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Vehicle Operators and Pedestrians

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Contents

Applicability of Electric Cars to Urban Driving

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The applicability of electric cars to urban driving depends upon the adequacy of their limited daily range for typical daily driving patterns and on the availability of electric power for recharging at their overnight parking places. On the basis of the Los Angeles origin-destination survey of 1967, distributions of daily urban driving distance were compiled for individual drivers and cars and then were combined with information on parking spaces to show the applicability of electric cars in future years. By 1980, lead-acid-battery cars with a daily range of 87 km (54 miles) between recharges could take over the urban travel of about a million second cars in Los Angeles households, or 17 percent of all area cars, with little loss of mobility. Advanced-battery cars with a range of 230 km (140 miles) could also serve as primary cars in households. However, limited availability of overnight recharging facilities may limit applicability to 46 percent of area cars in 1990 and 74 percent in 2000.

Electric cars can now be built with freeway capability and with ranges between battery recharges of more than 80 km (50 miles) in urban driving. Since this range is almost twice the daily average for U.S. automobiles, it suggests that electric cars could be widely useful, with valuable reductions in petroleum consumption and in air pollution. Conventional cars, however, are driven farther than 80 km (50 miles) in a day at least occasionally. To assess quantitatively the applicability of electric cars to urban driving, then, it becomes necessary to ask how frequently conventional cars are driven farther than the potential daily ranges of electric cars.

In a recent study of electric cars for future use in Los Angeles, we sought to answer this question (1). In the literature we were able to find little help: Although average daily travel for cars has frequently been determined, the distribution of daily driving distances had apparently never been reported. The only published distribution we found was "synthesized" by Kalish in a 1971 study of the market for electric cars (2). For lack of appropriate survey data, Kalish simply assumed a Poisson distribution function for the number of daily trips by an automobile. This distribution was then combined with an observed distribution of trip lengths (assumed to be independent) in arriving at a distribution of daily vehicle travel.

This paper reports on daily travel distributions compiled from detailed travel survey data in support of the aforementioned study of the impact of use of electric cars in Los Angeles (1). Also included is information on overnight parking places, which largely determine the availability of electricity for recharging the batteries of electric cars. The paper combines the new data with data on the potential range of electric cars to estimate the total number of conventional cars that might reasonably be replaced by electric cars in future years.

We assume in this paper that the battery of an electric car will be recharged overnight at the owner's residence. This means that total driving distance for a day is limited to the range of the car between recharges. To remove this limitation it would surely be possible to develop arrangements for quick battery exchange at battery service stations, but this would involve considerable investment of money, as well as elaborate institutional arrangements. In the short run, extensive networks of battery-exchange stations seem unlikely; in the longer run they are likely to become unnecessary because of the advances in battery technology.

Potential ranges of electric cars in this study were based on the capability demonstrated by the ESB Sundancer car in 1972 (3). Using an energy-efficient design and experimental lead-acid batteries, this car achieved an urban driving range of 80 to 88 km (50 to 55 miles) on the SAE Metropolitan Area Driving Cycle (4) and could reach speeds near 100 km/h (62 mph). Working from these and other data, Friedman (5) characterized four-passenger subcompact cars with lead-acid and advanced batteries as follows (1 kg = 2.2 lb and 1 km = 0.6 mile).

Battery Type	Battery Weight (kg)	Car Curb Weight (kg)	Urban Driving Range (km)
Lead acid	680	1554	87
Nickel zinc	494	1397	232
Zinc chlorine	259	1134	233

The lead-acid-battery car, though almost twice as heavy

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as the two-passenger Sundancer, achieved a similar urban driving range. The advanced-battery cars illustrate the prospects of much greater daily ranges, assuming that the technological advances suggested by current battery research programs bear fruit in the 1980s.

PATTERNS OF DAILY URBAN TRAVEL

The basic source of Los Angeles transportation data is the 1967 travel survey (6) conducted by the Los Angeles Regional Transportation Study (LARTS). The survey consisted of intensive interviews of a 1 percent sample of households in the LARTS area; data were recorded about each household, about its individual members, and about individual trips they had taken on the survey day. For each trip, the addresses of origin and destination, the mode of travel, the identity of the traveler, the purpose of the trip, and other descriptors were recorded.

The data base from the interviews has served since 1967 as the foundation for extensive analysis and projection of Los Angeles travel demand. But because the individual trip, rather than the day's travel by an individual or vehicle, was the basic analytic unit in this work, the results are not directly applicable to the question of the adequacy of range of electric cars.

To investigate typical vehicle use in an entire day, the basic Los Angeles survey data were reprocessed. Several reels of computer tape provided by LARTS detailed each of almost 200 000 trips recorded in the interviews. A separate reel of tape contained descriptions of households whose members made these trips.

A new computer program was developed to read and process the trip and household tapes (7). Basically, the program accumulated total distances traveled during the survey day for individual occupants and vehicles of each household. From this basic result, it then compiled distributions of daily travel distance, so that the percentage of persons or vehicles traveling more than a given total distance on the survey day could be determined. Ideally, the program might have compiled distributions only for total travel by each individual vehicle on the survey day. Unfortunately, however, the interviews did not record which vehicle in a multivehicle household was used for each of the trips reported by members of that household. Thus the program was only able to develop vehicle-distance distributions for vehicles at single-car households. The interviews did record which individual of the household made each trip, however, so that it was also possible to develop distributions of daily travel for individual drivers of the households.

The computer program assigned an approximate air-line distance rather than the actual over-the-road distance for each reported trip. Though the original interviews elicited addresses of trip origins and destinations, this level of detail was lost in subsequent coding that assigned each address to one of some 1200 traffic zones into which the study region was divided. Only the zones of origin and destination appeared on the tapes. Coordinates of zone centroids (centers of gravity of population) were provided by LARTS; but no detailed representation of the street and highway network could readily be obtained and used to determine actual over-the-road driving distances. Consequently, simple straight-line distances between zone centroids were used initially as trip distances; these were later adjusted upward to account for indirect routing through the streets.

For trips that began and ended in the same zone, the program assigned an average intrazonal travel distance that had been precomputed for each zone. This distance was taken to be half the air-line distance from the zone centroid to the centroid of the nearest neighboring zone. As will be shown later, resultant errors in total travel were minor.

In the processing of the survey data, attention was focused on those households that reported automobile trip details of the survey day. In consequence, almost a third of the survey households were not included in the development of daily distance distributions. Among the households omitted, the largest single category indicated automobile driver trips on the household data tape but had no corresponding trip descriptions anywhere on the trip tape. LARTS personnel suggest that this is at least partly the result of unusable trip descriptions given by survey respondents. Somewhat smaller numbers of households were also omitted for each of three reasons. They were vacant, had no cars, or reported no use of their cars.

