Nearly 1,000 drivers in the 64+ age group are killed each year at intersections; those killed yearly at intersections in all other age groups number about 4,000 (Table 6). Almost 70,000 drivers of the 64+ age group are injured yearly at intersections; the number of injured drivers in all other age groups is about 900,000 (Table 7). Nearly 40 percent of fatalities and 60 percent of injuries to drivers in the 64+ age group occur at intersections.

Most driver fatalities at intersections in the 64+ age group occur during daylight (Table 8), whereas in the 26 to 64 age group, about half occur during

TABLE 6 U.S. DRIVER FATALITIES, 1985

| | Intersection and Intersection-Related | | | |
|---|---|---|---|---|
| Age | No. | Percent of Total | Other[a] | Total |
| 15–25 | 1,542 | 16.4 | 7,848 | 9,390 |
| 26–64 | 2,317 | 17.7 | 10,780 | 13,097 |
| 64+ | 993 | 36.7 | 1,710 | 2,703 |
| Total | 4,852 | | 20,338 | 25,190 |

[a]Includes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

darkness. Similarly, most driver injuries in the 64+ age group occur during daylight. More than one-fourth of drivers are killed at intersections where traffic is not controlled by either signs or signals. Similarly, more than one-third of driver fatalities and injuries occur at intersections with no traffic control at all (Tables 9 and 10).

TABLE 7 U.S. DRIVER INJURIES FOR ONE YEAR OF THE PERIOD 1983–1985

| | Intersection and Intersection-Related | | | |
|---|---|---|---|---|
| Age | No. | Percent of Total | Other | Total |
| 15–25 | 369,998 | 44.0 | 471,461 | 841,459 |
| 26–64 | 519,219 | 48.2 | 557,618 | 1,076,837 |
| 64+ | 69,850 | 59.8 | 46,874 | 116,724 |
| Total | 959,067 | | 1,075,953 | 2,035,020 |

NOTE: Data do not include noninjury accidents (rated 0 on the Abbreviated Injury Scale) or "unknown if injured".

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 8 U.S. DRIVER FATALITIES, 1985: DAYLIGHT VERSUS DARKNESS

| | Intersection and Intersection-Related | | | Other[a] | | |
|---|---|---|---|---|---|---|
| Age | Daylight | Darkness | Total[b] | Daylight | Darkness | Total[b] |
| 15–25 | 678 | 861 | 1,542 | 2,681 | 5,144 | 7,848 |
| 26–64 | 1,247 | 1,069 | 2,317 | 4,830 | 5,906 | 10,780 |
| 64+ | 871 | 120 | 993 | 1,308 | 398 | 1,710 |

[a]Includes nonjunction, interchange, driveway, alley, ramp, grade crossing, crossover, and location unknown.

[b]Slight discrepancies are due to the omission of the "unknown" category.

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

These statistics lead to several conclusions. First, for pedestrians in the 64+ age group, 33 percent of fatalities and 50 percent of injuries occur at intersections. For drivers in the same age group, 40 percent of fatalities and 60 percent of injuries occur at intersections. It follows that roughly half of the safety problem of older persons occurs at intersections. This means that the intersection is a proper target for safety interventions.

Second, a relatively large number of pedestrians over 64 are killed at intersections (about 500 a year compared with approximately 800 in all other

TABLE 9 U.S. DRIVER FATALITIES, 1985: INTERSECTION TRAFFIC CONTROL

| Age | No Traffic Control | Signs, Signals, etc. | Unknown | Total |
|---|---|---|---|---|
| 15–25 | 544 | 981 | 17 | 1,542 |
| 26–64 | 692 | 1,599 | 26 | 2,317 |
| 64+ | 237 | 741 | 15 | 993 |
| Total | 1,473 | 3,321 | 58 | 4,852 |

SOURCE: Fatal Accident Reporting System data tapes, NHTSA, U.S. Department of Transportation.

TABLE 10 U.S. DRIVER INJURIES FOR ONE YEAR OF THE PERIOD 1983–1985: INTERSECTION TRAFFIC CONTROL

| Age | No Traffic Control | Signs, Signals, etc. |
|---|---|---|
| 15–25 | 151,864 | 218,133 |
| 26–64 | 182,185 | 337,036 |
| 64+ | 18,585 | 51,264 |
| Total | 352,634 | 606,434 |

SOURCE: National Accident Sampling System data tapes, NHTSA, U.S. Department of Transportation.

age groups). The situation is not nearly so bad for injuries (about 6,000 a year in the over-64 age group versus about 60,000 for other ages). Similarly, a fairly large proportion of drivers killed is in the 64+ age group (around 1,000 a year versus 4,000 in younger age groups). Again, the proportion is not nearly so high for drivers injured (about 70,000 a year versus 900,000). The consistent disparity between the proportion killed and proportion injured leads again to the conclusion that a large part of the problem is attributable to the increased likelihood of death as a result of injury.

Third, for overrepresentation to lead to countermeasure identification, it is important to separate involvement rate from frailty. It appears that much of what is seen as overrepresentation in age profiles of accident rates is due to frailty. Older persons appear able to adapt to the traffic environment so as to keep nearly constant the probability of being involved in an accident; they do not appear able to adapt sufficiently to keep the probability of injury or death constant.

Among the more detailed findings, the following deserve highlighting:

- Most pedestrian fatalities and injuries at intersections in the over-64 age group occur during daylight.
- The majority of driver fatalities at intersections in the over-64 age group occur during daylight.

- About half of the pedestrian fatalities at intersections (in every age group) are killed where traffic is not controlled by either signs or signals.
- More than one-fourth of drivers are killed and one-third injured at intersections where traffic is not controlled by either signs or signals.

## HOW INTERSECTIONS CAN BE MADE SAFER

Some clues about which ways of making intersections safer look promising and which do not have been provided by the discussion of the problems of older persons at intersections in the previous section. However, to make sensible suggestions about what could be done to alleviate these problems, one needs to understand the features of intersections that affect safety, to have a grasp of the process by which these features come into existence and the reasons these features are selected, and to appreciate the potential costs and benefits of change.

### Safety Gains and Social Costs

The prospect of having to deal with death, injury, and misery in terms of dollars and cents is not attractive. However, because this is public money, there is an obligation to spend it effectively. This means not spending that money to save one life when two could be saved for the same amount. Thus, discussing alternative courses of action in terms of costs and benefits is justified.

It would be more meaningful to measure both gains and costs with a common monetary yardstick, but the quality of information available for such an analysis is often insufficient. Nevertheless, it may be revealing to give an example. One necessary element of quantification is a monetary equivalent for an accident saved. The range of estimates is wide, as is evident from Table 11.

TABLE 11 MONETARY EQUIVALENT OF ACCIDENT SAVED *(3)*

| | Thousands of Dollars (1985) | | |
|---|---|---|---|
| Accident Severity | NHTSA[a] | NSC[b] | Kragh et al.[c] |
| Fatal | 395.6 | 256.5 | 1,348.7 |
| Injury | 11.1 | 13.2 | 10.1 |
| Property damage only | 1.4 | 1.2 | 1.9 |

[a]Based on 1983 estimates by National Highway Traffic Safety Administration.
[b]Based on 1984 estimate by National Safety Council.
[c]Based on Kragh et al. *(4)*.

The monetary equivalent of a representative intersection accident is a mixture of the appropriate proportion of accident severity multiplied by the applicable equivalent from Table 11 *(3)*. The result is usually between $8,000 and $45,000 per accident. Break-even charts for an $8,000 and a $25,000 accident are shown in Figures 8 and 9.

To show the use of a break-even chart, consider the following example. A stop-controlled intersection has substandard sight distance. It is estimated that of the three accidents that are expected to occur there each year, one is such that it could be affected by improving sight distance (the other two "expected" accidents occur when the road users can see each other clearly). Thus, the number of annual "target accidents" is one. It is also estimated that by extending the sight distance at this intersection by some specific amount, the probability that a target accident will occur is reduced by 20 percent. From Figure 9 it may be deduced that accident reduction alone can justify an annual expenditure of up to $5,000 when the monetary equivalent of a target accident is $25,000. (An annual expenditure of $5,000 is equivalent to a one-time expenditure of about $42,000 with a 20-year project life and 10 percent interest rate.) If a 2:1 benefit-to-cost ratio is required, the justified annual expenditure is $5,000/2 = $2,500.

This simple example is sufficient to illustrate what estimated information is needed for an analysis of costs and benefits: the annual number of target accidents, the reduction in the probability of target-accident occurrence

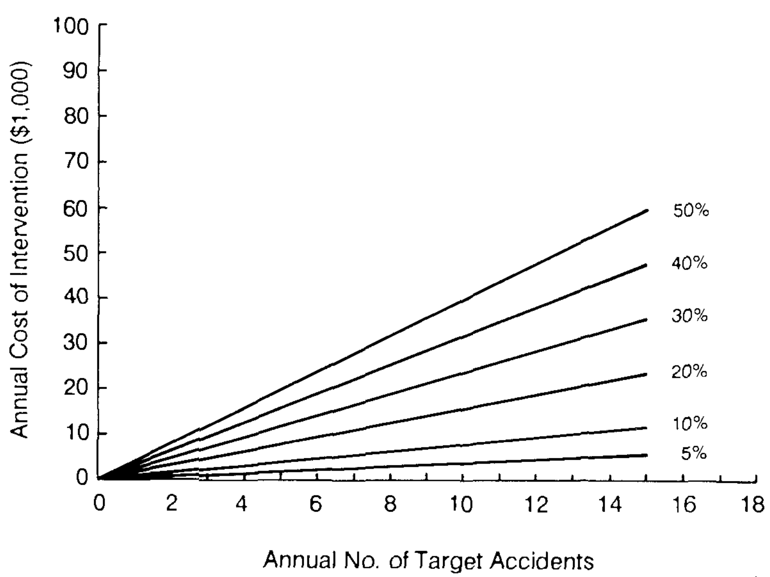



FIGURE 8 Break-even chart: $8,000 accident.

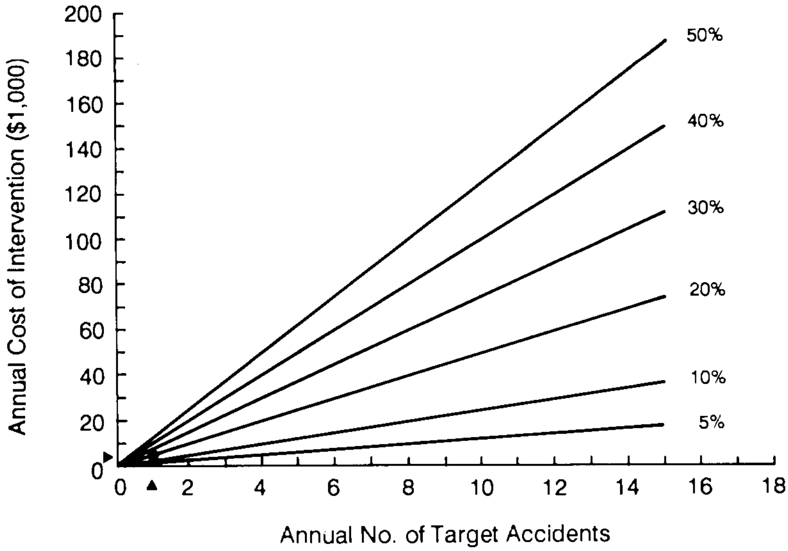



FIGURE 9 Break-even chart: $25,000 accident.

(which depends on the sight distance available now and what it would be once improved), the cost of the intervention, and the monetary equivalent of the target accidents. Obviously, much of the information required is often not available or is only an approximation. As a result, conclusions based on such analysis must also be tentative and approximate.

## The Design Driver

One of the recurring themes in discussions about the compatibility between roads and older persons is the appropriateness in design of using some driver characteristic that fits only a certain fraction of the road user population. Reaction time is one such characteristic. If, say, 85 percent of drivers have a reaction time of 2.0 sec or less, are the remaining 15 percent at peril? The issue, broadly stated, is this: what fraction of the population should be included in the various highway and traffic engineering design standards? Three points may be made. First, because the characteristics of the population are so diverse, a cutoff point must be selected. Second, the larger the proportion of the population to be accommodated, the more expensive the design. Third, the safety implications of a specific cutoff point and of including more of the population are not clear. It may thus be concluded that because the safety issues are unclear, some other basis than safety is being used to set design standards.

## Intersection Design

"An intersection is defined as the general area where two or more highways join or cross, including the roadway and roadside facilities for traffic movements within it" *(5)*.

The safety performance of an intersection is strongly influenced by the strategic decisions made before its creation about spacing (density), type (three-legged, four-legged), hierarchy and size (number of lanes, capacity, future traffic control), geometry, and so on. In addition, many intersections that exist today may not have existed a generation ago. This statement cannot be supported by examining the age distribution of those intersections now in existence because such data do not seem to exist. The alternative is to show a specific case (Figure 10). Although no specific case can be taken to represent the whole, and the rate of turnover in the inventory of intersections is not known, there is no reason to think that the process of creating them is going to stop.

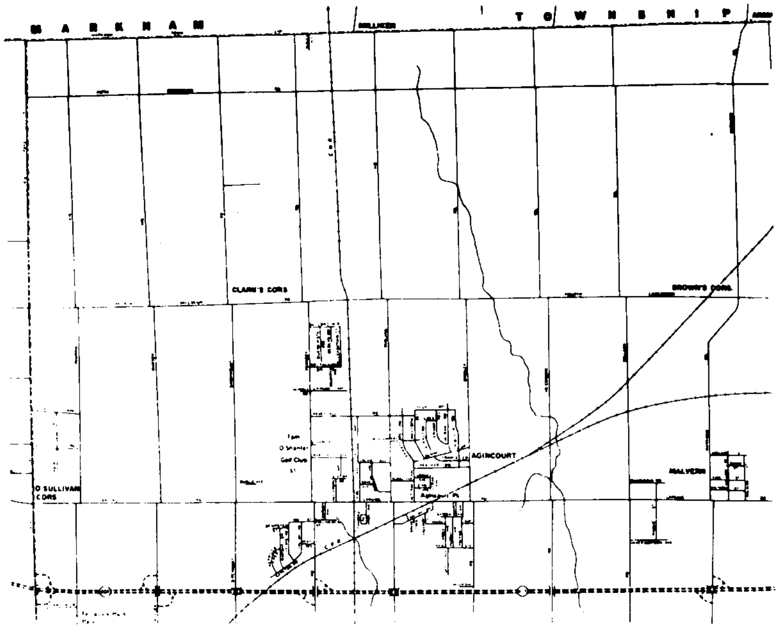
The extent of the intersection safety problem today is in part a result of the strategic decisions made about intersections in the past. By the same token, the extent of the safety problem in the future will in some measure depend on the manner in which these strategic decisions are being made now.

Although it may be natural to focus on safety improvements to existing intersections, such a focus leads to consideration of remedial measures rather than improvements by enhancing safety-related decisions made before the creation of the intersection. The distinction is similar to that between the treatment of existing illness and preventive medicine. Of course, both are important.

New intersections come into existence in two ways. They may be planned in conjunction with some land development or redevelopment project, or they may be created when a new road is integrated into the preexisting road network.