The overall characteristics of the processed sample are summarized below (1 km = 0.6 mile).

Item	Amount
Trip distance, km	
Total	992 788
Intrazonal	28 670
Total trips	130 800
Intrazonal	23 503
Overnight	516
External	584

Overnight and external trips—trips beginning or ending outside the study region—amounted to less than 1 percent of all trips. Neither was included in daily travel distributions. Intrazonal trips, though they amounted to 18 percent of all trips, accounted for only a small percentage of total travel distance. Thus intrazonal trips are unimportant in total daily travel distance, and the probable inaccuracies in the estimates used for intrazonal trip lengths will not significantly impair the results. "Cars" were defined in the survey processing for this project as either passenger automobiles or pickup trucks. In Los Angeles, it appears that most pickup trucks are used in essentially the same manner as personal automobiles. The survey asked whether each reported vehicle was capable of "long-distance commuting"; all but 3 percent of the vehicles were included in this category.

In Los Angeles there are essentially as many cars as drivers. On the survey day, 88 percent of all drivers reporting trips came from households with at least as many cars as drivers reporting trips. Thus in the great majority of cases, driver travel was not constrained by unavailability of a car.

This important point is the key to deriving useful results from a survey that did not report which vehicle was used for each trip. Essentially, it implies that driver travel and vehicle travel were similar, since 88 percent of drivers had vehicles available to them. There is no absolute assurance, of course, that drivers used all available vehicles, rather than waiting to take turns on a lesser number of preferred vehicles. Nevertheless, this seems likely to have been the case.

After the survey trips were computer processed, substantial adjustments were introduced manually in distance distributions. Adjustments were necessary for two reasons: first, because air-line distances, rather than over-the-road distances, were developed in the computer program and, second, because comparisons with other data indicate that, in the survey itself, respondents neglected to report a substantial amount of their actual travel.

Evidence of underreporting is presented in Table 1, which shows the discrepancy between survey results and independent control data with which the results were compared. The first four characteristics noted in Table 1 are modestly underreported in approximately the same amount, as might be expected. The corridor checks and vehicle-kilometers of travel, however, show a much greater discrepancy than might have been expected. Screen-line crossings—counts of vehicle movements across two lines bisecting the study area from north to south—were originally also much lower, according to LARTS personnel, but they were not stated in the report (6).

The LARTS adjustment of survey results was accomplished by increasing the numbers of reported trips by as much as 80 percent, according to trip type, with an overall upward adjustment of trip numbers of about 30 percent. The trip types increased most were those judged most likely to be neglected and underreported in a survey; work trips, which presumably are unlikely to be forgotten, were not increased at all.

In processing the LARTS data tapes for this study, individual adjustment of trip types was not feasible. Accordingly, the total number of trips was simply increased by 30 percent. In consequence, basic distance distributions for individual cars and drivers were uniformly increased by 30 percent.

To account for over-the-road routing rather than air-line distances between zones, daily travel distances were adjusted upward by an additional 23 percent. This figure was chosen to make the adjusted average trip length equal to that in the LARTS network modeling based on these and other survey data. Furthermore, the 23 percent adjustment is in reasonable agreement with a simple analysis. If trips are made between points randomly selected in a rectangular street grid, the average over-the-road travel distance can be shown to be greater than the air-line distance by a factor of $4/\pi$, a 27 percent upward adjustment. In actuality, however, it seems likely that trips will not be uniformly distributed in direction; in addition, there will probably be important diagonal streets and freeways to reduce travel distances that would otherwise be required in a rectangular grid, so a figure lower than 27 percent is appropriate.

The total adjustment applied in this study is thus +60 percent: +23 percent in individual trip distances due to actual rather than air-line routings, and +30 percent in number of trips taken due to apparent under-reporting of trips in the survey. After adjustment, the summary of the characteristics of travel reported above appears to be in reasonable agreement with other analyses and data, as indicated in Table 2. The distance per trip not only agrees with the LARTS network model run, but also agrees very closely with the average travel distance used by Kalish (2) in his synthesis of daily vehicle use. The number of trips per car is moderately higher than that of the network model run, as might be expected, since cars that were not used on the survey day were dismissed from this average. About 7 percent of the cars were in this category; if they were included, the trips per car after adjustment would be very close to that of the network model run. The lower value for trips per car reported by Kalish may be explained by its derivation from data recorded in a Chicago survey 10 years earlier than the LARTS survey. Overall, the average daily car travel is reasonably close to that implied by the LARTS models.

The effects of the adjustments of the survey distributions are shown in Figure 1. The upper curve in this figure shows the cumulative total number of drivers in the survey who drove less than the indicated distance on the survey day, before any adjustment. The lower curves show the results of the 23 percent adjustment for road rather than air-line distance and the 60 percent total adjustment to compensate for underreporting in addition. Also shown in Figure 1 are the daily range capabilities of the electric cars described by Friedman as summarized above. The adjustment is important: Based on the unadjusted distance distribution, the four-passenger lead-acid-battery car would have been adequate for 93 percent of the drivers surveyed; based on the adjusted distribution, it would have been adequate for only 83 percent.

For comparison, the distribution synthesized by Kalish for cars driven 19 300 km (12 000 miles) per year is included in Figure 1. Since the synthesis included overnight and long-distance travel, it is to be expected that it would deviate increasingly with distance from the other curves of the figure. In the lower ranges, however, and up to about 90 percent of daily travel distances, it is in reasonable agreement with the adjusted distributions of Los Angeles travel distance.

Two of the most important categories of travel for which distributions were produced are shown in Figure 2. The first of these is for the daily travel distance of drivers who had cars available to them on the survey day—drivers, that is, from households reporting at least as many cars as drivers on the survey day. The other distribution shown is for the daily travel of a single car in households reporting one car driven by two drivers on the survey day. In such instances, it is to be expected that the travel desires of two drivers would cause the car to be used more than a single driver might use it, but less than two separate cars would be used. This is the case; cars used by two drivers typically travel 50 to 80 percent farther in a day than cars used by only one driver.

Distributions were also produced for other cases, such as individual drivers in one-, two-, and three-car households. They are not much different, however, from the distributions shown in Figure 2.

If several drivers using a single car were common in Los Angeles, the daily range requirement for electric cars would be substantially increased and consequently much more difficult and expensive to meet. However, this is not the case. Some 88 percent of drivers did have a car available on the survey day. And with increasing rates of automobile ownership, the availability of cars to drivers will be even higher in the future. It therefore seems reasonable to use the distributions of daily travel for these drivers with cars available to determine what electric cars will be required to do in the future.