When land is developed, the street layout is often selected by an architect, engineer, town planner, or land surveyor. It is then approved or modified by the authorities. The eventual street and intersection layout is influenced by the commercial considerations of the developer; by the tax-base interest of the municipality, its zoning bylaws, and other official town-planning documents; and by a variety of established professional practices and design philosophies. These in turn take into consideration such factors as the function of the street, street capacity, access needs, density, and type of land use. In any case, the location, density, hierarchy, and shape of intersections are products of the street and lot layout process.

When land is redeveloped, there is often less freedom of choice. The level of decision making and design in this case is more detailed, intricate, and complex and may involve a variety of professionals and representatives of the

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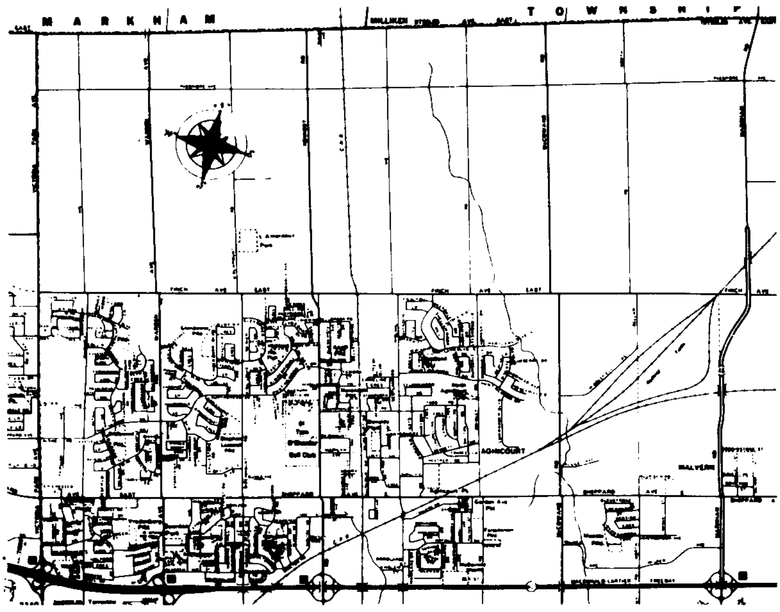


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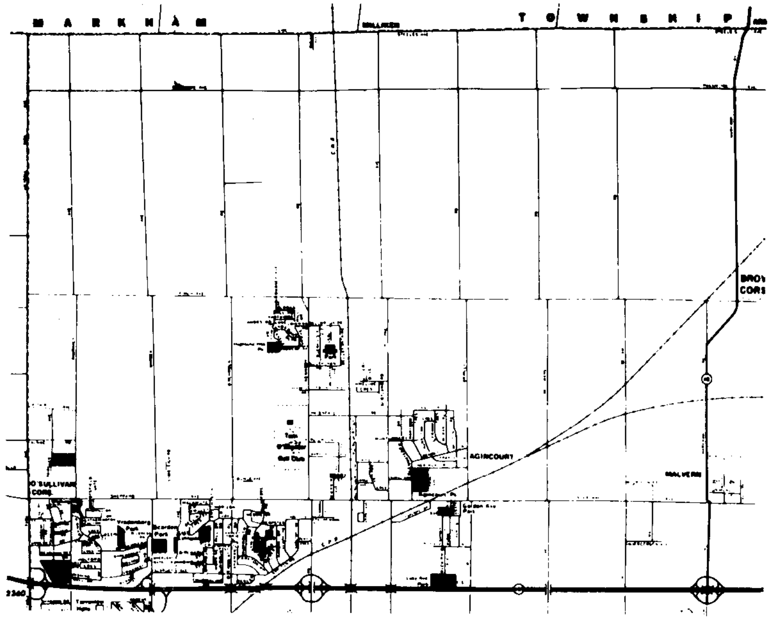
FIGURE 10 The evolution of part of Metropolitan Toronto.

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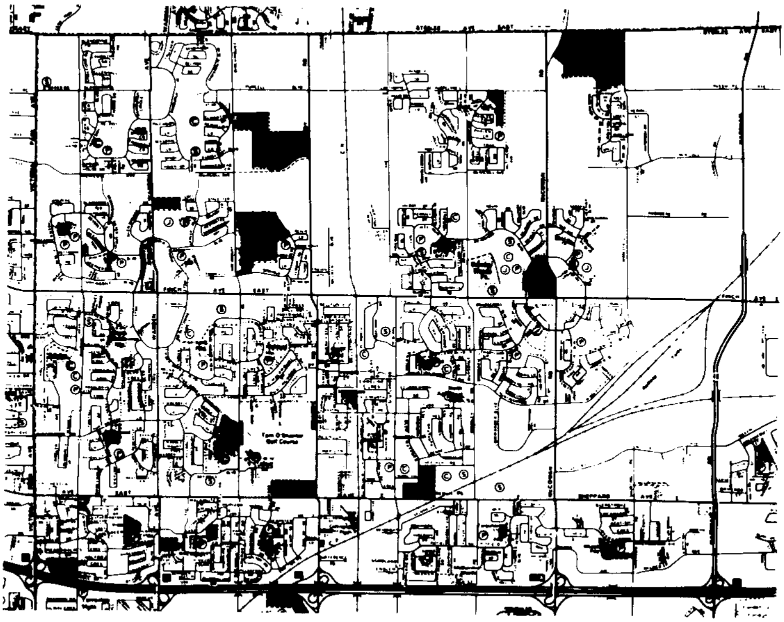

**1981**

public. Similar constraints often exist when a new road is built into the preexisting network. The decision of where to cross existing roads (route choice, alignment) and how to cross (at grade or grade separated, at right angles or otherwise) often requires detailed engineering and other input.

Once an intersection has been built and equipped with the appropriate markings and traffic control devices, it continues to evolve, as does the pattern of human activity that generates the traffic on it. Increasing volumes of traffic may bring in their wake changes in traffic control devices, demand for restrictions (of turns or parking) to enhance capacity, requests for services not now provided (say, of left-turn bays or pedestrian-actuated signals). Changes in technology and cost may induce replacement of some equipment (say, traffic-responsive microprocessor-based control for electromechanical fixed-time controllers). Advances in engineering know-how and practice as well as shifting societal concerns may also be the agents of change at intersections (e.g., the adoption of new warrants for the installation of pedestrian signals or demands for curb cuts to allow freer use by those in wheelchairs).

A schematic summary of the process that shapes intersections, the professions and professionals involved, and the principal sources that guide their decisions is shown in Table 12. This taxonomy may be a useful framework within which to provide detail about the various decisions that have an effect on the safety of intersections. As is true for all taxonomies, this one is to a large extent artificial. The five classes of decisions or actions (A to E) may be too coarse, overlap somewhat, and perhaps leave important gaps. Still, they serve as a guide for coverage in a systematic fashion.

Accordingly, decision elements A, B, and C will be discussed respectively under the headings Density and Hierarchy; Form, Size, and Angle; Left-Turn Lanes; and Geometrics. Elements D and E will be covered under Level of Traffic Control, Traffic Signal Control, and Crosswalk Markings.

### *Density and Hierarchy*

For pedestrian or driver, old or young, intersections are the most dangerous parts of the road network. This is where the paths of conflicting traffic streams cross, and is therefore where road users will most often collide. The road network weaves individual trips into a specific pattern of traffic streams by adopting a particular intersection density and hierarchy.

The safety problem created by the need to accommodate conflicting traffic streams at an (at grade) intersection can be alleviated but cannot be eliminated. There should be a choice of how many intersections to have (density) and what the proportion of the various capacity classes (hierarchy) should be. Examination of several subdivision plans, some recent and some up to 20 years old, reveals that similar residential densities can be served by a wide

TABLE 12 CREATION OF AN INTERSECTION

| Decision Element | Considerations | Practitioner Involved | Information Source |
|---|---|---|---|
| A: Intersection density and hierarchy | Land use, access needs, population density | Town planner, architect, surveyor | a |
| B: Intersection form, size, and shape | Safety, volume, origin-destination, capacity | Town planner, architect, highway designer, traffic engineer | b, c, f |
| C: Geometric design (sight distance, channelization, corner radii) | Safety, turning and through volumes, level of service, pedestrian needs, right-of-way, vehicle characteristics | Highway designer | b, c, f |
| D: Traffic control | | | |
| D1: level of control (Stop, Yield, signal, or no control) | Safety, vehicle delay, vehicle and pedestrian volumes, capacity, level of service, speed | Traffic engineer, highway designer | d, f |
| D2: signal control [coordination, actuation, provision for turns and pedestrians, timing (green time and clearance intervals, Walk/Don't Walk intervals), hardware design] | As for D1, plus Walk speeds, driver perception-reaction time, crossing distances | Traffic engineer | d, e, f |
| E: Lighting, signing, and crosswalks | Safety, driver and pedestrian characteristics, traffic control, intersection design | Traffic engineer, highway designer | b |

NOTE: Information sources are as follows: (a) town planning guidelines, (b) Institute of Transportation Engineers recommended practices, (c) AASHTO geometric design policy *(5)*, (d) *Manual on Uniform Traffic Control Devices* (MUTCD) *(6)*, (e) *Highway Capacity Manual (7)*, (f) local policies and procedures.

variety of street networks differing in the number of intersections per mile and per acre. Thus, even within the constraints of reality, the town planner, architect, surveyor, or engineer can devise alternative route networks that may differ significantly in terms of their future safety.

In Finland where roads were undifferentiated, road users were not separated, and land use was mixed, there were 40 to 100 accidents per year per million vehicle kilometers; where roads were differentiated, road users were separated, and land use was uniform, the corresponding rate was found to be 5 to 20. In Sweden injuries per 10,000 inhabitants were found to vary from 1.4 to 10.4 in different residential areas. In Germany "loop streets" in residential areas were found to have between 7.0 and 16.2 accidents per million vehicle kilometers per year, whereas for cul-de-sacs the corresponding range was 3.1 to 11.5 *(8)*. Thus, one can conclude that alternative designs may differ widely in safety performance.

With this conclusion as a point of departure, both theory and practice were reviewed. A cursory examination of the standard town planning literature did not reveal any guidance on the relationship between the future safety of a development and the street network designed for it. Thus, so it appears, those who design or approve the street and intersection layout do not have explicit guidance in the standard and accessible professional literature. Guidance for traffic engineers is also sparse. Even major source documents such as the Institute of Transportation Engineers (ITE) guidelines offer only the principle that (*9*, p. 3) "the fewer intersections there are, consistent with other requirements, the fewer accidents there will be." A small sample of consultants and civil servants actively engaged in the practice of street design and approval for land development was contacted. Although several design alternatives are usually examined, consideration of future intersection safety in a proposed development or redevelopment is not quantitatively or explicitly examined in either the design or the approval process.

The need to design street networks with safety in mind appears to be getting considerable attention in Europe (especially for residential neighborhoods in the Netherlands and Sweden), some attention in Australia, and little attention in North America.

Recently Van der Molen *(10)* summarized the experience with *woonerven* in Holland. Brindle, a leading expert in this field at the Australian Road Research Board, states *(11)* that street spacing is an example of "potentially effective practices" that "appears not to be covered by the guidelines, nor reflected in common practice." In Sweden, specific guidelines have been compiled *(12)* giving, for various categories of streets, desirable spacing, with minimums and maximums. (Minimum desirable spacing ranges from 100 m for local streets to 1200 m for regional distributors.)

In North America, the selection of street hierarchy and spacing appears to be largely a matter of local tastes and the design philosophy of the planner or architect. It does not fall naturally under the heading of geometric design or traffic engineering. This is perhaps why important organizations such as the American Association of State Highway and Transportation Officials (AASHTO) and ITE either are vague or give no firm guidance on this matter. Where guidance is given, safety does not seem to be one of the criteria considered explicitly. Thus, for example, recommended spacing for arterial streets takes into account (*13*, p. 540) "typical urban traffic demands, considerations of traffic signal timing and freeway distribution requirements." In other cases, some recommendations are made on the basis of considerations central to a specific discipline but marginal in the broader context of transport planning. ITE *(14)* suggests that intersection spacing on major streets is "strongly related to left turn storage requirements on the major street." In another ITE document (*9*, p. 1) safety is recognized as the first factor to consider in the design of a road network and "principle" No. 13 is that "there should be a minimum number of intersections." However, only the usual standards of geometric design such as sight distance, pavement width, or curve radii are discussed in useful detail.

Thus, it is distinctly possible that street networks are being built that are inferior in safety. This is particularly important for the safety of older persons. They, as a group, carry out more of their activity as drivers or pedestrians close to their residence than do younger cohorts.

Two questions arise. First, do feasible alternative street designs differ significantly in future safety? Second, will the difference have some impact on the eventual selection of an alternative? The answer to these questions determines the magnitude of the potential benefit. If practically feasible alternatives do not differ much in safety or if considerations other than safety determine the final outcome, the action contemplated can have no benefit.

Neither question can be answered on the basis of current experience or data. On the matter of intersection density it may be interesting to note that on some highways the accidents per 100 million vehicle-mi increase from 200 to nearly 600 as the number of intersections per mile increases from 0 to 12 (*5*, p. iii). Explicit and quantitative attention to safety in the formulation of feasible street and network alternatives might produce a 10 to 20 percent reduction in future intersection accidents. Were the development or redevelopment project to contain concentrations of older persons, explicit and quantitative attention to their future safety would have a somewhat higher payoff for this cohort.

The cost of implementing such a safety-conscious design is, first, that of developing the ability to comply with it; second, that of engaging in a quantification of safety for important development and redevelopment projects; and third, that of ensuring compliance with the design.

Consider a subdivision development for 2,000 persons. If in new residential areas there are about 6 accidents per 1,000 persons a year (*8*, p. 90), the number of target accidents is 12. With an assumed effectiveness of 10 to 20 percent and the monetary equivalent of an accident of $25,000, the break-even cost is $30,000 to $60,000 a year. The one-time cost of safety-conscious design and its supervision, amortized for a long period of time at 10 percent, comes to $300,000 to $600,000. Even if a 3:1 benefit-cost ratio were required, an investment in safety-conscious design of about $100,000 seems easy to justify.

Most products (appliances, drugs, toys, etc.) cannot be put into service without explicit attention to their health and safety performance by both manufacturers and regulatory agencies. Because the building of roads and intersections has important health and safety repercussions, it seems extraordinary that, contrary to common practice with other products, a road network may be designed, approved, and built without explicit consideration being given to its future health and safety performance. A strong case exists for consideration of the following recommendation for action:

• When an area is being developed or redeveloped, the "safety future" of several alternative street networks should be explicitly evaluated.

Before the foregoing requirement is implemented (and thereby development is encumbered by additional engineering costs and society by another layer of regulatory and surveillance activity), it is appropriate to demonstrate that the payoff is indeed substantial. Accordingly, the following research is recommended:

• Research should be undertaken to determine the differences in safety performance of alternative feasible street networks (including intersection density and hierarchy) in development and redevelopment projects.

The first recommendation is far reaching and therefore may not be easy to implement. However, some less far-reaching actions could be implemented easily and in the shorter term.

It is a matter of common sense and responsibility that professional work be based on professional knowledge. At this time, there are no documents to consult for guidance in assessing the future safety of a proposed street network. Such a source, with simple tables or graphs, would be welcomed by current and future professionals alike and would promote the development of a more safety-conscious professional practice. Accordingly, the following action is recommended:

• Guidance should be provided for professionals in estimating the future safety performance of the street networks they design and approve. Ways should be sought to ensure that such guidance will be published and used in undergraduate training and professional development.