It should be noted that a basic assumption is required to make survey results useful in estimating the applicability of electric cars. This assumption is that the distribution of daily travel distances for all days in the life of a single typical car is the same as the distribution of daily travel distances for the survey sample of cars on a single day.

It should also be noted that individual daily driving in Los Angeles is not unusual or unlike that in other U.S. cities. The survey usage of 46 km/day (28.6 miles/day) in Table 2 corresponds to about 15 610 km/year (9700 miles/year), after allowance is made for the 7 percent of surveyed cars that were not driven on the survey day or included in the average. This is close to the average annual driving distance of 15 340 km (9531 miles), reported for the entire United States in 1967 (8). Though nonurban trips would add a small percentage, it seems likely that driving in Los Angeles by individuals is reasonably representative of that in other large U.S. cities.

APPLICABILITY OF ELECTRIC CARS

The basic limitation on the applicability of electric cars is their daily range capability. A limited-range car is not really applicable to the needs of a driver if it frequently cannot go as far as he or she might wish during a single day. On the other hand, it is not necessary to insist that the electric car be able to do everything that its gasoline counterpart might, nor satisfy all a driver's needs every day. Any compromise definition of applicability is, of course, arbitrary, but it seems safe to say that applicability will require adequate range for the great majority of the driver's travel days.

Capability adequate for 95 percent of urban driving days has been adopted here as a criterion of applicability. Figure 2 shows that, under this definition, the advanced-battery cars are applicable to the needs of urban drivers in general, 98 percent of whom travel less than the cars' ranges on a typical day. Furthermore, these cars are applicable to the needs of two drivers sharing a single car at a household. On the other hand the lead-acid-battery cars under this definition are not applicable to the travel of the average driver.

Despite its range limitation, the lead-acid-battery car by 1980 could perform the role of second car in a two-car household as long as the second car is defined to be that car used less on each day. It may be assumed that, in a two-car household, the probability of long-distance travel by one car on a given day is independent of that for the other car. In this case, Figure 3 shows the probability that the second car in a two-car household will be driven less than the indicated range or that the second and third cars in a three-car household will be driven less. On 97 percent of the days, the four-passenger lead-acid-battery car would be capable of the travel demanded of the lesser used car in the two-car household. On only 91 percent of the days, however, could two of these cars perform the functions of both secondary cars in a three-car household, which falls short of the adopted applicability threshold.

In practice, of course, applicability of an electric car to a driver's needs presumes overnight recharging facilities. Unless such facilities can reasonably be provided, the car cannot be considered applicable even if its range is adequate. To investigate the possibility of overnight recharging, the LARTS 1967 travel survey tapes were also processed to show the kinds of parking available by household type. A summary of these results follows.

Category	Percent
Area households with off-street parking	87
Area cars with off-street parking	74
Single-family dwellings with off-street parking	89
Other dwellings with off-street parking	83

Overall, only 74 percent of area cars in 1967 had off-street parking. Cars parked overnight on the street are obviously poor candidates for recharging, which requires electric power at levels usually met only from 220-V outlets. If the electric car is to be one of several cars at a household, however, all that is necessary is that the household have at least one off-street parking space, and a larger number of households—87 percent—fall in this category. Not every off-street parking space, however, is equally adaptable for recharging facilities; in multi-family residences with large parking lots, provision of 220-V, individually metered outlets for recharging could be a significant problem.

Accordingly, the best candidates for recharging batteries are single-family households with off-street parking. As shown, about 89 percent of such dwellings have at least one off-street parking space.

The number of automobiles that the lead-acid-battery electric car might functionally replace would thus be the same as the number of single-family households with two or more cars and off-street parking. To determine this number, survey data and 1990 projections by LARTS were employed. The results appear in Table 3.

The population projection in Table 3 follows currently accepted Series E projections of the Bureau of the Census and is applicable to California's South Coast Air Basin, a region containing greater Los Angeles. LARTS projections were based on more rapid overall population growth (Series D projections), as expected several years ago. Accordingly, LARTS figures were adjusted downward to correspond to the indicated population. They were also adjusted for the difference between the LARTS and air basin boundaries. Values at years intermediate to the LARTS survey and projection years were obtained by linear interpolation.

According to Table 3, 1 140 000 single-family housing units in Los Angeles will have more than one car by 1980. If 89 percent of these have some off-street parking, then lead-acid-battery electric cars could be applicable in 1980 for slightly more than one million Los Angeles households. Although this implies applicability to the roles of only 17 percent of all Los Angels automobiles in that year, it is still a very large number on an absolute basis, especially since the standards of applicability involve minimum sacrifice and inconvenience on the part of the drivers and households.

The advanced-battery cars, as noted previously, are applicable to the daily urban travel of most drivers. Recharging problems remain, however, so applicability will still be limited to households with ready recharging capability. In this case, single-family households are again the most promising for having that capability. Assuming that 74 percent of the cars in single-family households have off-street parking, in accord with the areawide figure shown above, electric cars would be applicable in more than three million cases in 1990—46 percent of all individual automobiles in the area. In the longer term, as electric cars come into general use, we may expect that provision for recharging batteries will be made in the off-street parking provided by multiunit buildings. Thus by 2000, electric cars might be applicable everywhere there are off-street parking places. If the current 74 percent rate continues to prevail, this would make electric cars applicable in 5 624 000 cases, to 74 percent of the total car population. This result and the previous estimates of applicability are also given in Table 3.

Projections of applicability are, of course, different from projections of markets, market penetration, and sales. The applicability projections show the number of cars that could be electrified in future years with relatively little restriction on urban driving due to range limitations. Whether electric cars will be applied to this or some lesser extent depends heavily on various other factors, including costs.

The lead-acid-battery electric car, for example, is applicable only as a second car. Most second cars, however, are older, used cars, purchased at relatively low prices. New lead-acid-battery electric cars would thus generally be excluded on grounds of cost. Naidu and his associates estimate that the primary market for electric cars, comprising upper income households that operate new second cars, is only about 1 percent of the total new-car market in the United States (9).

Naidu's market would be captured by electric cars only to the extent that they appear competitive with conventional cars in price, performance, and other characteristics. This appears unlikely in the near future: Projected costs for subcompact cars with lead-acid or

Table 1. Comparison of LARTS Los Angeles survey results with independent controls.