Much of the needed research has already been done and has been published. It needs to be assembled and critically reviewed so as to determine what the best practice is on the basis of the information available. This gives rise to the following research need:

• A procedure should be devised on the basis of current research by which the safety performance of a planned street network can be quantified. The procedure developed will be used to provide the guidance specified in the preceding recommendation.

These recommendations for action and research appear to mesh well with a new proposed ITE policy for residential streets *(15)*, which recognizes the inadequacies within and on the collector and arterial road system and the need for professional involvement in resolving the resulting problems.

The first of the preceding recommendations agrees in spirit with those for a safety-conscious design process in the recent TRB Special Report 214 (*3*, pp. 190–193). The other recommendations are similar in spirit to what has been recommended in the same report for safety research and training (*3*, pp. 208–212). In fact, many of the recommendations here should be considered an added argument for the Special Safety Task Force that Congress has asked the Secretary of Transportation to set up.

*Form, Size, and Angle*

*Form* The two most common forms of at-grade intersections are that with three legs (T-intersection) and that with four legs (cross intersection). In some cases (e.g., when a new road is built across existing roads), no real choice of form exists. In other cases (e.g., when a new subdivision is designed), both intersection forms could be used. It appears that, as in the case of intersection density and hierarchy, the selection of intersection form is more a matter of taste than of explicit consideration of future safety.

The T-intersection has only 9 possible conflict points, whereas the cross intersection has 32. Thus, for older persons the relative simplicity of the former is attractive. Because the safety of older persons at intersections could be significantly affected by the choice of intersection form, more explicit guidance is needed about the safety performance of alternative intersection forms under different traffic and pedestrian flows. Once such guidance is available, choice of form for new intersections should be made on that basis.

Of the existing authoritative guidelines, two are worth mentioning. In the ITE guidelines for subdivision streets it is stated (*9*, p. 3): "From the standpoint of hazard, use of two T-type intersections with proper offset is preferable to using one cross-type." The AASHTO Green Book *(5)* recommends that the staggering of intersections be done only if traffic crossing the major street is moderate.

*Size* Intersection size, or number of approach lanes, and type of traffic control are based on a match of capacity with design (demand) volume. For any particular intersection, there does not seem to be much practical latitude for choice: once the design volumes have been ascertained, the number of approach lanes follows. The design volumes in turn are determined by intersection density, hierarchy, and form.

Even though the latitude for choosing the proper number of lanes is limited, two issues deserve mention. First, wide approaches (more than two lanes in each direction) make the accommodation of pedestrians difficult. Not only is the crossing hazardous, the need to provide for pedestrians reduces the capacity of the intersection *(16)*. Second, the size of an approach is affected by the decision to build a left-turn (storage) lane. This decision affects the safety of pedestrians as well as vehicles. More will be said about both subjects later.

To some extent, the physical size of the intersection depends on the width of the lanes. The ITE guidelines *(9)* suggest a minimum lane width of 11 ft and specify 12 ft as "desirable." It is also suggested that wider lanes be avoided because they "increase pedestrian crossing distances." Nevertheless, according to the guidelines, a range of opinions exists, with tolerable variations of lane width from 9 to 14 ft. One philosophy of particular interest is that narrowing intersection lanes not only reduces pedestrian crossing distances, but also lessens the speed of motorists, and therefore enhances safety, particularly for pedestrians. For lane-width selection, AASHTO *(5)* differentiates among local, collector, and arterial streets, and furthermore whether these are urban or rural. Thus, for example, the minimum lane width for a local road in a rural area is 9 ft (*5*, p. 464), whereas in an urban area a lane should be (*5*, p. 474) "at least 10 ft wide. Where feasible they [lanes] should be 11 ft wide." Still, where severe limitations exist (*5*, p. 475), "9 ft lanes can be used in residential areas." Still different considerations apply for the width of a lane used for turns, which is governed by the kind of vehicles assumed to be turning. Thus, for example, a single-unit truck or bus that before turning occupies 8.5 ft of a lane sweeps a path 13.6 ft wide as it turns (*5*, p. 730). A semitrailer takes 8.5 to 20.6 ft. One can readily see the safety issue that emerges: how to mediate between the need to accommodate larger turning vehicles and the interest of the pedestrian whose crossing distance is thereby prolonged.

*Angle* The angle at which the centerlines of the intersecting roads meet is the intersection angle. It is commonly agreed that it should be a right angle. Some sources give 75 degrees as the minimum, whereas AASHTO states (*5*, p. 724): "Angles above approximately 60° produce only a small reduction in visibility, which often does not warrant realignment closer to 90°." In this context, "visibility" usually means "unobstructed sight distance" (5, p. 774), that is, how far one can see with the appropriate turning of the head. However, the need for extensive head movement is in itself a problem for the older segment of the driving population, which may not have been taken into account in AASHTO's geometric design policy. Fortunately, most intersections are built at right angles. Because the need to engage in extensive, often difficult and slow head movement at acute-angle intersections may be a real difficulty for older drivers, affecting their safety, the use of an acute angle in intersection design should be explicitly justified.

*Left-Turn Lanes*

Safety is an important benefit in the provision of left-turn lanes, which can reduce opportunities for rear-end collisions. In addition to safety benefits, left-turn lanes also reduce vehicle stops and delays and make the intersections simpler to use, thus benefiting older drivers.

In fact, it would appear that the only reasons for not providing a left-turn lane are either that the right-of-way is not available or is too costly or that the road space is needed to carry through traffic. There is perhaps another reason, which has not yet been explored: that a left-turn lane prolongs pedestrian walking distances or narrows the refuge island.

In principle, therefore, the decision to provide a left-turn lane should be made on the basis of a comparison of benefits and costs. To illustrate how such a comparison would be made, consider the addition of a left-turn lane to an intersection approach. The right-of-way, construction, and maintenance costs are, say, $60,000, which is equivalent to about $7,200 a year. Calculations (based on traffic flow and approach speed) show that on the approach one should expect to see one rear-end accident a year. If the monetary equivalent of a target accident is $25,000, it takes a 35 percent reduction in rear-end accidents to break even on accident reduction alone. Were a 35 percent reduction obtainable, the other benefits (reduced delay, increased freedom from conflict) might go toward increasing the ratio of benefits to costs.

Several attempts have been made to come up with a set of guidelines based on the economics of the situation *(17–21)*. Although AASHTO does not provide guidance beyond recommending that left-turn lanes be installed where volumes are high and speeds fast, several jurisdictions have warrants based on volumes and approach speeds *(22–24)*.

A considerable body of information already exists about the safety effects of left-turn lanes. Thus, ITE guidelines *(14)* quote Box *(25)* in suggesting that "studies have demonstrated that accident experience is significantly reduced when left-turn storage lanes are provided at intersections of 2-way major streets."

An FHWA report *(26)* suggests that the provision of left-turn channelization at nonsignalized intersections, if combined with curbs or raised bars, will reduce accidents by 70 percent in urban areas and by 65 and 60 percent in suburban and rural areas, respectively. If channelization is painted, accidents will be reduced by 15 percent in urban areas and by 30 and 50 percent in suburban and rural areas, respectively. At signalized intersections, it is suggested *(26)* that left-turn channelization with a left-turn phase will reduce accidents by 36 percent; without the left-turn phase, by 15 percent. It is also suggested that adding left-turn lanes without signals can decrease accidents by 19 percent on urban two-lane roads, and by 6 percent on urban roads with more than two lanes, and increase accidents by 6 percent on rural roads with more than three lanes. Adding left-turn lanes with signals will reduce accidents in the last two categories by 27 and 54 percent, respectively.

Jorgensen and Associates *(27)* give costs and safety benefits of adding left-turn lanes. These lanes are estimated to reduce accidents by varying amounts depending on whether the intersection is rural or urban; is four-legged, cross, or T; or has added signals. Adding turn lanes without signals at four-legged intersections increases accidents 6 percent and with signals at rural T-intersections, 42 percent. Jorgensen and Associates also reproduce the California Division of Highways accident reduction factors, which specify that left-turn lanes reduce accidents by 15 or 36 percent if a turn phase is added to the signal. The basis of all these data is not clear.

Elsewhere in the literature, there seems to be agreement that left-turn lanes considerably reduce rear-end accidents but might increase left-turn accidents, but perhaps this only occurs because there tend to be more turns when left-turn lanes are provided. For example, McCoy et al. *(28)* did a cross-sectional study of uncontrolled approaches to two-lane rural highways and found that those with left-turn lanes had a lower (not statistically significant) rear-end accident rate and a higher (not statistically significant) left-turn accident rate than did those without. At least one study [David and Norman *(29)*] concurs that left-turn lanes are not always safety-effective.

To sift through this mass of evidence and select what is valid is a major undertaking because much of what is reported suffers from serious deficiencies of method. We speculate that left-turn lanes reduce rear-end accidents mainly, and the amount of reduction may vary from 20 to 60 percent.

In summary, it is clear that in many circumstances left-turn lanes are of benefit to all. Nevertheless, again there is no authoritative guidance on the conditions under which a left-turn lane should be built, which may cause opportunities for improvements to be forgone. If the profession chooses not to issue complex warrants because of the variability in local conditions, the practitioner should be provided with a clear procedure enabling him to determine the quantitative descriptors of the situation and how to make a rational decision on the basis of local conditions. Currently, such a procedure does not seem to exist, thus, the following recommendations:

- The knowledge now available should be critically reviewed, summarized, and cast into the form of a procedure usable by engineers.
- A procedure to analyze the need for left-turn lanes should be included in the ITE handbook or perhaps even in the AASHTO geometric design policy.

### *Geometrics*

This section includes discussions of sight distance, channelization, and curb-corner radii.

*Sight Distance* The provision of proper sight distance is thought to greatly reduce the possibility of conflict. How much is proper depends on the type of traffic control, but the philosophy remains the same—to enable a vehicle entering the intersection to avoid conflict with vehicles on other approaches. The most conservative provision is for uncontrolled intersections. Preferred practice *(5)* is to provide a clear "sight triangle" that allows drivers to see the intersection and the traffic on the intersecting road in sufficient time. Uncontrolled intersections are perhaps few, and ITE *(9)* recommends that the intersection of local streets be designed to operate without any traffic control device whenever possible. For uncontrolled intersections AASHTO (*5*, p. 777) suggests using "2.0 sec for perception and reaction plus an additional 1.0 sec to actuate braking."

An entirely different case arises when the vehicle has to stop at the intersection before crossing or turning. Now it becomes important to complete the maneuver safely even if another vehicle comes into view just as the maneuver begins. In calculating the time required to complete a crossing maneuver, AASHTO (*5*, p. 781) suggests using 2.0 sec as the interval between the driver's first looking for oncoming traffic and the instant that the car begins to move. Shorter times may be used in urban areas. It is noted (*5*, p. 782) that the required sight distance is only very slightly affected by the reaction-time value chosen. Thus, using 1.0 sec instead of 2.0 sec reduces sight distance by about 15 percent.

There is a great deal of evidence that although older persons do not necessarily react much more slowly to stimuli, they do take longer to make up their minds, particularly in complex situations. In addition, the decision to enter an intersection (from a minor road) requires extensive and repeated head movement, a task that becomes increasingly difficult with age. Thus, the situation that a driver faces when approaching an intersection or when deciding to enter an intersection after stopping is indeed complex.

The currently used sight distances may place some older persons in difficult situations. We conclude that the safety of older persons at intersections may be adversely affected when too short a design reaction time is used in the calculation of intersection sight distance and that further study of this issue is required.

The FHWA synthesis *(30)* gives results of several studies. The first finds that in projects aimed at improving intersection sight distances, safety benefits outweigh costs 5.33 to 1. Because of faults in collecting and analyzing those data, the results are not reliable. The second study cited also indicates a large accident reduction by removing obstructions at intersections. However, in this case high-accident locations were selected for improvement, and it is possible that much of the noted reduction was due to regression to the mean. Two more studies, one pertaining to rural intersections in Michigan and the other to

Virginia, indicate that intersections with poor sight distances have higher accident rates.

Additional information is given by David and Norman *(29)*, who found intersections with a shorter "sight radius" to have generally higher accident rates. The study uses its findings to provide estimated accident reductions obtainable by increasing sight distances (*29*, p. 76). Unfortunately, these results cannot be trusted either. The authors calculate accident rates at sites that differ in "sight radius" and attribute the difference to visibility only. Of course, sites that differ in "sight radius" differ in several other important respects as well. This single-variable cross-sectional method of analysis leads the authors to many paradoxical conclusions (e.g., more illumination or the provision of left-turn lanes increases the accident rate).

On the whole, research results reinforce the premise that longer sight distances at intersections are in the interest of safety. However, there is no useful guidance on the circumstances in which long sight distances are important and the extent of safety improvement that can be expected.

As noted earlier, the design reaction time (e.g., 2.0 sec) only influences sight distance slightly when a truck is the design vehicle. In this case, the time needed to accelerate and clear the intersection dominates the design calculation. The same is not true when a car is taken to be the design vehicle.

Were almost all intersections designed with sufficient sight distance so that trucks could cross them safely, there would be no reason to worry about older drivers of passenger cars because cars need much less time than trucks to accelerate and clear the intersection. Unfortunately, not only do the AASHTO guidelines neglect to state clearly that intersections must have sufficient sight distance to allow trucks to cross safely, they even allow for larger-than-normal acceleration when a passenger car is assumed to be the crossing vehicle (*5*, p. 782). The only guidance given is that the designer use (*5*, p. 19) "the largest design vehicle likely to use that facility with considerable frequency." Therefore, there may exist in the United States many intersections deemed not to be used by trucks with "considerable frequency" at which a serious problem may exist for all drivers encountering a truck. We do not know how many intersections in the United States fall into this category. Therefore, stock-taking is recommended first:

- A survey of design practice (what proportion of intersections are designed to be crossed safely by trucks) and of existing intersection sight triangles (what proportion of intersections can be crossed safely by SU and WB-50 units) should be conducted.

Should it turn out that a significant proportion of intersections have been built and are being designed so that they pose a potential safety problem, thought should be given to the modification of design standards and procedures and also to a program of remedial action. Accordingly, the following is recommended next:

- Research to ascertain the relationship among intersection accidents, conflicts, and the sight triangle should be conducted, and a program of remedial action should be established for the rectification of those intersections at which such action is cost-effective.

The last consideration is modification of existing design standards and procedures. The sight triangle provided depends on what the designer selects to be the largest vehicle to cross with "considerable frequency." This is so vague that one could elect to design for an accelerating passenger car and build intersections with rather short sight triangles. Because of the large site-to-site variability it does not seem sensible either to declare explicitly what "considerable frequency" means or to demand the use of a longer reaction time in all designs. Rather, a design procedure is needed that allows and requires the design engineer to examine the safety and cost consequences of the sight triangles at each intersection being designed. The benefit of such a design process would be that the potential for inexpensive safety improvements is not overlooked nor do rigid standards force the unjustified expenditure of resources. Thus, the following is recommended:

- The standards and design procedures for intersection sight triangles should be modified because there is reason to believe that when a passenger car is taken as the design vehicle, the sight distance is too short for many older drivers, who take longer to make decisions, move their heads more slowly, and wish to wait for longer gaps in traffic. The modification should require an explicit analysis of safety and cost consequences in each case.

Suppose that the engineering required will cost \$500 per intersection, or about \$60 annually. Suppose furthermore that at an average intersection at which the issue of the sight triangle arises there is 0.2 target accident a year. It takes only a reduction of 1 percent in the probability of target accident occurrence to justify the added cost of engineering. This kind of "back-of-the-envelope" calculation shows again that investment in sound safety engineering pays better than remedial action after the hazard has manifested itself in the form of accidents in police records.

*Channelization* The merits of channelization have been widely recognized and it is commonly used in practice (*5*, p. 752):

> An at-grade intersection in which traffic is directed into definite paths by islands is termed a channelized intersection. An island is a defined area between traffic lanes for control of vehicle movements. Islands also provide an area for pedestrian refuge.

Various minimum dimensions for islands are suggested in sources such as the AASHTO geometric design policy *(5)*, for example, minimum width (4 to 6 ft) for pedestrian refuges, minimum area to command drivers' attention (50 to 100 $ft^2$), and minimum length of side for triangular islands (12 to 15 ft). With regard to when islands might be considered useful, the *Traffic Control Devices Handbook (31)* suggests that they be used to reduce pedestrian clearance intervals or to accommodate those who walk more slowly than the "design" walker, or both, and that they are particularly useful in urban areas, on exceptionally wide roads, or at irregularly shaped (skewed) intersections where the combination of heavy pedestrian and vehicle volumes can make pedestrian crossing difficult or dangerous.

The safety effect of intersection channelization projects is described by Hagenauer et al. (*30*, Chap. 5). In one study the channelization of intersections was found to reduce accidents by 32 percent and injury accidents by 50 percent. In another study intersection channelization projects had an average benefit-cost ratio of 2.3.

In the context of this paper, two situations deserve special attention. First, inasmuch as channelization in general serves to simplify an otherwise ambiguous and complex situation, it stands to reason that, when an existing intersection can be channelized, doing so might enhance both the safety and the mobility of older persons. In this case the interests of the older person seem to coincide with the interests of others (pedestrians and drivers).

The second situation to be considered is the case in which the intersection is still on the drawing board and one has to decide whether it will be large enough to allow channelization. In this case the interests of pedestrians and drivers may not coincide. The presence of islands is unlikely to offset the disadvantage of large intersection size for the pedestrian.

Another element deserving attention is the provision of refuge islands. Their dimensions and minimum sizes to accommodate wheelchairs are discussed in the AASHTO geometric design policy (*5*, p. 758). The *Manual on Uniform Traffic Control Devices* (MUTCD) defines refuge islands as (*6*, p. 5A-1) "a place of safety for pedestrians who cannot cross the entire roadway width at one time in safety because of changing traffic signals or oncoming traffic." The MUTCD also lists conditions in which refuge islands are particularly useful: on multilane roadways, in large or irregularly shaped intersections, and in signalized intersections to provide a place of safety between different traffic streams. The manual also suggests that refuge islands do not have to be a part of a channelization scheme or the continuation of a median.

In summary, the safety of older persons at intersections would be positively affected by more extensive use of channelization when conditions make it practical, and pedestrian safety could be particularly enhanced by the provision of refuge islands even when these are not part of a comprehensive channelization scheme.

*Curb-Corner Radii* Curb-corner radii are the radii of curves that join the curbs of adjacent approaches. Their purpose is to facilitate the movement of right-turning vehicles, usually trucks, and their increasing size affects safety negatively in a number of ways.

First, the larger the curb-curve radius the larger the distance that the pedestrian has to cover when crossing the road. Thus, for a sidewalk whose centerline is 6 ft from the roadway edge, a 15-ft corner radius increases the crossing distance by only 3 ft. However, a 50-ft radius increases this distance by 26 ft (or 7 sec of additional walking time). It is widely believed that the longer the crossing distance the greater the hazard to pedestrians, even though, when the corner radius is large enough, there may be space for refuge islands. Second, larger curb radii may induce drivers to negotiate the right turn at a higher speed. Third, the larger the radius the wider the turn, which makes it more difficult for the driver and the pedestrian to see each other.

The design of curb-corner radii is covered in considerable detail in the AASHTO geometric design policy. The main determinant is the selection of the design vehicle. Typical minimum recommended radii are 30 ft for turns by passenger cars and 50 ft for single-unit trucks (*5*, p. 736). For rural conditions the policy leans toward serving the single-unit truck. In urban areas (*5*, p. 742), "curb radii of 10 to 15 ft are reasonable . . . . However, on arterial streets carrying heavy traffic volumes it is desirable to provide corner radii . . . of 30 to 50 ft for most trucks and buses to expedite turns."

It is worth noting that the design philosophy is in this case single-mindedly vehicle oriented. Although there is no substantial problem with 10- to 15-ft radii, the desire to expedite turns by large vehicles at intersections on urban arterials and at most rural intersections makes these crossings inhospitable to pedestrians in all three ways mentioned earlier. One could contrast this design philosophy to the alternative shown in Figure 11 *(32)*. This design is not without obvious merit. It is an attempt to make the pedestrian visible and to reduce the speed at which vehicles might turn, which is desirable at intersections in which complex situations might arise. The safety of older persons at intersections and particularly of pedestrians may be affected when large curb radii are provided. Therefore the shaping of the curbs at intersections so as to recognize the interests of both the pedestrian and the driver deserves attention.

## Traffic Control

### *Level of Traffic Control*

Going from lower to higher levels of traffic control, the main choices are (a) none, (b) Yield sign, (c) Stop sign (two-way or multiway), and (d) traffic signal. Decisions on appropriate levels of traffic control are guided by warrants such as those provided in the MUTCD *(6)*.

*Yield and Stop Signs* In general, Yield signs are warranted where it is seen necessary to assign right-of-way to the major road "but where a stop is not

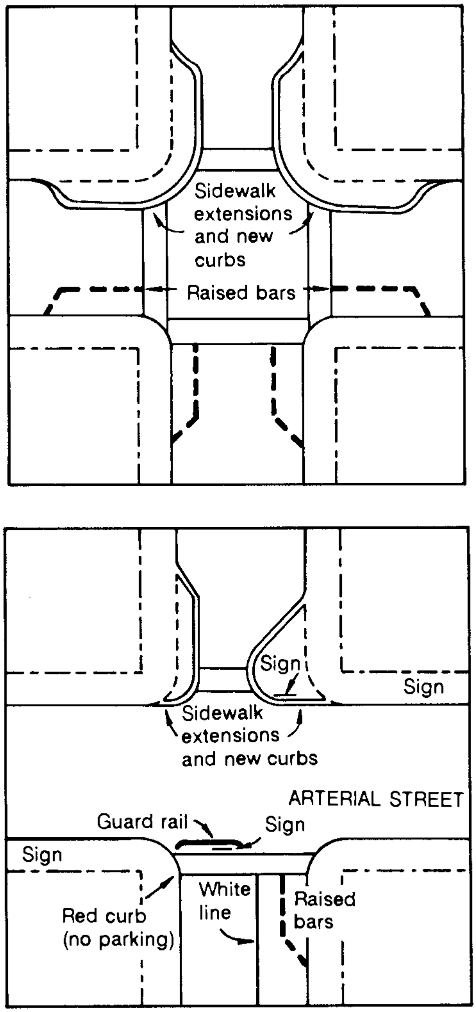


FIGURE 11 Pedestrian-conscious intersection layouts *(32)*.

necessary at all times, and where a safe approach speed on the minor road exceeds 10 mph" *(6)*. Stop signs are warranted, among other circumstances, "where application of the normal right-of-way rule is unduly hazardous" and "where a combination of high speed, restricted view, and serious accident record indicates a need for control by the STOP sign" *(6)*. Multiway Stop signs are considered "an interim measure" where volumes call for a traffic signal but there is no money to install one. They are also warranted where five or more correctable accidents occurred in a year.

In practice, the Yield sign is seldom used (even though it does not appear to be less safe than a Stop sign). Which intersections are left uncontrolled, which get the two-way Stop, and which are equipped with multiway stops depends strongly on local practice and pressures. As a result, many Stop signs and the majority of multiway stops are installed even though they are unwarranted in the spirit of the MUTCD. In many cases, the installation of Stop signs is in response to demands from the public. (Often the reason is safety, but sometimes the real motive may be neighborhood pressure to keep through traffic from using residential areas.)

As one might expect, the safety of an intersection can be significantly affected by the level of traffic control provided. Thus, for example, the replacement of two-way Stop control by four-way Stop control reduces accidents by 50 percent or more *(33)*. Table 4 shows that of the 524 pedestrians 64 years and older who were killed at intersections in 1985, 247 were killed at intersections with no traffic control.

Little is currently known about the safety implications of various forms of control at intersections. As a result, little substantive guidance is provided to professionals on this matter. The opportunity for safety gains by providing such guidance should be pursued.

Studies on the safety effect of changing from no control to Stop or Yield control are cited in two main sources [FHWA synthesis *(30)* and National Cooperative Highway Research Program (NCHRP) Report 162 *(27)*]. In the synthesis a comprehensive review of several studies by Hall et al. *(34)* is cited in which it was found that Yield signs at low-volume crossings reduced accidents by 20 to 60 percent and that little additional reduction (10 percent) was achieved by using Stop signs instead. Hall et al. provide no further information about these studies, however. These reductions appear to accord with those found by Kell *(35)*, who found 44 and 52 percent fewer accidents after conversion to Yield control in two cities. NCHRP Report 41 *(36)* gives accident reductions of 23 and 63 percent after conversion of three uncontrolled intersections to Yield control. None of these studies give any information on whether or how the size of the safety effect depends on volume. One work that purported to address that issue is a cross-sectional study by Stockton et al. *(37)*, who found that in urban areas uncontrolled intersections with major-road volumes of less than 1,500 vehicles per day had fewer accidents than Yield-controlled intersections with similar volumes. Stop-controlled intersections had the highest rate. For volumes between 1,500 and 4,000 vehicles per day, Stop-controlled intersections still had the highest rate, but Yield control had a lower rate than no control. Because Stockton's study, unlike the others mentioned, is not a before-and-after comparison, one cannot infer that the different accident rates are due to differences in traffic control.

Some of the foregoing evidence is old (dating from the 1950s), much of it relies on very few data, most of what is written consists of quoting what someone else has quoted on the basis of a third person's findings, and the experimental setting is such that when one encounters contradictory evidence (e.g., the findings by Stockton et al.), it is difficult to come to a consensus.

If Yield and Stop signs were used according to the spirit of the MUTCD, they would have a positive safety effect. However, as these signs are used in practice, it is more difficult to anticipate their effect. It appears that Yield signs are largely nonexistent and that most Stop signs induce a Yield type of behavior by drivers.

Insight about the costs and benefits of Stop and Yield control can be provided by citing two well-known studies. In the first, Stockton et al. *(37)* estimated annual capital costs along with vehicle operating and user time savings for various types of control conversions and entering-volume combinations (Table 13). The difference in annual accident rates for existing intersections with each type of control was then taken as due to differences in control, which is perhaps incorrect, as mentioned earlier. On this basis, they suggested, for example, that in some cases conversion from Yield to Stop control will increase accidents, and vice versa. With the expected accident costs taken into account, Table 14 specifies the conditions under which one or the other of the minor forms of control would be preferred.

The other study is by Upchurch *(38)*, who performed a sophisticated analysis of vehicle, user, and accident costs for Yield- and two-way and four-way Stop-controlled moderate-volume intersections (those that do not warrant signalization but had more than 500 vehicles per day on the minor road). (In contrast, Stockton et al. studied intersections with less than 500 vehicles per day on the minor road.) Upchurch concluded: "For accident rates used in this

TABLE 13 AVERAGE ANNUAL HIGHWAY COSTS OF STOP, YIELD, AND NO CONTROL *(37)*

| | | Highway Agency Cost ($) | | Expected Avg Annual Savings ($) by Minor-Roadway Volume (vpd) | | | | |
|---|---|---|---|---|---|---|---|---|
| Existing Control | Proposed Control | Three Legs | Four Legs | 100 | 200 | 300 | 400 | 500 |
| Major-Road Volume ≤2,000 vpd | | | | | | | | |
| Stop | Yield | 7 | 11 | 240 | 480 | 720 | 960 | 1,200 |
| Stop | No control | 5 | 5 | 44 | 88 | 132 | 176 | 220 |
| No control | Yield | 14 | 23 | 196 | 392 | 588 | 784 | 980 |
| Major-Road Volume >2,000 vpd | | | | | | | | |
| Stop | Yield | 7 | 11 | 244 | 488 | 732 | 976 | 1,220 |
| Stop | No control | 5 | 5 | 155 | 310 | 465 | 620 | 775 |
| No control | Yield | 14 | 23 | 88 | 176 | 264 | 352 | 440 |

NOTE: vpd = vehicles per day.

TABLE 14 RECOMMENDED CRITERIA FOR SELECTING LEVELS OF INTERSECTION CONTROL *(37)*

| Sight Distance | Accident History | Major Roadway Volume | |
|---|---|---|---|
| | | <2,000 vpd | >2,000 vpd |
| Adequate | 0 | No control | – |
| Adequate | ≤2 | Yield | Yield |
| Adequate | 3 | Stop[a] | Stop[a] |
| Adequate | 4+ | Stop | Stop |
| Not adequate | – | Stop | Stop |

[a]If minor roadway is greater than 300 vpd, Yield control is appropriate for intersections with less than four accidents in 3 years.

study, Yield control is the most economical type of control, regardless of volume." However, he found it necessary to caution: "This finding must be treated with care because of the uncertainty associated with the accident rates which were used." [He used, "skeptically," those rates in NCHRP Report 41 *(36)*.] Upchurch also showed that two-way Stop control might have been preferred sometimes if different accident rates had been assumed. These studies highlight how sensitive the choice of type of intersection control is to assumptions about the safety benefits of making changes. Upchurch laments that "additional research on the safety relationship must be conducted before Yield and Two-way Stop control before Yield control can be recommended to replace Stop control on a widespread basis."

Because much of the safety problem occurs at intersections that are not signalized, the following research on Stop and Yield sign use is recommended:

- A study should be made to obtain factual data on how Stop and Yield signs affect safety and traffic performance at a specific site and how the policy of such sign installation affects driver behavior at such signs in general.

*Multiway Stop* A critical review of the substantial body of literature on the safety of conversion from two-way to multiway Stop control was published in 1985 *(33)*. Table 15 *(39)* confirms that total accidents are reduced by at least 40 percent, with similar percentage reductions for pedestrian accidents. There are some lingering doubts, however; recent work *(40)* has shown that accidents saved might have "migrated" to surrounding unconverted intersections; also, many traffic engineers believe that excessive control leads to a general disrespect by the public for traffic signs.

Multiway Stop control is known to increase vehicle and user costs; rational decisions to install multiway Stop control can be made by weighing these

TABLE 15 MOST LIKELY PERCENTAGE OF ACCIDENT REDUCTIONS *(39)*

| Accident Type | San Francisco | Philadelphia | Michigan | Toronto | Combined |
|---|---|---|---|---|---|
| Right-angle | 84 | 78 | 64 | 48 | 72 |
| Rear-end | –305 | 20 | 19 | 22 | 13 |
| Left-turn | 33 | – | –7 | 25 | 20 |
| Pedestrian | 66 | 40 | – | 42 | 39 |
| Fixed-object | – | –30 | – | – | – |
| Injury | 74 | 74 | 62 | 63 | 71 |
| Total | 62 | 47 | 59 | 37 | 47 |

extra costs against what appear to be substantial safety benefits. Upchurch *(38)* found that in most cases two-way Stop control is economically preferable to four-way Stop control. The latter is preferable at low-volume intersections or where the minor-street volume is approximately equal to the major-street volume. As for the Yield sign control, Upchurch found that the decision is very sensitive to assumptions on accident rates. To shed light on this issue, an example is provided.