Characteristic	Discrepancy (%)	Source
Population	-5.7	Data from various government agencies
Housing units	-4.0	Data from various government agencies
Car ownership	-8.2	Department of Motor Vehicles registration data
Resident cordon check[a]	-7.4	External survey
Corridor checks (average of seven corridors)	-20.2	Actual ground count
Vehicle-kilometers of travel		
Total	-18.6	National Highway Functional Classification Study
Freeways only	-16.8	1967 Annual Traffic Census

[a] To obtain information on travel by persons who were not residents of the area, drivers entering and leaving the study area were interviewed as they crossed a cordon line surrounding the area. Data from resident drivers obtained at the cordon were compared with external trip data from the home interview study.

Table 2. Comparison of values for daily car travel.

Source	Distance per Trip (km)	Trips per Car per Day	Distance per Car per Day (km)
Adjusted sample	9.33	4.9	46.0
LARTS	9.33	4.6	44.4
Kalish	9.17	3.7	33.8

Note: 1 km = 0.6 mile.

Figure 2. Adjusted distributions of daily travel for two categories of drivers.

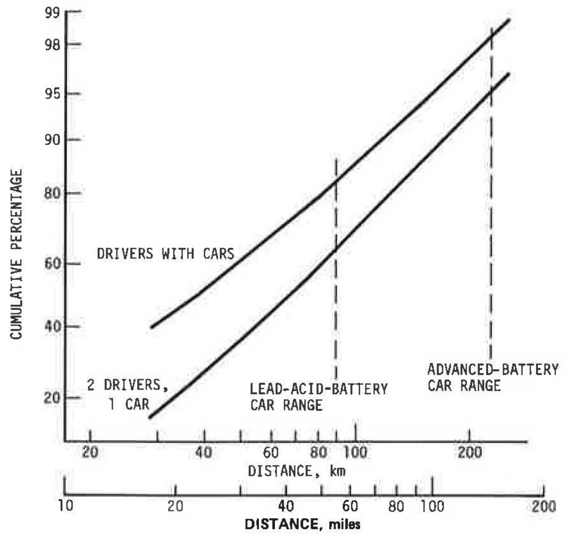

Figure 1. Adjustments of surveyed daily travel distributions.

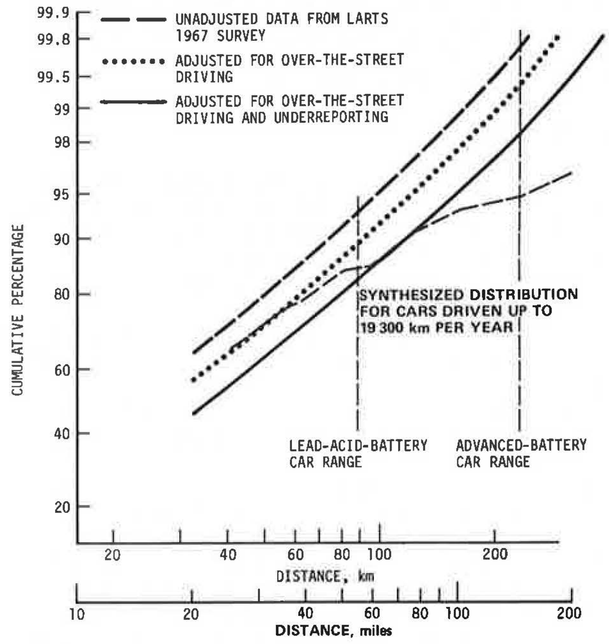

Figure 3. Adjusted distributions for multivehicle households.

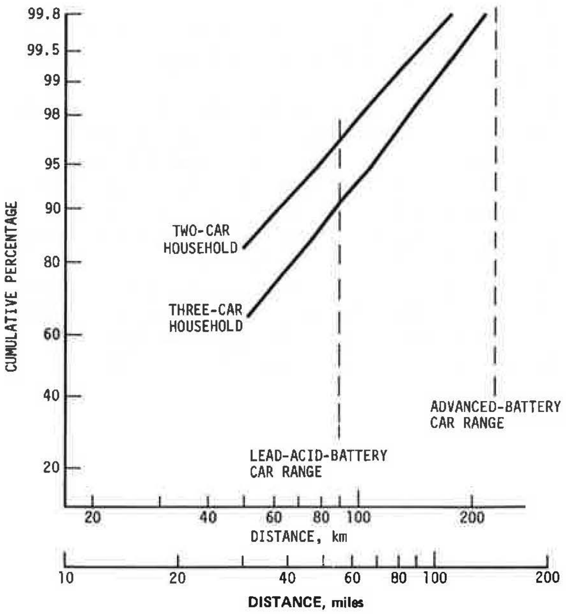

Table 3. Distribution of housing units and cars and extent of applicability of electric cars in the Los Angeles area.

	1970		1980		1990		2000	
Item	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Population and car ownership								
Population	9 700 000		10 600 000		11 600 000		12 400 000	
Cars	5 060 000		5 880 000		6 730 000		7 600 000	
Cars at single-family housing units	2 720 000	57.7	3 400 000	58.0	4 190 000	62.2	5 060 000	66.5
Single-family housing units								
With cars	1 840 000	55.0	1 980 000	52.7	2 110 000	50.3	2 200 000	47.9
With two or more cars	1 050 000	31.5	1 140 000	30.3	1 220 000	29.1	1 280 000	27.9
Applicability of electric cars								
Cars			1 001 000	17	3 099 000	46	5 624 000	74
Daily vehicle travel, km			29 000 000	11	145 000 000	46	272 000 000	74

Note: 1 km = 0.6 mile.

nickel-zinc batteries are substantially higher than projections for conventional subcompact cars and are about as high as those for conventional standard-sized cars (10). A major advance in battery technology will be needed to eliminate this cost differential, since much of it arises from battery depreciation.

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Describing and Shaping Merging Behavior of Freeway Drivers

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This paper discusses the freeway merging behaviors observed in three types of design and draws conclusions about specific behaviors to be promoted, as well as those to be discouraged. Means of achieving these ends through traffic engineering and public education are discussed.

Freeways have proved to be much more forgiving of driving error and much less likely to induce errors than less expensive arterial highways. Drivers have not had much guidance in how to drive on freeways, and, in spite of many years of experience, no clear set of rules has been forthcoming. Moreover, designers are not always aware of what drivers do, and opinions of what drivers should do vary among those responsible for design, operation, and maintenance of freeway-quality roadways.

Before a behavior can be established as "best," "ideal," or "optimal," the variety and relative frequency of observed behaviors should be established. In addition, the best behavior should remain invariant through the expected range of variables such as volume of traffic, relative volumes of ramp and through traffic, vehicle mix, and driver familiarity.