Consider an intersection with a total entering volume of 1,000 vehicles per hour, equally distributed among its four approaches. On the basis of data from Byrd *(41)*, converting this intersection to four-way Stop control is estimated to increase user costs by about $10,000 a year. With two-way Stop control such intersections are expected to have about one or two accidents per year. To justify conversion on the basis of accidents saved, and with $25,000 as the cost of a representative accident, one would have to count on an 80 percent reduction in the expected number of accidents, which is not realistic.

As before, the results of such an example should not be taken to indicate whether a measure can be justified in economic terms. The purpose of the example is to focus on two points. First, the numbers used in the calculation are of a very dubious nature. The user-cost figure is obtained by converting seconds of delay into fragments of cents and summing these for thousands of motorists. It is even assumed that those who do not stop legally incur a cost. The merit of expressing accidents in terms of dollars and the magnitude to be used behind the dollar sign are equally questionable.

The decision to replace control by signs with control by traffic signals is governed by detailed warrants, and the MUTCD now requires (*6*, Part IV-C) that the decision be based on a comprehensive study. Most signals that are warranted are installed when vehicular traffic volumes are sufficiently high. In other cases, signals can be warranted by some combination of vehicle volumes, pedestrian volumes, and accident records (where five or more correctable accidents occurred in a year).

*Traffic Signals*

As Table 16 shows, much has been published about the safety effects of installing signal control, but there is little consistency in the results *(42–49)*. There is, however, some empirical support for the intuitive conclusion—that signal installation is likely to increase rear-end accidents and decrease right-angle accidents. If the latter type of accident predominates at a site, it seems likely that, on balance, signals would improve safety at that site.

TABLE 16 CHANGE IN PROPORTION OF ACCIDENTS AFTER SIGNAL INSTALLATION *(42–49)*

| | | | Percentage of Change by Accident Type | | | | |
|---|---|---|---|---|---|---|---|
| Author | Location | No. of Signals | Total | Rear-End | Right-Angle | Injury | Left-Turn |
| Solomon *(42)* | Michigan | 39 | −23 | −200 | +51 | +20 | n/a |
| King and Goldblatt *(43)* | Virginia | 30 | −24 | −181 | +34 | +18 | −16 |
| King and Goldblatt *(43)* | Michigan | 33 | −8 | −84 | +45 | n/a | −236 |
| NYS DOT *(44)* | New York | 39 | +7 | +21 | +13 | −11 | −13 |
| Hammer *(45)* | California | 170 | +21 | −90 | +76 | +32 | +14 |
| Clyde *(46)* | Michigan | 52 | −34 | −98 | +45 | −11 | −66 |
| Short et al. *(47)* | Milwaukee | 31 | +2 | −37 | +34 | −6 | n/a |
| Vey *(48)* | 22 cities | 599 | +20 | −37 | +56 | n/a | n/a |
| Schoene and Michael *(49)* | Illinois | 30 | −16 | −221 | +48 | −26 | |

In the studies cited in Table 16, pedestrian accidents either were not reported or were so few that the results were inconclusive. In the study of 31 installations by Short et al. *(47)*, pedestrian accidents decreased from 18 to 12 in 3 years. In the study of 39 intersections by the New York State Department of Transportation *(44)*, accidents increased from 0.1 a year to 0.2 a year after signal installation. Data from Yagar *(50)* for Metropolitan Toronto suggest that installation of signals at 25 intersections with pedestrian protection decreased the pedestrian accident rate about 40 percent; on the other hand, at the 43 installations with no prior protection, the pedestrian accident rate increased about 20 percent. These data, however, were based on an average of fewer than 30 pedestrian accidents a year. Yagar points out that the 20 percent increase is insignificant.

Recognizing that the overall safety effect of signal installation must depend on a variety of factors, some researchers have attempted to identify the circumstances in which signal installation might enhance safety. The warrant for installing signals implies that they might enhance safety if accidents exceed some number. However, what evidence there is to support this belief appears to be tainted by statistical shortcomings in the analyses. Information from traffic engineers and from the literature indicates that signals are rarely installed because of a safety warrant, but mainly on the basis of traffic volume. In many cases, no warrants are satisfied, and the findings of many studies have led traffic engineers to the belief that only warranted installations increase safety. Again, most of these studies are fraught with methodological problems that make their findings useless.

It is assumed that once signals are warranted and funds permit, they will be installed. In the following example only the costs and benefits of installing a signal that might be good for safety but does not meet existing volume warrants are considered. Changes in pedestrian accidents are ignored because there are no adequate data on which to base such a discussion.

Suppose that one is contemplating installing signals at a two-way Stop-controlled intersection with a total entering volume of 12,000 vehicles per day that is distributed over time and by approach, so that the signal volume warrants are not met. There are four right-angle accidents (the MUTCD safety warrant requires five) a year, and signal installation is expected to increase this by 30 percent. However, rear-end accidents are less severe, so the increase in these accidents is estimated to cost $12,000 a year. Annualized costs of installing and maintaining a signal are about $12,000 a year. Given a requirement for a 2:1 benefit-cost, a further savings of $11,000 needs to be realized to justify the installation. It is estimated that this can be done if the signals save each entering vehicle an average of about 5 sec. That this is reasonable is not clear.

What this example reveals is that the decision to install a signal for safety reasons is very sensitive to the actual number of target accidents, to the delay savings, and, quite importantly, to the assumed safety effect.

Even though by now there are in the United States about 300,000 signalized intersections, it is not known what the safety of signalization is under specific circumstances. This must reflect the lack of data on the safety repercussions of the decision to install traffic signals. In view of this deficiency, the following recommendation is made:

- Research should be undertaken to enable the professional to estimate for a specific site the expected safety effect of conversion to traffic signal control.

*Traffic Signal Control*

After a decision has been made to install traffic signal control at an intersection, a series of technical choices follows. These choices are discussed in the following section, including the relative merits of isolated versus coordinated signals; pretimed versus actuated signals; number, type, and duration of signal phase; clearance intervals; and cycle time.

*Reaction Time and Walking Speed* Preliminary to the discussion of these choices, two characteristics of older persons used as parameters in traffic signal control design need to be addressed, namely, reaction time and walking speed. The assumed driver-reaction time affects the duration of the "inter-green period" (also called the vehicle clearance interval, yellow change and clearance interval, or yellow plus all red).

The issue of the design driver has already been addressed. The assumed speed of walking may affect the amount of green signal time allocated vehicles and, if separate pedestrian signals are provided, also the duration of the clearance interval for pedestrians.

Perception-Reaction Time The yellow signal, which usually lasts from 3 to 6 sec, warns the driver of an impending change to a red signal. Included in this interval is time for the driver to perceive and react (by using the brake) to the yellow signal. Various sources, including the ITE handbook *(13)*, indicate that current practice assumes a perception-reaction time of 1 sec. The adequacy of this interval has been questioned. It is not clear to what percentage of drivers this figure applies or should apply. If, as seems to be currently favored, the 85th-percentile driver is selected, the 1-sec perception-reaction time appears to be inadequate. Wortman and Matthias *(51)* found that the 85th-percentile value at most intersections approached 2 sec. Gordon et al. *(52)* estimated a median perception-brake reaction time of 1.23 sec and recommended using the 85th-percentile value of 1.77 sec—both values are quite close to the observations by Wortman and Matthias.

Several studies have measured brake-reaction times in circumstances different from those occurring at the onset of the clearance interval, but it is not known whether these findings are transferable to vehicle clearance intervals. Olson and Sivak *(53)* estimated reaction time of unalerted drivers to an obstacle in their lane while they were cresting a hill and found a 95th-percentile driver-reaction time of 1.6 sec—a finding obtained for both older (60 to 84 years) and younger (18 to 40 years) drivers. Johansson and Rumar *(54)* measured brake-reaction time to an audible signal and estimated that, for unanticipated situations, it was 1.5 sec or longer in 10 percent of the cases.

On the basis of this information one would tend to conclude that the perception-reaction time now in use (1 sec) is already too short, and that this shortfall may be particularly hard on older persons. In fairness, one has to make clear that the issue is more complicated than the mechanistic application of a formula. First, the premise of the formula used to calculate the duration of the clearance interval is that the driver should behave legally; he should be able to either stop or clear the intersection without violating the local law. The relationship between the duration of this interval and safety is a different matter. It has less to do with what is assumed to be a proper reaction time and more with how drivers behave at the onset of the yellow signal and how this behavior depends on its duration.

Second, if a longer perception-reaction time was used in the calculation, the duration of the clearance would also be extended, with two consequences. What is added to the clearance interval is taken away from the length of time for the green signal, increasing the frequency of stopping and vehicular delay and affecting safety adversely. In addition, it is widely believed that if long clearance intervals were provided, drivers might gradually begin to encroach on these. Thus, the 1-sec perception-reaction time appears to be used more as a device to get reasonable results than as a serious reflection of actual reaction times. A meaningful discussion of this issue should concern the duration of the clearance interval and its impact on safety, which will be covered under Separate Pedestrian Signals.

Walking Speed The MUTCD *(6)* is somewhat vague about walking speed. It cites an assumed normal walking speed of 4 ft/sec, but refers to research showing that one-third of all pedestrians cross the street more slowly, with 15 percent crossing at or below 3.5 ft/sec. In the *Traffic Control Devices Handbook (31)*, which provides interpretation of the MUTCD, it is stated that "those having slower walking speeds have the moral and legal right to complete the crossing once they have legally entered the intersection."

Some traffic engineers seek guidance from the ITE handbook *(13)*, in which it is stated that some engineers use a walk speed of 4.0 ft/sec, but it is suggested that (*13*, p. 221) "for relatively slow walkers, speeds of from 3.0 to 3.25 ft/sec would be more appropriate." No reference is made to an ITE Technical Committee estimate of 3.7 ft/sec for mean crossing speed or to the 1965 ITE handbook *(55)*, in which it was estimated that 35 percent of pedestrians were excluded by the 4.0-ft/sec design value. More recently, ITE Committee 4 A-6 conducted a survey in Florida at a location with a large population of elderly pedestrians and recommended (presumably for such locations) a walk speed of 2.5 ft/sec, which provided adequate crossing time for 87 percent of those pedestrians *(56)*.

Elsewhere in the literature, there is conflicting guidance on walk speeds. Sleight *(57)* reported on a Swedish study by Sjostedt in which the average adult and older person were found to walk at 4.5 ft/sec and distribution curves showed about 20 percent of the older persons crossing at speeds less than 4.0 ft/sec. For that group, the 85th-percentile speed was 3.4 ft/sec. On the basis of these numbers, Sleight suggested that "there would be safety justification for use of speeds around 3 to 3.25 [ft/sec] in order to safeguard the relatively slow walkers." However, Dahlstedt points out *(58)* that the Swedish study on which Sleight's often-cited numbers are based is not representative of the average pedestrian, dealing only with "pedestrians who have been troubled or interfered by approaching cars." In this regard, Dahlstedt refers to findings by Moore *(59)* that average walking time was 5 ft/sec if an approaching car was within 3 sec away but 4 ft/sec if approaching cars were not too close. In

Dahlstedt's own study *(58)*, those 70 years or older were instructed to cross an intersection at fast, very fast, or normal speed. Their results show that what is considered fast by about 60 percent of these older pedestrians is slower than 4 ft/sec. At normal, comfortable speed, almost 90 percent crossed at less than 4 ft/sec, and the 85th-percentile speed (15 percent were slower) was about 2.2 ft/sec.

That walk speed depends on a variety of environmental factors and pedestrian characteristics was a highlight of research by Ugge *(60)*. Pedestrian speeds were estimated for two types of nonsignalized crosswalks: (a) marked and signed (protected) and (b) unprotected. The mean crossing speeds were 4.2 and 6.9 ft/sec, respectively. The respective figures for the slowest group (elderly women) were 3.56 and 6 ft/sec. Ugge also found that the closer an approaching vehicle was to the crossing the faster was the mean crossing speed.

*Choices and Decisions* The main choices and decisions in traffic signal control are discussed singly and in some semblance of the order of importance; however, in practice they are linked and made jointly.

Type of Signal Perhaps the first decision is whether the signal should be timed independently of its neighbors or coordinated with them to allow continuous flow (green wave) as much as possible. Coordination is generally desired on arterial streets and where intersection spacing makes it useful; it can reduce the frequency of stopping and of delay and is thought to be good for safety of both vehicles and pedestrians. Even though the decision of signal coordination may affect safety, the safety repercussions of this choice are not well understood.

Next a decision has to be made on whether the signal phases are to be of fixed duration (fixed-time control) or continuously adjusted on the basis of the instantaneous detection of traffic (traffic-actuated control). Fixed-time control is often chosen when traffic volumes are stable, when a decision has been made to coordinate signals, or when considerations of economy, simplicity, and reliability are important. Traffic-actuated signals are "semiactuated" when confined to minor-road approaches and "full actuated" when detectors are placed on all approaches. Actuated signals require a decision on how far from the stop line to detect traffic. This distance (*13*, p. 746) "may vary from one car length up to 500 ft." From the point of view of safety, actuated signals have the potential to time the onset of yellow so that no approaching cars are placed in the difficult situation of either having to stop abruptly or of entering the intersection during the clearance interval.

The decisions about whether to have a coordinated signal system and whether signals should be fixed-time or actuated are linked. It stands to reason that these decisions have an important effect on safety. However, this effect seems to be terra incognita. Thus, we cannot explore the question further and note only that inasmuch as signal coordination and the choice between fixed-time and actuated signals are likely to have important safety repercussions, there is need to find out what these are and to make these findings available to those who make such choices. Only then can safety considerations affect decision making.

Signal Timing Signal timing involves decisions about the duration of the signal cycle, its phases, and the clearance interval. These aspects are detailed in sources such as the ITE handbook *(13)* and the *Highway Capacity Manual* (HCM) *(7)*, the aim of which is to minimize delay to vehicles. The discussion here will concern the relation between decisions on signal timing and the safety of older drivers and pedestrians.

Long cycle times (100 to 110 sec) tend to be used for intersections at which vehicle flows are near capacity. If a group of intersections is coordinated, the longest cycle time found in the group will be used at all these intersections. Long cycle times necessitate long pedestrian waiting times, which increase the inclination to walk during the red signal phase. It is in this manner that the choice of signal cycle time may affect pedestrian safety.

The duration of green given to an intersection approach has to be long enough for both pedestrians and vehicles, moving forward together at the green light, to have sufficient time. This amount of time is important when the street is wide and the amount of green required by vehicles is short. In other cases the duration of green is governed by vehicular traffic demand. A design walking speed of 4 ft/sec is used. Several sources have suggested that as many as one-third of pedestrians (mainly older persons) walk more slowly. The adoption of a slower design walking speed will increase the minimum duration of green. For example, at a walk speed of 3 ft/sec a pedestrian crosses a 60-ft-wide road in 20 sec compared with 15 sec at 4 ft/sec. Giving an additional 5 sec of green to one approach, where it may not be needed to accommodate vehicles, takes away the 5 sec of green time from another approach, which may already be congested. Thus, the decision to include a larger proportion of the pedestrian population in the design speed may in many cases increase congestion.

The last element of signal timing is the duration of the vehicle clearance interval, which separates the green and the subsequent red signals. Guidelines for computing the duration of vehicle clearance intervals are given in most authoritative sources. The calculation depends on what is legal locally, the approach speed, the intersection width, and the assumed perception-reaction time. Adding 1 sec to the perception-reaction time increases the clearance interval by 1 sec. Generally, a minimum of 3 sec is used, with a maximum of 5 to 6 sec. At the end of the vehicle clearance interval an all-red phase is often used.

A slower design walking speed and a longer design perception-reaction time would have similar effects. Both would diminish the amount of time available for the movement of vehicles. Nevertheless, a slower walking speed would only affect relatively few approaches, at which it would diminish the vehicular green by a fairly large amount (say, 5 sec). In contrast, were a longer perception reaction time to be universally adopted, a small amount of time (about 1 sec) would be taken away from the green time on every approach.

These considerations carry over to the timing of pedestrian signals. There should be enough time for the pedestrian who starts to cross just as the Walk indication is ending to reach the opposite curb safely. The flashing Don't Walk signal usually provides the necessary time; the duration of this interval again depends on the design walking speed. To accommodate slower walkers, more time would have to be allocated to the flashing Don't Walk aspect, which could be done at the expense of the vehicular green or, more likely, the duration of the Walk aspect, with dubious safety consequences.

Design walking speed and design perception-reaction time feature prominently in various signal-timing decisions. Concern about the safety and mobility of older persons is often tied to the concern that these design parameters are not suited to their abilities. Therefore, it is appropriate to examine the effects of change in these design parameters on safety and the associated costs.

Because considerable space will be devoted to the protection of left-turning traffic, a brief comment about right-turning traffic is in order. In this respect, very little seems to be left to be decided. One can only comment with some bitterness that nowadays allowing right-turn-on-red (RTOR) in the United States is the rule, and disallowing it is the exception. This is the end result of a curious historical development. The practice of allowing RTOR started in the West and for a long time the official position of the ITE was to actively discourage it. However, to allow vehicles to turn right when there is no traffic is common sense and is popular with drivers. Thus, when during the energy crisis jurisdictions would have lost money if they had not switched to RTOR, the practice spread from the West like wildfire. Research consistently showing that with RTOR pedestrians and cyclists are being injured at alarmingly higher rates has been ineffectual in changing this practice. Even the ITE pronouncements have gradually been modified and now a complete reversal of policy has occurred, which is being defended on the basis of a most questionable logic.

### *Minimum Green*

Changing the design walking speed from 4 ft/sec to 3 ft/sec affects minimum green time. While the pedestrian is crossing the main road, the minor road has a green light. Thus, the time it takes to cross the main road dictates the duration of the minimum green.

Table 17 gives the minimum green times required for various crossing distances. Minimum green requirements are affected in slightly different ways depending on whether a separate pedestrian signal (Walk–Don't Walk) is provided.

TABLE 17 MINIMUM GREEN TIME VERSUS CROSSING DISTANCE AND SPEED OF WALKING

| Walking Speed (ft/sec) | Green Time (sec) by Crossing Distance (ft) | | | | |
|---|---|---|---|---|---|
| | 20 | 30 | 40 | 50 | 60 |
| 5.0 | 4.0 | 6.0 | 8.0 | 10.0 | 12.0 |
| 4.0 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 |
| 3.5 | 5.7 | 8.6 | 11.4 | 14.3 | 17.1 |
| 3.0 | 6.7 | 10.0 | 13.3 | 16.7 | 20.0 |

*No Pedestrian Signal* With no pedestrian signal, pedestrians cross the main road when the minor-road vehicles have a green light. In practice, green times are rarely less than 7 sec. Therefore, even pedestrians walking at 3 ft/sec should have no problem crossing a two-lane road. At the other extreme, pedestrians walking at 3 ft/sec can easily cross the main road if it is less than 60 ft wide (about six lanes) and the minor road is getting at least 20 sec of green time.

A problem exists in crossing situations in which the main road is wider than the crossing distances indicated in Table 17 whereas the green time for the minor road is less than the values given for the slowest walking speed. Zegeer *(61)* believes that these situations are rare. However, information from Metropolitan Toronto indicates that more than half of the semiactuated signals (which account for about 50 percent of the signals in that city) might be thus affected. A semiactuated signal gives a green signal to the minor road when a vehicle on that road triggers the detector. If no more vehicles are detected, the green light returns to the main road. Thus, when a semiactuated signal is used and minor-road traffic is light (a typical circumstance), most pedestrians have to cross the main road at the assumed design walking speed.

*Separate Pedestrian Signals* The MUTCD *(6)* requires the Walk message be displayed for at least 7 sec to allow pedestrians time to notice and react. In addition, a pedestrian clearance interval is required, as mentioned earlier. Thus, when a separate pedestrian signal is provided, the green phase for the minor road should be at least 7 sec plus the pedestrian clearance interval. In addition, when a separate pedestrian signal is provided, it is much more likely that the requirements of slower pedestrians are not met if the minor-road traffic determines the duration of the minor-road green. Therefore, perhaps paradoxically, slow walkers may encounter marginal conditions more often when separate pedestrian signals are provided.

Separate pedestrian signals are discussed in more detail in a later section.

*Numerical Example* Consider a minor road with a two-way volume of 5,000 vehicles/day that intersects a major road 60 ft wide carrying 20,000 vehicles/day. The intersection is controlled by a two-phase signal with a 70-sec cycle consisting of a 45-sec green phase for the major road, a 15-sec green phase for the minor road, and two 5-sec clearance intervals. The 15-sec interval is just long enough for pedestrians to cross the major road. If the design walking speed were 3 ft/sec instead of 4 ft/sec, the minimum green time required to cross the major road would be 20 sec. If the cycle time remains fixed, the major-road green has to be reduced to 40 sec. This change is estimated to increase delay on the major road by about 3 sec/vehicle and to reduce delay on the minor road by about 2 sec/vehicle. The net annual extra delay is 5,070 vehicle-hr, which, on the basis of costs given by Cottrell *(62)*, translates into about $10,300/year in extra fuel and travel-time costs.

The target accidents in this example are those occurring to pedestrians at the far end of the crossing. Data from Zegeer et al. (*61*, Table 22) show about 0.5 pedestrian accident yearly for this type of intersection. Considering that this may occur on any approach and on the entire length of the crossing, it might be assumed that there is 0.5/8 = 0.07 target accident a year. Even if a pedestrian accident were valued at $50,000 and the change from 4 ft/sec to 3 ft/sec were to eliminate all target accidents (rather than just reduce the probability of their occurrence), 0.07 x $50,000 is still less than $10,300. However, an increase in rear-end accidents due to the increased red time on the major road has not been taken into account.

One can debate at length the propriety and morality of this kind of cost accounting. Can one legitimately add a few seconds of delay for a multitude of drivers and compare these with the suffering of seven anonymous pedestrians injured in 100 years? Even if such reasoning is commonly used, it seems a somewhat absurd device for making wise decisions. Surely the problem is not only that people are being injured but also, and perhaps primarily, that they fear being injured. Thus, to confine our thinking to the objective count of corpses might be too narrow a perspective, a scope that disregards the concept that people—and perhaps older persons in particular—wish not only to be safe but also to feel safe. Similarly, one should not plunge into the calculus of costs and effects without pausing to ponder the "balance of rights." Surely no one would think that what we decide to do for the terminally ill is a matter of weighing costs and benefits. A civilized society is guided on this matter by other considerations as well. Older persons through no fault of their own walk more slowly than young persons and are not as nimble in stepping out of harm's way. Is it fair to use a design walking speed that causes many of them to feel threatened?

Thus, the cost of giving more green time to the pedestrian (and the minor road) is an increase in vehicle delay on the main road. The benefits might lie in somewhat fewer pedestrian accidents and less pedestrian anxiety and frustration. The balance of costs and benefits depends on the specifics of every case (main-road and minor-road traffic, main-road width, pedestrian volumes, the speed of walking at the site, etc.). It follows that to use one design walking speed for all situations is perhaps convenient but wrong.

The design walking speed of 4 ft/sec should be retained as the maximum. However, when designing signal timing, the engineer should be required to base the minimum green time on a site-specific analysis. This would ensure that 4 ft/sec would be used only where it could be justified and where no better solution can be found.

The following research and actions are recommended:

- A design procedure should be developed to allow the determination of a minimum green time for pedestrian crossings on the basis of site-specific data and explicit analysis.
- Signal installations now in service at which pedestrians have to cross at a speed of at least 4 ft/sec should be identified and it should be determined whether the current timing is justified or better solutions can be found.
- Appropriate guidelines and requirements should be established so that the design and timing of future signal installations are based on the aforementioned design procedure.

*Protection for Left Turns*

Left-turn protection is important because of accidents involving left-turning vehicles. It has been found *(62)* that 45 percent of vehicle collisions and 29 percent of collisions with pedestrians at signalized intersections involve a left-turning vehicle, although only 10 to 15 percent of the traffic turns left. Robertson estimates that left-turning vehicles are three times more hazardous to pedestrians than through-moving ones *(63)*. The task of turning left is difficult, especially when the through traffic has the right-of-way and pedestrians are using the crosswalk. For older persons the difficulty of the task is compounded by their slower and less accurate decision making in complex situations as drivers and their diminished nimbleness as pedestrians.

The traffic engineer can elect to restrict left turns or to accommodate the left-turning traffic. If the decision is to allow left turns, three main signal-phasing options arise for signalized intersections: protected, permissive, or protected-permissive. In the first option, a separate left-turn phase is provided (e.g., by a green arrow) during which the left-turner's right-of-way is "protected." In the second option left-turning vehicles are permitted to fend for themselves by finding gaps in the opposing traffic (a solid green indication). In the third option the first two options are mixed—protection during a part of the green and permission to use gaps in the oncoming traffic during the rest. These three options affect the quality of service for vehicles (in terms of frequency of stopping and delay) and the safety of both vehicles and pedestrians. Accommodating left-turning vehicles during gaps in the oncoming traffic causes the least delay for the through vehicles, whereas protecting left-turning traffic with a green arrow delays the through traffic. According to Fambro and Woods *(64)*, for every left-turn accident during a protected phase, 10 would have occurred without protection. This number may be exaggerated, but it stands to reason that providing a separate left-turn phase reduces accidents in which left-turning vehicles are involved.

Clearly, the decision on the appropriate accommodation of left-turning traffic is a matter of striking a balance between safety and other indexes of service. To this end, it is important to know the safety repercussions of alternative courses of action.

A recent survey of state and local agencies *(65)* revealed a great diversity of practice in the accommodation and protection of left-turning traffic. One-third of the respondents did not use any warrant or technique to decide when or what protection to provide for left-turning traffic. The criterion for the majority is at least three to five left-turn accidents in a year, a disturbing practice. Perhaps this is because there is no relevant MUTCD warrant. [A corresponding Canadian document *(66)* provides a numerical warrant based on through, left-turning, and pedestrian traffic.] Accidents involving left-turning vehicles are especially acute for older road users. There are several standard options that the traffic engineer may use to accommodate left-turning vehicles, and these apparently have very different safety consequences. In addition, current practice is marked by great diversity and insufficient guidance. The safety of older persons as drivers and pedestrians may be significantly affected by the choice of left-turn treatment. Detailed examination of the safety facts and the relevant trade-offs is required.

*Safety Issues* Agent and Deen *(67)* report an 85 percent reduction in left-turn accidents accompanied by a 33 percent increase in rear-end accidents, producing a 15 percent reduction in total accidents following introduction of separate left-turn phases at 24 intersections. On this basis, one might expect that if some protection were removed (to provide protected-permissive signal phasing), there would be an increase in left-turn accidents. A before-and-after comparison of 17 intersections so altered *(68)* indicated a sixfold increase in left-turn accidents and a 20 percent increase in other accidents. The same study examined the effect of changing 17 signals from protected-permissive to fully protected status; the number of left-turn accidents decreased by a factor of 7, but the number of other accidents almost doubled. More recently, Agent

*(69)* found that left-turn accidents increased about fourfold at 11 approaches after conversion from protected to permissive phasing; total accidents, however, did not change. All the studies mentioned so far are the simple before-and-after type. Thus, it seems likely that the reported safety changes might be exaggerated because of a statistical pitfall that plagues this type of study. A few of the studies of the cross-sectional type were reviewed, in which differences in safety at intersections with different types of left-turn protection are assumed to be due to differences in protection. As indicated elsewhere, this assumption is not a good one and will lead to incorrect results.

In conclusion, there does seem to be a consistent indication that the protected signal phasing is the safest, whereas the permissive phasing is the most unsafe. However, numerical estimates of safety cannot be provided until methodologically sound analysis has been performed.

*Costs and Benefits: Protected-Permissive to Protected Phasing* Cottrell *(62)* examined the net cost of changing from protected signal phasing to protected-permissive phasing. At a typical arterial intersection with 2,600 left turns a day, the increased delay to left-turning vehicles would cost about $11,000 a year. If there are 20,000 through vehicles a day, extra annual delay to these vehicles, based on data by Upchurch *(70)*, is estimated to cost $20,000 a year. Assuming operating and installation costs of $1,000 a year, one would require a savings of about 2.5 accidents a year at a 2:1 benefit-cost ratio to justify conversion. The data given by Cottrell suggest that left-turn accidents for such an intersection are likely to be reduced by about this much. Thus, the decision appears to be a close one in this case, which emphasizes the need for a careful trade-off of safety benefits with user and vehicle costs.

*Costs and Benefits: Protected to Permissive Phasing* Consider an intersection similar to that in the foregoing example: two opposing lanes, 2,600 left turns a day, and 20,000 through movements a day. According to Upchurch *(70)*, there would be a negligible change in delay to left-turning vehicles. The extra delay per through vehicle is estimated at 15 sec, giving extra user costs of about $60,000 a year *(62)*. Extra capital and operating costs are estimated at $500 a year. Accident savings based on Upchurch's data are about 14 left-turn-related accidents a year. This seems exaggerated, but a net savings of about five such accidents a year would justify the conversion at a 2:1 benefit-cost ratio.

In both examples, it is apparent that the decision is very sensitive to assumptions about the expected safety changes. In previous discussions it was suggested that current information on this issue is sketchy and clouded by uncertainty. Accordingly, the following recommendation is made:

- Rational decisions on changing from one type of left-turn protection to another are strongly dictated by the expected changes in safety. New research to correctly estimate these expected changes is vital.

*Separate Pedestrian Signals*

The MUTCD *(6)* recommends the use of pedestrian signals when a traffic signal is warranted because of large pedestrian volumes, when pedestrians cannot see the vehicle signal, and when an exclusive pedestrian phase is to be provided. Robertson et al. estimate that 85 percent of the pedestrian signal indications do not meet the MUTCD warrants *(71)*.

In the past, the MUTCD defined the meaning of Don't Walk and Walk in both the "flashing" and "steady" modes. Readers who were not students of the MUTCD had difficulty guessing what the MUTCD meant by a flashing Walk or Don't Walk. So did most pedestrians, as was shown repeatedly. The MUTCD now recommends not using the flashing Walk and Don't Walk, but practice has not caught up with this recent change.