It would be desirable to establish a set of "ideal paths" for each type of driving maneuver. Driver educators, enforcement agencies, safety groups, and design groups do not always have common working assumptions, and it is clear that driver behavior is not fully in accord with any one authority.

The present study of merging situations was part of a project entitled "Remedial Driving Techniques for Freeways and Interchanges" (1). Among the goals of the project were the specification of a set of proper and improper driving behaviors related to specific freeway segments and the recommendation of remedial treatments to eliminate or reduce the improper behaviors observed. Two features of the project must be made clear. First, the project was designed to be useful to the highway research community rather than directly to operating agencies at this time. Second, the orientation was strictly behavioral, i.e., it was intended to describe the behaviors observed and to make recommendations for specific driver behaviors.

The data were thus observational, rather than statistical, in order to describe the variety of events and behaviors that occur in traffic situations. Once the variety and relative frequency for each type have been established a determination of those behaviors to be encouraged and those to be discouraged can be attempted. Data on such factors as acceleration noise and headway distributions were not collected. Also, because of the importance of observing the typical range of behaviors that might occur, unobtrusive means were used to gather the data.

Ideal behavior does not necessarily imply ideal geometry or roadway design. While a great number of variations in design could be listed, this study was limited to three types of on-ramps that are typical of the variety of roads of the freeway type that are now in use.

Although accident records have been used as a basis for comparing characteristics, they cannot easily be used alone for identifying high-accident sites on freeways because of the relatively low accident rate and the inherent problems in pinpointing both the locations and the causes of freeway accidents. In addition, sites of a large number of minor accidents may never be identified because these incidents do not become part of the accident record. In fact, many of these minor accidents could have become major accidents, given small variations in the conditions or traffic at the time.

Related to this same problem are the definitions of erratic maneuvers, conflicts, critical incidents, driver errors, and a variety of other concepts related to traffic safety or driver behavior.

Three merging sites were selected by using relative accident records and other considerations such as proximity, the kind of design, engineering and administrative opinions of problems in the area, and the traffic mix. The first site had a fairly long parallel acceleration lane, the second had a very short taper for acceleration, and the third had an intermediate length taper for acceleration. While the length of the acceleration area is but one of the many variables that might be compared in

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entrance ramp design, the merge maneuver is likely to be strongly affected by the time available for the information processing and for the maneuvering and timing patterns dictated by this overall length.

PROPER AND IMPROPER MERGING MANEUVERS

It is generally agreed that the merge maneuver is basically a yield entrance into a stream of traffic and thus should be executed in a manner that does not interrupt or disrupt other traffic. Drivers of trucks and other large vehicles are restricted by the braking and acceleration capabilities of their vehicles during merging. The truck merge thus becomes a limiting case, which can serve as a rough model of the proper maneuver if a single optimal maneuver is to serve for virtually all traffic. Detailed models may have to be developed separately for vehicles with high and low acceleration and braking characteristics. For now, only one model will be discussed; it is based on cars and trucks with "average" performance.

A proper merge consists of observation, gap selection and gap pacing, the merge itself, and the assumption of the characteristics of the mainstream traffic. In the observation phase, the driver must establish a plan to take the vehicle into a gap in traffic without disrupting that traffic. The errors made in observation include (a) failure to monitor the mainstream traffic at all, (b) failure to monitor soon enough to provide sufficient time for selection and pacing of the gap, and (c) failure to observe other ramp vehicles ahead and behind.

Gap selection and gap pacing require realistic estimates of time, speed, and distance in terms of the vehicle's characteristics and other conditions. The gap selection errors include (a) planning to merge when there is no gap, expecting mainstream traffic to give way and create a gap; (b) selecting a gap that is too small, again requiring mainstream traffic to adjust during and after the merge; and (c) demanding an unusually large gap, unnecessarily delaying other ramp traffic and thwarting the expections of mainstream drivers, who expect a merge to be made when conditions are reasonable.

In the merging maneuver itself, the vehicle follows the planned path to enter the selected gap. Errors include (a) stopping on the ramp when gaps already exist that are sufficient for the merge; (b) driving unnecessarily slowly when gaps already exist; (c) entering the mainstream at too low a speed; (d) entering the mainstream at an unusual point, such as crossing the physical or painted gore or suddenly pulling in from the edge of the road beyond the edge line of the taper; (e) entering the mainstream at an unusually sharp angle, requiring sharp path-correction maneuvers that might disrupt other traffic or induce the loss of control; and (f) entering the mainstream before earlier ramp vehicles have begun their merge. Out-of-turn entries can be observed when the later ramp driver is more aggressive than the earlier driver. Trouble arises when the two vehicles attempt to merge into the same gap, which is not big enough for both of them, and the added complexity of multiple merges may overload the information capacity of the drivers involved.

There are also mainstream errors, which include (a) unnecessary application of the brake when a proper merge is being executed ahead; (b) lane changes into lane 1 (the shoulder lane) near the merge point; (c) lane changes into lane 2 or farther left without proper signaling or clearance; (d) straddling a lane line, edge line, or median line; and (e) sudden acceleration in lane 1 near the merge point.

Yielding

There are still problems in the definition of "proper" tactics in the ramp merging maneuver. It is generally accepted that a merging driver is required to yield to mainstream traffic by virtue of the fact that this involves entering one roadway from another roadway. Many states have chosen to make this explicit by installing yield signs along entrance ramps. The lack of agreement is illustrated by one recent judicial decision that the driver on the ramp has the right of way since he is to the right of the mainstream traffic. The Manual on Uniform Traffic Control Devices (MUTCD) says yield signs "may be used on an entering roadway without an adequate acceleration lane, but in a well-designed interchange, the sign would interfere with the free merging movement, and should not be used under those circumstances" (2).

In Pennsylvania the policy seems to conform to this, and yield signs are to be installed on "substandard" ramps or "when necessary" in the opinion of the district engineer (3). It appears that, in practice, the yield sign is used almost universally for entrance ramps, and Pennsylvania drivers probably expect to see it there.

As to the location of the yield sign, the MUTCD says it should be erected "at a point where the vehicle is to stop if necessary to yield the right of way." The manual also allows the use of a stop line for either a stop or a yield sign if the stopping position is not obvious. The point at which the driver is to stop is thus presumed to be the location of the yield sign itself. It is likely that a survey of drivers would reveal that this is not widely understood, and observation of behavior strongly implies this is so. Moreover, there is no assurance that the sign position is appropriate in every case, which leads drivers to rely on their own judgment as to where to stop. In the absence of specific guidelines, each agency responsible for traffic signs installs the sign as it judges proper. This leads to variations in locations at best and gross errors in placement at worst. Clearly, sign location could be improved in a number of instances. But if the driver is unaware of the definition of a proper merge and the meaning of the yield sign or hesitation point, the sign's location alone will not do much to improve driver behavior in the merge.