A recent ITE survey of practice *(72)* paints the following picture. About half the signals in urban areas have separate pedestrian indications, whereas the majority of reported signals in state jurisdictions do not. Practice in the six districts into which U.S. members of the ITE are divided is diverse. In four districts pedestrian signals are operated as the steady Walk. In two districts the majority are the flashing Walk, although the steady Walk is used also. In one district 18 percent of the indications are the steady Walk and, at the same time, no other traffic is allowed to move across the crosswalk. Two-thirds of the traffic engineers in the ITE survey permit right-turn-on-red at all signalized intersections even when pedestrians have a separate signal indication and an exclusive signal phase. The traffic engineers surveyed believe that only 4 percent of pedestrians understand the meaning of a flashing Walk and that 39 percent understand the meaning of the flashing Don't Walk. Members of the ITE committee that conducted the survey conclude, "It is apparent . . . that most decisions regarding pedestrian control are based on engineering judgment and local preferences."

Pedestrian signal timing influences pedestrian behavior. When pedestrians are asked to wait for long times, when they have to wait at the curb for no apparent reason, and when the Walk signal is displayed for only a few seconds and followed by a long Don't Walk message, pedestrians begin to disregard the signals. This mode of behavior may be contagious; it may render useless those pedestrian indications that are essential.

In short, the safety of pedestrians at signalized intersections may be both positively and negatively affected by the decision to install pedestrian signals and to allow vehicle flow concurrently with conflicting pedestrian flow. Older persons more than others tend to use crosswalks at intersections. They most likely believe that a separate pedestrian signal is there to protect them and perhaps are surprised and frustrated to find vehicles crossing their paths legally. They may develop the "false sense of security" most often blamed for the poor safety showing of pedestrian signals. They are the segment of the population that is perhaps most harmed by the lack of solid professional criteria on which to base decisions about pedestrian signals and vehicle movements.

The principal reason to have a separate pedestrian signal is that the duration of the minimum green time is calculated on the assumption that the pedestrian begins to cross just as the green signal for the vehicles comes on. Of course, many pedestrians begin to cross later, and the minimum green will not be long enough for them to reach the opposite curb. Nor will many of those who begin to cross late in the green be able reach the curb by the end of the vehicle change interval (yellow plus all red), which is usually 3 to 5 sec long.

There is growing recognition that the provision of pedestrian signals is not always good for pedestrian safety. The lack of uniformity in the devices and in timing strategies, the misunderstanding of the meaning of flashing Walk and Don't Walk messages, and the false sense of security provided to pedestrians are the reasons most often cited for their ineffectiveness. In addition, specific knowledge on when the installation of pedestrian indications is in the interests of safety and when it is not is scarce.

In one of the few studies on this subject, Zegeer et al. *(61)* found that intersections with standard pedestrian signals had slightly higher pedestrian accident rates than intersections with no pedestrian signals. As they note, a study that compares one set of sites with a different set of sites "does not show cause and effect relationships," so one cannot conclude from these results that pedestrian signals do not improve safety.

It does appear that under some conditions pedestrian signals directly or indirectly improve safety, although Robertson et al. *(71)* are not specific about what these conditions are. Pedestrian signals are surely necessary when the pedestrian cannot easily see the vehicle signal or when it may be confusing. Robertson et al. estimated that some 85 percent of the pedestrian signals in existence are perhaps not useful. In most cases, however, it is unclear whether the signals are good or bad for safety and by how much safety is affected.

For example, consider a crossing 30 ft wide that now does not have a separate pedestrian indication. The vehicle green time is long enough for those who begin crossing at its onset. The vehicle change interval is 4 sec of yellow plus 2 sec of all red. A pedestrian starting at the last moment of green and walking at 5 ft/sec will reach the opposite curb before the end of the all-red period. Because 5 ft/sec is faster then the design walking speed, the temptation is to consider separate pedestrian signals. Because the vehicle green time is long enough, one could have a steady Walk signal for 7 sec and a flashing Walk for 10 sec—long enough for even those walking at 3 ft/sec to reach safety. The annual cost [based on data from Robertson and Carter *(73)*] for pedestrian signals is about $150. It would take only a saving of 0.01 accident a year to justify this cost. Unfortunately, whether pedestrian signals will in fact increase safety in this situation is unclear. All that can be said is that they will cost some money, they will increase pedestrian delay, they will put more persons in a position in which they will disobey a signal, and some persons may believe that they are getting more protection.

A few cases in which the installation of pedestrian signals might be considered useful are as follows:

1. Left-turning vehicles are given a separate phase (green arrow or equivalent) and pedestrians have to wait until the end of this phase. Pedestrian signals are needed to convey this arrangement to pedestrians. Because there is no choice in this case, the question of costs or benefits does not arise.
2. Pedestrian pushbuttons are installed at a semiactuated signal to improve the efficiency of green time use. In this case, installation is justified strictly for operational reasons, and safety improvement is not the issue. Without a pedestrian signal, every time the minor-road traffic is allowed to proceed, enough green time is provided for pedestrians to cross. Thus, green time is "wasted" for every phase in which only a few vehicles enter the intersection and no pedestrians cross. With a pushbutton pedestrian signal, pedestrian crossing time is provided only when this signal is actuated.

Many competent researchers, notably Robertson et al. *(71)* and Zegeer et al. *(61)*, have recognized the sorry state of affairs in the area of providing pedestrian signals, their timing, and the message displayed. Similarly, many useful suggestions for improvement have been made. Still, the state of disarray remains. It would be presumptuous for us to make specific recommendations on a subject that many have explored in greater detail. Our impression is that within the context of pedestrian behavior as it now exists, whether pedestrian signals are provided (in those cases in which they are not essential) and what their timing is matters little to safety. The function of these signals seems to be mainly to clarify who is to blame for an accident in what part of the signal cycle.

Still, for the pedestrian, the current state of affairs is of serious concern. Is it true that a false sense of security is created by pedestrian signals (or crosswalk markings)? If so, one should surely insist that unnecessary installations be removed. Not knowing the answer to this question should be a strong impetus for action, not complacency. In conclusion, the following action is recommended:

- Pedestrian signals should be provided to enhance safety. Traffic engineers should be aware of the influence of their professional decisions about the timing of signals and the policies and practices for their provision on behavior of pedestrians.

## Crosswalk Markings

There is very little material on cost associated with the marking of a crosswalk. The decision to mark a crosswalk should therefore be based on whether safety will be enhanced. Nevertheless, the literature on this subject is inadequate also.

Herms *(74)* has done perhaps the best-known study on this subject. In 5 years of accident experience at 400 unsignalized intersections that had one marked and one unmarked crosswalk, 177 and 31 pedestrians were hit, respectively. After correction for differences in pedestrian volume, approximately twice as many pedestrian accidents occurred in marked crosswalks as in unmarked ones. Herms attributes the difference to lack of caution by pedestrians when using marked crosswalks. In the largest number of pedestrian accidents, the vehicle struck the pedestrian on the far side of the street that the pedestrian was crossing.

These results might be questioned for two reasons. First, could it be that intersections with marked crosswalks differ from those with unmarked ones? Herms finds, for example, that between 5:00 and 7:00 p.m. all accidents that occurred were at marked crosswalks. The highest incidence was among pedestrians 70 years or older, who had 35 accidents in marked and 7 accidents in unmarked crosswalks. Second, the assumption was made that because the marked and unmarked crosswalks were on opposite sides of a major street, both had the same vehicle volumes. The decision on which approach was to have the marked and which one the unmarked crosswalk must have been based on some criterion, but it was not given. Was it the accident rate, or could it be that there is relatively more potential for pedestrian-vehicle conflict at marked crosswalks?

A three-year before-and-after study in Vancouver *(75)* found that pedestrian accidents increased 86 percent at 55 intersections after crosswalks had been marked. Rear-end collisions increased 32 percent. It is unclear whether there were before-and-after differences in pedestrian and vehicle traffic and, if so, whether such differences were accounted for. It was pointed out that marked crosswalks did not give the pedestrian any further legal rights, because they already had the right-of-way over vehicles at unmarked as well as at marked crosswalks. This, it was believed, created confusion among motorists and pedestrian alike.

Contrasting evidence is provided by a few studies. A study cited in the 1965 ITE handbook (*55*, Chap. 4) found that painted crosswalks reduced violation of the pedestrian's right-of-way and that pedestrians tended to use the painted crosswalk in preference to an unpainted one. (At the two major intersection approaches, one crosswalk was painted, and one was left unpainted.)

Untermann states, without providing supporting evidence, that (*76*, p. 34) "painted crossings on roadways reduce pedestrian accident risks about 50 percent." He argues, "Many elderly people have difficulty perceiving perpendicularity, and the painted crosswalk helps to keep them from wandering away from the general direction of the other side of the street."

In an extensive study Knoblauch et al. *(77)* found that unmarked crosswalks had 24.8 percent of exposure for their population of intersections and 61.2 percent of accidents, whereas marked crosswalks had 75.2 percent of the exposure but only 38.8 percent of accidents. [In that study, exposure is taken as the sum of the products of conflicting pedestrian-vehicle flows (*PV*). Although this measure tends to make high-volume sites appear safer, no other reasonable exposure measure would alter the finding that marked crosswalks had more exposure but fewer accidents than unmarked ones. Using the square root of *PV* would indicate that marked crosswalks are three times as safe as unmarked crosswalks.]

In summary, it is unclear at this time whether marked crosswalks are safety-effective. It does appear that under certain (unknown) conditions, marked crosswalks do improve safety. Indeed, even though Herms' study showed that unmarked crosswalks were safer, he concludes that "marked crosswalks will continue to be a useful traffic control device" and recommends limiting such crosswalks to only those locations where they are warranted. These sentiments were echoed by Braaksma *(75)*.

## SUMMARY AND RECOMMENDATIONS

From research on older persons and intersection accidents, it appears that the age profile of injuries due to motor vehicle accidents is very malleable. Its shape depends on what is chosen to serve as the denominator of the injury or accident rate of interest. Thus, when the fatality rate is computed "per licensed driver," noticeable overrepresentation begins around 65 to 70; the rate for men is more than twice that for women. However, when the rate is computed on a "per unit of travel" basis, the driver fatality rate begins to climb around the age of 50 and the difference between male and female drivers is small.

The accident data show a mixture of two phenomena: the frequency with which people are involved in a crash and the chance of injury or death as a result (frailty). Older persons have a larger chance of being fatally injured in a crash of fixed severity. When this effect is accounted for, a very different set of age profiles emerges. Not only does the per-licensed-driver rate show no sign of increasing with advancing age, the rate for older persons is dwarfed by that of young men. Similarly, when the frailty effect is eliminated from the data, the plot of the per-unit-of-travel rate also changes: the rate begins to climb only around the age of 70, and its ascent is much slower. A similar line of reasoning applies in the case of the pedestrian fatality rate, which leads to the conclusion that older pedestrians are not overrepresented in crashes, simply much more vulnerable.

The statistics presented lead to several conclusions. First, for pedestrians in the 64+ age group, about 33 percent of fatalities and 50 percent of injuries occur at intersections. For drivers in the same age group, 40 percent of fatalities and 60 percent of injuries occur at intersections. It follows that roughly half of the safety problem for older persons involves intersections.

Second, a relatively large number of pedestrians over 64 are killed at intersections (some 500 per year compared with approximately 800 in all other age groups).

Third, for "overrepresentation" to lead to countermeasure identification, it is important to separate "involvement rate" from "frailty" (the likelihood of injury or death as a result of an accident). It appears that much of what is seen as overrepresentation in age profiles of accident rates is due to "frailty." Older persons seem to be able to adapt to the traffic environment so as to keep nearly constant the probability of being involved in an accident; they do not seem to be able to adapt sufficiently to keep constant the probability of injury or death.

Many of the intersections we use now did not exist a generation ago. Our grandchildren will likely make the same observation. Therefore, the intersection safety problem must be viewed within the dynamics of the process by which intersections are created and the transformations that they undergo. Review of this process indicates that important decisions affecting safety are made in the early stages of development or redevelopment. These are the decisions by which the density and hierarchy of intersections are set. In making them, as a rule, no explicit professional attention is being given to safety. Yet it is these early choices that build future accidents into the transport network. Unfortunately, explicit authoritative guidance on this matter is not available in standard professional literature.

Inasmuch as older persons are active mainly close to their residence, their safety is particularly strongly affected by these early choices. Accordingly, the safety of older persons at intersections could be increased if alternative road designs were explicitly evaluated at the planning stage in terms of their future safety repercussions. The professionals and institutions in charge of planning and approving plans for development and redevelopment should assume the responsibility for the creation of the tools needed for the safety evaluation of street networks and for the training of professionals in their use.

A number of specific design elements are reviewed for their potential effects on safety and cost. The first is the decision to provide a left-turn lane. These are known to reduce rear-end accidents and also delays. However, there is no officially sanctioned procedure for engineering design or analysis by which the practitioner can reach a rational decision on when to provide a left-turn lane. This lack of guidance may lead professionals to overlook opportunities to enhance both the safety and the level of service at some intersections. Several recommendations, both for research and action, are made.

The question of sight distance at intersections is explored next. On the whole, research results reinforce the commonsense belief that longer sight distances enhance safety. However, there is very little knowledge about the extent of the safety improvement that can be expected.

When the design standards are examined in detail, it appears that the assumptions used for perception-reaction time matter little. What governs the design outcome (that is, whether the sight distance is long or short) is the design vehicle. If the design vehicle chosen is an automobile, not a truck, sight distances will be too short for those who are slow to make up their minds or to turn their heads. Again, research and actions are recommended to improve design practice and rectify problems when it is cost-effective.

Once an intersection has been designed and constructed, short of reconstruction, one must look to changes in intersection operation to improve safety. It is somewhat surprising to find that there is no consensus on the safety effect of changing the level of traffic control from none to a Yield sign and from that to a Stop sign. Converting two-way Stop control to multiway Stop control reduces accidents by about 40 percent, but delay and stops by motorists are substantially increased. It appears that there is no economic justification for the use of the multiway Stop. Research is recommended to obtain more factual data on which to base decisions about level of traffic control.

The decision on when and where to use traffic signals raises similar problems. Even though in the United States about 300,000 signals have been installed, it is not known what safety effect to expect and under what circumstances. Research on this topic is in order.

The decision to protect left-turning traffic has important safety repercussions. Knowledge of the safety implications associated with providing one type of protection or the other is sketchy. Nevertheless, traffic engineers must make decisions based on expected safety changes. Thus, new research to correctly estimate these expected changes is vital.

The economic comparison of accidents saved by designing for a walking speed of 3 ft/sec instead of 4 ft/sec is examined. It appears that the delay to main-road traffic usually swamps savings in pedestrian accidents. However, were one to impute a cost for the anxiety of those pedestrians who walk at less than 4 ft/sec, the outcome of the economic analysis could be reversed.

The balance of costs and benefits depends on many local factors: main-road and minor-road traffic, volume of pedestrians, road width, distribution of walking speeds, and so on. Therefore, the use of a universal design walking speed is perhaps convenient but certainly leads to inferior design in many cases and does not appear to be fair to the large elderly portion of the population. It is recommended that 4 ft/sec be retained as the maximum allowable design speed, but that the signal timing be designed on the basis of a site-specific analysis.