The lack of driver conformance to stop lines and marked crosswalks where signs are not installed indicates that, in general, the driving public feels that it is better qualified than anonymous traffic engineers and line-painting crews to judge the point at which it is necessary to stop. This feeling is justified in enough cases that little confidence is placed in the official markings and enforcement is, at best, difficult and spotty. This lack of confidence in stop-line placement might also be expected to carry over into a routine use of a line in conjunction with the yield sign, unless special provisions are made. Both the meaning of and confidence in traffic control devices must be established before conformance can be expected.

Merging Behavior

Although differences in opinion may exist, the following details of the merging maneuver are considered proper here. The driver approaches the ramp and assumes the recommended ramp speed. Continuing down the ramp, the driver observes through traffic to determine the probability of an available gap, the vehicle mix, the mainstream speed, and prospective lane changes by mainstream vehicles. At a point prior to the physical or painted gore, the driver has determined whether a gap exists or a wait will be necessary. If no wait is necessary, i.e., a sufficiently wide and stable gap in traffic is available, the vehicle is accelerated gradually from ramp speed to approximately the speed of traffic in lane 1. After attaining speed and confirming that the gap remains and that the maneuver will not interfere with other vehicles, the driver crosses the boundary into lane 1. The boundary crossing is made in a gradual, continuous manner, with lateral movements sharp enough to make the entry obvious to other drivers but not so sharp as to require large lateral accelerations or large path-correcting steering upon entry to lane 1.

If the through traffic is likely to prevent a continuous merging motion, the driver either slows to wait for a slightly later gap or stops to wait for a gap to appear. The stop or the slowing is done in such a manner that the ramp driver has room remaining for acceleration to mainstream speed, has a sufficient view of through traffic, and can slow or stop at a point consistent with the expectations of drivers following the merging vehicle on the ramp. In many cases, it is appropriate for the vehicle to accelerate on the ramp to move ahead of slow-moving vehicles in lane 1. Unnecessary hesitation or stopping is avoided in the merging maneuver, and the path of entry is such that room remains for evasive actions in event of a miscalculation or unseen vehicle. This implies that the driver will not use the full paved taper routinely except when there is a very short acceleration area. A merge is not made unless the ramp is clear ahead, i.e., all previous ramp drivers either have merged or have made their point of merge obvious.

Since the combination stop-turn signal system used in the design of most American vehicles increases the likelihood of confusion of the turn signal with the stop signal and since the stop signal is of prime importance to the drivers following the merging vehicle, no turn signals are used in a merging maneuver until just before the actual crossing of the lane 1 boundary is anticipated. Entry into lane 2 or lanes farther left is made only after the path has been established in lane 1 and after signaling. No merging path crosses the physical gore, the painted gore, or any solid painted lines. A dashed line across the mouth of the acceleration area shows the area through which crossing is proper and places the responsibility to yield clearly on the merging driver throughout the merge maneuver.

The observational data are available in our final report (1). Obviously, not every detail of the merging maneuver can be analyzed from field observations with respect to accident-inducing qualities among its possible variations. The proper maneuver as described in this paper has been derived from logical analysis as well as from observations of specific interactions related to driver actions. The data are summarized briefly in the following discussions to the extent that they support or refute specific points.

STUDY SITES

The design of site A (Figure 1) is good according to modern standards for a partial cloverleaf without collector-distributor roadways (see, for example, Baerwald, 4). The parallel acceleration lane is 264 m (865 ft) from the physical gore to the end of the taper. The painted gore, 21 m (70 ft) long, and a taper of 67 m (220 ft) are included in this length. The yield sign is 15 m (50 ft) upstream of the physical gore. The ramp is on a downgrade and the view of it is reduced for eastbound through traffic by a left curve and a bridge structure for the crossroad grade separation.

The design of the ramp and its elevation above the through traffic give the ramp driver a good view of oncoming traffic for selection of gaps. The acceleration lane is long enough to allow almost any unimpeded vehicle to attain mainstream speed before merging into lane 1. The taper at the end of the acceleration lane to notify the driver of the remaining room for merging is obvious. There is a bridge that narrows the shoulder available for evasive maneuvers beyond the taper, but the total length of the acceleration area makes this a minor problem.

Site B (Figure 2) has an S-turn approach with the only acceleration area consisting of a 46-m (150-ft) taper section and the painted gore area, giving 61 m (200 ft) from the nose of the physical gore to the end of the taper. The ramp is on a downgrade with good visibility of the traffic exiting immediately before this ramp and of the through traffic. Just beyond the end of the taper there is a small bridge that prevents the extension of the taper.

Site C (Figure 3) is almost identical to site B except that the acceleration area is somewhat longer. The taper and the painted gore area allow 96 m (315 ft) for attainment of mainstream speed. Visibility is good from the downgrade ramp.

Merging Behavior and Length of Acceleration Area

In order to bring about smoother interaction among vehicles in the area of a merge, a common model must be supplied to drivers so that they know what is expected of them and how to carry out the requirements of the model.

Site A

Since the acceleration area for site A appears adequate, the MUTCD would not recommend installation of a yield sign at all. This implies that the drivers know where to yield and how to accelerate so as to bring the vehicle to mainstream speed by the time it enters lane 1. This is a questionable assumption, especially in view of the variability of design of acceleration lanes currently encountered and the recognized inability of drivers to accurately estimate distances. The driver should have some signal to indicate where to hesitate, if necessary, so that sufficient acceleration room remains for each specific site.

Although the acceleration area of site A is 264 m (865 ft) long, only 38.9 percent of all vehicles made use of the last 181 m (595 ft) for acceleration before entering lane 1. The last 140 m (455 ft) was avoided by 86.6 percent, and the last 67 m (220 ft), the taper, was avoided by 97.3 percent of the drivers. Contrary to what might be predicted, less of the acceleration area is used when traffic volumes increase. Truck drivers tend to merge almost as early as car drivers but they are much less variable in their point of entry, implying more of a common, if not optimal, performance standard among them. In general, somewhat more of the acceleration lane should be used so that the variability of entry point into lane 1 is reduced.

The merging maneuver is executed with a variety of degrees of success in terms of smoothness and efficiency in traffic flow. At site A, 60.4 percent of the cars merged with a good speed profile, 2.1 percent slowed unnecessarily, and 0.5 percent stopped for no apparent reason. Unnecessary hesitations were more common among drivers who led a platoon of ramp vehicles than among those who either were alone on the ramp or were within a platoon. Assuming the same kinds of drivers were involved both in platoons and in lower traffic volumes, in which single vehicles were more likely, this could be interpreted as reaction to social pressure to conform to the mistaken idea that a safe merge requires a stop or slow entry. A similar trend by lead vehicles is seen with the earlier entry into lane 1. Here this pressure leads to use of less of the available acceleration area. Earlier entry could also be interpreted as aggression in "staking a claim" to a position in lane 1. Whatever the reason, the effect is to increase the variability in merge maneuvers, to reduce the likelihood of smooth, high-speed merges, and ultimately to increase the perceptual load on interacting drivers.

Site B

For ramps of clearly inadequate design, such as that in site B, the hesitation point or yield point might be situated considerably earlier than the physical gore and may be arrived at through a compromise between providing adequate acceleration area and providing a sufficient view of mainstream traffic. In this case, the 61-m (200-ft) acceleration area would allow the attainment of only about 29 km/h (18 mph) for a semitrailer unit or approximately 64 km/h (40 mph) for a high-powered passenger car starting from a dead stop at the present yield sign. In the second half of the taper, the vehicle would begin to encroach on lane 1, requiring a longer gap in traffic for merging at such slow speeds.

Clearly the stop, if it is to be made, should be made back far enough to allow acceleration to reasonable speeds compared with the 88-km/h (55-mph) limit. According to the Traffic Engineering Handbook (4), about 122 m (400 ft) is required to accelerate from a dead stop to 48 km/h (30 mph) for small passenger cars and most single trucks and buses and to 85 km/h (53 mph) for high-powered automobiles. Moving the hesitation point farther back on the ramp will give some additional acceleration distance, but it is not possible to provide the 122 m (400 ft) desired. Other considerations, such as the angle of the ramp at that point and visibility of through traffic farther up the ramp for planning the merge, enter into the location of this hesitation point.

On this site, cars and trucks were almost equally likely to run off the road—3.3 percent. This indicates excessive information loading of the driver or inadequate use of available information. Up to 27 percent of the ramp vehicles came to a complete stop, with the most common stopping points being in the painted gore area or the taper itself. Overall, 56.1 percent of all vehicles either stopped or slowed drastically. Obviously, stops that late in the merge, and even slow driving in these areas, would prevent a proper, full-speed merge. Drivers again tended to enter the mainstream as quickly as possible without necessarily attaining maximum possible speed. For example, even with the very short acceleration area on this site, 18.9 percent of the drivers had already merged before they entered the 46-m (150-ft) taper area by crossing the gore or the gore paint.

Poor geometrics can be compensated for to some extent by greater driver skill in gathering and using the information that is available. Monitoring of through traffic was not done early enough by some drivers. There was a tendency for drivers who monitored late, i.e., near the painted gore or beyond, to stop or to make slow approaches in their merges. This seems to indicate lack of skill or confidence, since the late monitoring of traffic does not allow time for merge preparation, especially on a short ramp like this one. The smoother, high-speed merges were made by those who did their observations farther up the ramp and then committed themselves to merges before the painted gore area was reached. The data showed a tendency for drivers who monitored to make smooth merges, while those who were not observed to monitor mainstream traffic seemed to make fewer good merges. This result was not statistically significant, however. About 10 percent of all the drivers at site B were not observed to monitor at all. Clearly, some means of increasing early monitoring and planning of the merges is important when the merging maneuver is tightly constrained.

Site C

While the acceleration distance is inadequate at site C according to modern standards, the driver, making use of all the available length for acceleration, can approach the criteria for a proper merge maneuver. The observational data from sites B and C confirm that the additional 35 m (115 ft) in the acceleration area of site C was of considerable advantage. Whereas 3.3 percent of all single or lead vehicles ran off the edge of the pavement during merging at site B, only 0.5 percent did so at site C. Ironically, the last 32 m (105 ft) of the acceleration area at site C was virtually unused. About 37 percent of all drivers observed at site C entered lane 1 while 64 m (210 ft) of the acceleration area still remained, and only 51 of the 1432 vehicles observed (3.6 percent) drove on the last 32 m (105 ft) of the acceleration area. The extra 35 m (115 ft) at this site seems to be required by most drivers but only as insurance, for use exclusively if sudden need should arise.

It will come as no surprise to most readers that truck drivers are more aggressive in merging. However, their behavior as a group at all three sites implies a common, relatively well-defined model of the proper behavior. Both the vehicle's characteristics and the truck driver's attitude tend to make this model less flexible, and car drivers who do not conform to the truck driver's expectations are vulnerable. A common expectation as to speed profiles, hesitation points, and lane 1 entry points, based roughly on the truck driver's model, seems most conducive to smooth total operation.

Approaches to Remediation

Because site B is the most restricted by its design, the remedial treatments are most critical for this site. The same treatments should be applicable to all or most merges, however, for consistency in driver expectation.

First, the observation of through traffic is required for planning and executing a smooth merge. A clear, obvious observation area must be provided. This may require posting signs in some cases to encourage early observation. It may also require the paving or special treatment of small shoulder areas since even well-maintained grass can reduce the view of through traffic in many older designs. A tutorial sign may be desirable where the observation distance is good but the acceleration area is short. It would be located up the ramp as for as possible and would advise drivers to CHECK HERE FOR FRWY TRAFFIC. This might increase the preview and merge-planning time. At this time techniques for placing such tutorial signs have not been evaluated specifically for the remedial treatment of any site. Driver awareness of the need to observe early will have to be achieved through education in the proper merging concepts, although this need would seem to be self-evident.

Second, the hesitation point should be marked. Education of drivers alone will probably not achieve proper stopping or slowing points in view of the variety of lengths, grades, geometries, and conditions of visibility that will continue to be encountered. The yield sign has, in theory, served this purpose, but its location is not fully thought out in routine use. The concept of where to slow and how to merge must be instilled by driver and public education. However, the "yield-point" concept might be established for marking an optimum distance in advance of the acceleration lane for any necessary hesitation. The ramp driver is supposed to have enough information at this yield point so that either stopping or slowing can be used as needed or a steady acceleration can be maintained to approximately the speed of through traffic and, at the same time, the vehicle can remain relatively independent of preceding ramp vehicles. To reduce the time pressure on drivers, it is desirable to separate the vehicle-following task from the merging task and also to encourage early monitoring for planning the merge maneuver and merging at lane 1 speed.