On the provision of separate pedestrian signals, it is noted that pedestrians may not know what the flashing signals mean. A bewildering variety of practice among localities as to what indications are used, the circumstances in which pedestrian signals are installed, and what vehicular traffic is allowed to move concurrently with the pedestrian compounds the problem. There is also a belief that in many cases pedestrian observance of these signals is very poor and that this is due in part to the preceding questionable practices. It is recommended that pedestrian signals be provided and that traffic engineers be aware of the influence of their professional decisions about the timing of signals and the policies and practices for their provision on the behavior of pedestrians.

Some general issues emerge from the detailed findings in this discussion. In many cases, perhaps most, we find that to increase safety one has to make sacrifices, which are measured not only in money but also in delay to road users. Who is to decide what the right balance is? Even though a great deal of thought has been given to the estimation of "value of time" and "cost of accidents," basic questions remain. The questions are not mainly about whether the values assigned to life or time are correct; they are also about the attitude that once such estimates have been published, they can be added, multiplied, compared, and otherwise manipulated as if one were dealing with measured properties of inanimate matter. Society has put on the shoulders of the highway and traffic engineer a task not commonly given to them—that of making decisions about the road user's time and about his health. Highway and traffic engineers have very little background or training that would allow them to discharge these responsibilities particularly well.

The safety consequences of many design decisions are not well known. Recommendations in this paper aim to bring about an engineering practice in which safety is an explicit element of design. Only then will one have a "safety-conscious design" and only then will action that shapes the safety of intersections be based on factual knowledge.

## REFERENCES

1. L. Evans. *Fatal and Severe Crash Involvement Versus Driver Age and Sex.* GMR-5721. General Motors Research Laboratories, Warren, Mich., 1987.
2. J. E. Todd and A. Walker. *People as Pedestrians.* Office of Population Censuses and Surveys, London, undated.
3. *Special Report 214: Designing Safer Roads.* TRB, National Research Council, Washington, D.C., 1987.
4. B. C. Kragh et al. Accident Costs for Highway Safety Decision Making. *Public Roads,* Vol. 50, No. 1, June 1986.
5. *A Policy on Geometric Design for Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 1984.
6. *Manual on Uniform Traffic Control Devices for Streets and Highways.* FHWA, U.S. Department of Transportation, 1978, revised 1983 and 1986.

7. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
8. *Traffic Safety in Residential Areas.* Organization for Economic Cooperation and Development, Paris, 1979.
9. *Recommended Guidelines for Subdivision Streets—A Recommended Practice.* Institute of Transportation Engineers, Washington, D.C., 1984.
10. H. H. Van der Molen. *Pedestrian Ethology.* University of Groningen, Netherlands, 1983.
11. R. E. Brindle. Some Aspects of Town Planning and Road Safety. Presented at New Zealand Roadway Symposium, Wellington, 1983.
12. *Principles for Urban Planning with Respect to Road Safety.* SCAFT, Sweden, 1968.
13. W. S. Homburger, L. E. Keefer, and W. R. McGrath (eds.). *Transportation and Traffic Engineering Handbook.* Prentice-Hall, Inc., Englewood Clifs, N.J., 2d ed., 1982.
14. *Guidelines for Major Street Design—A Recommended Practice.* Institute of Transportation Engineers, Washington, D.C., 1984.
15. K. R. Agent. Guidelines for the Use of Protected/Permissive Left-Turn Phasing. *ITE Journal,* July 1987, pp. 37–42.
16. V. R. Vuchic. Pedestrian Crossing Time in Determining Widths of Signalized Traffic Arterials. *Transportation Science,* Vol. 1, No. 3, 1967, pp. 224–231.
17. J. Craus and D. Mahalel. Analysis and Operation and Safety Characteristics of Left-Turn Lanes. *ITE Journal,* July 1986, pp. 34–39.
18. M. D. Harmelink. Volume Warrants for Left Storage Lanes at Unsignalized Grade Intersections. In *Highway Research Record 211,* HRB, National Research Council, Washington, D.C., 1969, pp. 1–18.
19. C. G. Hammer. Evaluation of Minor Improvements. In *Highway Research Record 286,* HRB, National Research Council, Washington, D.C., 1969, pp. 33–45.
20. S. L. Ring and R. L. Carstens. Guidelines for the Inclusion of Left-Turn Lanes at Rural Highway Intersections. In *Highway Research Record 371,* HRB, National Research Council, Washington, D.C., 1971, pp. 64–74.
21. J. Lee. *Developing Left-Turn Lane Guidelines for Priority Intersections in the State of Kansas.* Report FHWA-KS-78-1. University of Kansas Center for Research, Lawrence, 1978.
22. *The Layout of Major/Minor Junctions.* TA20/81. United Kingdom Department of Transport, London, 1981.
23. *A Policy on Geometric Design of Rural Highways.* American Association of State Highway Officials, Washington, D.C., 1965.
24. *Road Design Manual for Rural and Urban Roads Other Than Freeways* (metric ed.). Australia County Roads Board, Victoria, Jan. 1974.
25. P. C. Box. Intersections. In *Traffic Control and Roadway Elements—Their Relationship to Highway Safety,* Chap. 4, Highway Users Federation for Safety and Mobility, Washington, D.C., 1970.
26. W. F. McFarland et al. *Assessment of Techniques for Cost-Effectiveness of Highway Accident Countermeasures.* Report FHWA-RD-79-53. FHWA, U.S. Department of Transportation, 1979.
27. R. Jorgensen and Associates, Inc. *NCHRP Report 197: Cost and Safety Effectiveness of Highway Design Elements.* TRB, National Research Council, Washington, D.C., 1978.
28. P. T. McCoy, W. J. Hoppe, and D. V. Dvorak. Benefit-Cost Evaluation of Left-Turn Lanes on Uncontrolled Approaches of Rural Intersections. In *Transportation*

*Research Record 1026*, TRB, National Research Council, Washington, D.C., 1984, pp. 40–43.

29. H. A. David and J. R. Norman. *Motor Vehicle Accidents in Relation to Geometric and Traffic Features of Highway Intersections*, Vol. 2. Report FHWA-RD-76-129, FHWA, U.S. Department of Transportation, 1975.
30. G. F. Hagenauer, J. Upchurch, D. Warren, and M. J. Rosenbaum. Intersections. In *Synthesis of Safety Research Related to Traffic Control and Roadway Elements*, Chap. 5. Report FHWA-TS-82-232. FHWA, U.S. Department of Transportation, 1982.
31. *Traffic Control Devices Handbook*. FHWA, U.S. Department of Transportation, 1983.
32. N. Kennedy, J. H. Kell, and W. S. Homburger. *Fundamentals of Traffic Engineering*, 8th ed. Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1973.
33. E. Hauer. *Review of Published Evidence on the Safety Effect of Conversion from Two-Way to Four-Way Stop Control*. Publication 85-02. Department of Civil Engineering, University of Toronto, Ontario, Canada, 1985.
34. D. L. Hall, K. C. Sinha, and H. L. Michael. Comprehensive Evaluation of Nonsignalized Control at Low-Volume Intersections. In *Transportation Research Record 681*, TRB, National Research Council, Washington, D.C., 1978, pp. 10–12.
35. J. H. Kell. Applications of Yield Right-of-Way Signs. *Traffic Engineering*, July 1958, pp. 18–22.
36. *NCHRP Report 41: Effect of Control Devices on Traffic Operations*. HRB, National Research Council, Washington, D.C., 1967.
37. W. R. Stockton, R. Q. Brackett, and J. M. Mounce. *Stop, Yield and No Control at Intersections*. Report FHWA-RD-81/084. FHWA, U.S. Department of Transportation, 1981.
38. J. E. Upchurch. Guidelines for Use of Sign Control at Intersections to Reduce Energy Consumption. *ITE Journal*, Jan. 1983, pp. 22–34.
39. J. Lovell and E. Hauer. The Safety Effect of Conversion of All-Way Stop Control. In *Transportation Research Record 1068*, TRB, National Research Council, Washington, D.C., 1986, pp. 103–107.
40. B. N. Persaud. "Migration" of Accident Risk after Remedial Blackspot Treatment. *Traffic Engineering and Control*, Vol. 28, No. 1, 1987, pp. 23–26.
41. M. N. Byrd and D. B. Stafford. An Analysis of Vehicle Delay and Road User Costs at Unwarranted Four-Way Stop Sign Controlled Intersections. Presented at the 63rd Annual Meeting of the Transportation Research Board, 1984.
42. D. Solomon. Traffic Signals and Accidents in Michigan. *Public Roads*, Vol. 30, No. 10, 1959, pp. 234–237.
43. G. F. King and R. Goldblatt. Relationship of Accident Patterns to Type of Intersection Control. In *Transportation Research Record 540*, TRB, National Research Council, Washington, D.C., 1975, pp. 1–12.
44. *Effect of Signalization*. Traffic and Safety Division, New York State Department of Transportation, Albany, 1982.
45. C. G. Hammer. *Evaluation of Minor Highway Improvements—Part 77, Traffic Signals*. California Division of Highways, Sacramento, 1970.
46. M. N. Clyde. Michigan Study Indicates Signals Increase Accidents. *Traffic Engineering*, Vol. 35, No. 2, 1964, p. 32.
47. M. S. Short, G. A. Woelfe, and C. J. Chang. Effects of Traffic Signal Installation on Accidents. *Accident Analysis and Prevention*, Vol. 14, No. 2, 1982, pp. 135–145.

48. A. H. Vey. Effect of Signalization on Motor Vehicle Accident Experience. *Proceedings, Institute of Traffic Engineering*, 1933.
49. G. W. Schoene and H. L. Michael. *Effects of a Change in the Control Device on Intersection Accidents*. Engineering Reprint CE 237. Purdue University, West Lafayette, Ind., 1968.
50. S. Yagar. *Safety Effects of Converting Intersections in Metro Toronto to Pedestrian Crossovers or Traffic Signal Control*. Department of Civil Engineering, University of Waterloo, Ontario, Canada, 1985.
51. R. H. Wortman and J. S. Matthias. Evaluation of Driver Behavior at Signalized Intersections. In *Transportation Research Record 904*, TRB, National Research Council, Washington, D.C., 1983, pp. 10–20.
52. D. A. Gordon, H. W. McGee, and K. G. Hooper. Driver Characteristics Impacting on Highway Design and Operations. *Public Roads*, June 1984, pp. 12–16.
53. P. L. Olson and M. Sivak. Perception-Response Time to Unexpected Roadway Hazard. *Human Factors*, Vol. 26, 1986, pp. 91–96.
54. G. Johansson and K. Rumar. Drivers' Brake Reaction Times. *Human Factors*, Vol. 13, No. 1, Feb., 1971, pp. 23–27.
55. J. R. Baerwald (ed.). *Traffic Engineering Handbook*, 3rd ed. Institute of Traffic Engineers, Washington, D.C., 1965.
56. ITE Committee 4 A-6. Traffic Control Devices for Elderly and Handicapped Pedestrians. Institute of Transportation Engineers, Washington, D.C., undated.
57. L. Sjostedt. *Fotgangare vid Overgangsstallen*. Special Report 57. Statens Vaginstitut, Stockholm, Sweden, 1967. Cited in R.B. Sleight. The Pedestrian. In *Human Factors in Highway Traffic Safety Research* (T. W. Forbes, ed.), John Wiley & Sons, Inc., New York, 1972, pp. 224–253.
58. S. Dahlstedt. *Walking Speeds and Walking Habits of Elderly People*. National Swedish Road and Traffic Research Institute, Stockholm, Sweden, undated.
59. R. L. Moore. Psychological Factors of Importance in Traffic Engineering. Presented at the International Study Week in Traffic Engineering, Stresa, Italy, Oct. 1–5, 1956.
60. A. J. Ugge. *Pedestrian and Driver Behaviour at Pedestrian Crossing*. M.S. thesis. Department of Civil Engineering, University of Toronto, Ontario, Canada, April 1973.
61. C. V. Zegeer, K. S. Opiela, and M. J. Cynecki. *Pedestrian Signalization Alternatives*. Report FHWA/RD-83/102. FHWA, U.S. Department of Transportation, 1985.
62. B. H. Cottrell, Jr. Guidelines for Protected/Permissive Left-Turn Signal Phasing. In *Transportation Research Record 1069*, TRB, National Research Council, Washington, D.C., 1986, pp. 54–61.
62. J. C. N. Ng, E. Hauer, and J. Lovell. Are Longer Signal Cycles Safer? In *Proceedings, 12th Annual Meeting of the Institute of Transportation Engineers*, District 7, Canada, Hamilton, Ontario, Canada, June 1987.
63. H. D. Robertson. The Application of Pedestrian Signals at Traffic-Signalized Intersections. *Public Roads*, Vol. 48, No. 3, 1984, pp. 81–87.
64. D. B. Fambro and D. L. Woods. Safety Benefits of Left-Turn Signal Phasing Alternatives. *ITE Journal*, 1981.
65. N. Lalani, D. Cronin, D. Hattan, and T. Searls. A Summary of Warrants for the Installation of Left-Turn Phasing at Signalized Intersections. *ITE Journal*, April 1986, pp. 57–59.

66. *Uniform Traffic Control Devices for Canada*, 3rd ed. Roads and Transportation Association of Canada, Ottawa, 1976.
67. R. Agent and R. C. Deen. Warrants for Left-Turn Phasing. In *Transportation Research Record 737*, TRB, National Research Council, Washington, D.C., 1979, pp. 1–9.
68. Left-Turn Phase Design in Florida. *ITE Journal*, Vol. 52, No. 9, 1982, pp. 28–35.
69. K. R. Agent. Guidelines for the Use of Protected/Permissive Left-Turn Phasing. *ITE Journal*, July 1987, pp. 37–42.
70. J. E. Upchurch. *Guidelines for Selecting Type of Left-Turn Phasing*. In *Transportation Research Record 1069*, TRB, National Research Council, Washington, D.C., 1986, pp. 30–38.
71. H. D. Robertson, H. D. Berger, and R. F. Pain. *Urban Intersection Improvements for Pedestrian Safety*. Vol. 2: *Identification of Safety and Operational Problems at Intersections*. Report FHWA-RD-77-143. FHWA, U.S. Department of Transportation, 1977.
72. ITE Technical Council Committee 4A-15. Pedestrian Control at Signalized Intersections. *ITE Journal*, Feb. 1986, pp. 13–15.
73. H. D. Robertson and E. C. Carter. The Safety, Operational, and Cost Impacts of Pedestrian Indications at Signalized Intersections. In *Transportation Research Record 959*, TRB, National Research Council, Washington, D.C., 1984, pp. 1–7.
74. B. F. Herms. Pedestrian Crosswalk Study: Accidents in Painted and Unpainted Crosswalks. In *Highway Research Record 406*, HRB, National Research Council, Washington, D.C., 1972, pp. 1–13.
75. What Not To Expect from Crosswalk Signals. *Civic Administration*, Vol. 19, No. 5, May 1967, pp. 32–33. Cited in J. P. Braaksma. *A Survey of Special Crosswalks in Canada*. TP981-CR7708. Transport Canada, Ottawa, Sept. 1976.
76. R. K. Untermann. *Accommodating the Pedestrian—Adapting Towns and Neighbourhoods for Walking and Bicycling*. Van Nostrand Reinhold Company, New York, 1984.
77. R. L. Knoblauch, H. N. Tobey, and E. M. Shunaman. Pedestrian Characteristics and Exposure Measures. In *Transportation Research Record 959*, TRB, National Research Council, Washington, D.C., 1984, pp. 35–41.