Third, the entry path should be defined more completely, especially for substandard ramps. Solid lines can be used to indicate no-crossing areas. Education and well-devised enforcement activities will be needed to get this implemented. The gore paint marking can be extended to reduce the incidence of sharp angle entries. Short, broad dashed lines across the mouth of the acceleration area will remind the through driver of the possibility of merging traffic and will make the entry into lane 1 by a merging vehicle obvious, emphasizing the driver's responsibility to yield. The dashed line denotes the area in which crossing is expected and indicates that crossing near the gore and in the last part of the taper is to be avoided. Part of the taper (most of it where the acceleration area is reasonably long) is to be kept for evasive actions only; it is not now routinely used, and its use should be discouraged further to reduce the variability among drivers. Even with very short acceleration areas, the majority of drivers avoid the last part of the available taper or acceleration lane. This should be recognized, and, though somewhat greater use of the available acceleration area is to be encouraged, the reservation of the final portion for emergencies only should be marked as such with a solid line separating it from lane 1.

Yield Points

The yield-point concept has many components that have to mesh properly. The prescribed behaviors must be possible and natural (if not automatic) but probably somewhat different from those now commonly observed. Drivers who wish to merge must first ascertain that the ramp is clear ahead. Only then can they decide whether there is a gap available for their merge. If there is none, they must delay by slowing or stopping. Marking the delay point is the new element—the point should be far enough forward that the merge information is available before acceleration to the merging speed is begun and far enough back that prior vehicles on the ramp have already committed themselves to a merging maneuver, eliminating both the possibility of collision and the need to continue to observe them. For ramps that must hold several vehicles waiting to merge, the empty section between the yield point and the merge point should not be long. It must allow acceleration time, stopping distance for an aborted merge if the driver feels he was unwise in choosing a gap, and a good view of mainstream traffic to provide the merge-planning information.

Figure 4 shows the yield-point concept applied to site B. The treatment consists of additional striping, reloca-

Figure 1. Site A: adequate accleration area.

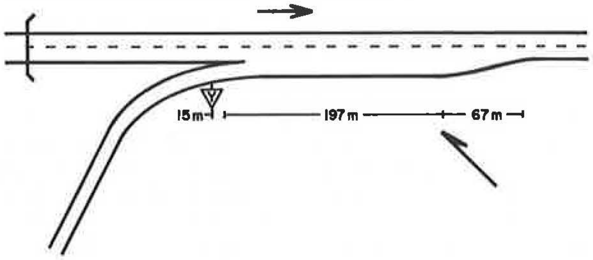


Figure 2. Site B: extremely short acceleration area.

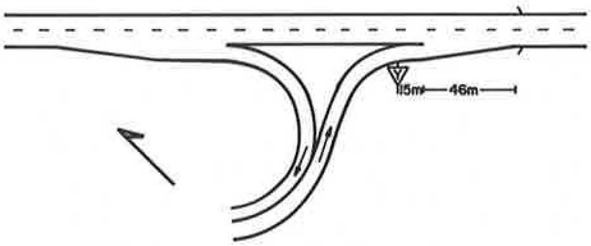


Figure 3. Site C: short acceleration area.

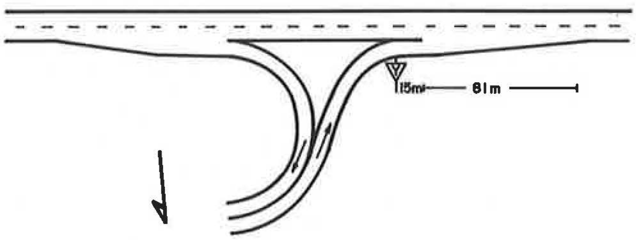


Figure 4. Yield-point concept applied to the worst case design.

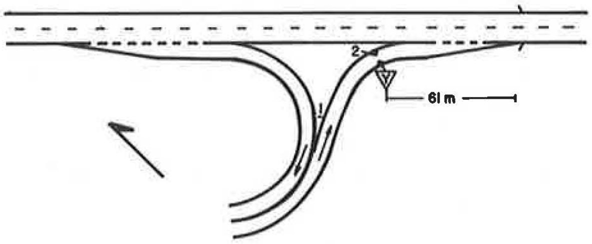


Figure 5. Yield-point concept applied to an adequate design.

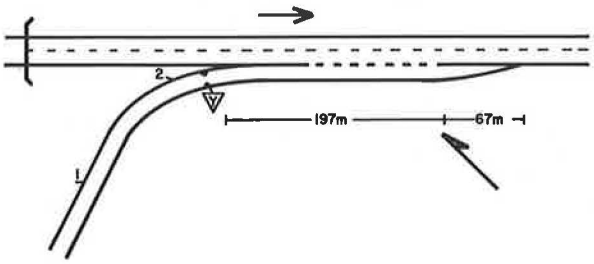
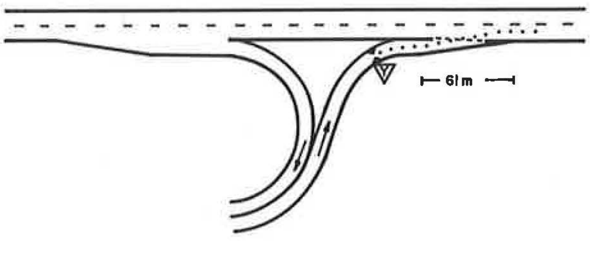


Figure 6. Yield-point markings and merge-path marks where a single path is acceptable.



tion of the yield sign, addition of the suggested yield-point triangular pavement markings, and two tutorial signs to help inform the driver of the proper merge tactics.

The striping of the gore makes the gore appear wider at the physical nose, and it extends farther into the acceleration lane to encourage small-angle entrance into lane 1. "Elephant tracks" (short, broad dashed lines delineating the edge of lane 1) are used to make crossing of the lane 1 boundary clear to both merging and through drivers. The striping also extends back from the taper. This area is not often used by drivers, and this fact is recognized by reserving the area for emergency use only.

Relocating the yield sign is intended to aid in several ways. First, it marks the point for stopping or slow driving if a wait is necessary so that the remaining acceleration area is as long as possible. Second, it more strongly discourages out-of-turn merges or merges across the gore. It also encourages monitoring of mainstream traffic for a reasonable preview. From this position the driver can look for traffic by turning about 120 deg, as opposed to 170 deg from the present location of the yield sign.

Since the merge-point markings are unknown to the driving public, some posting of tutorial signs is advisable. Sign 1 bears the legend, YIELD POINT AHEAD—CONTINUE IF CLEAR. Without further explanation, drivers probably would look for something special but would not stop unnecessarily because the familiar yield sign is present. The markings indicate a boundary, while the CONTINUE IF CLEAR message shows that this boundary can be crossed if gaps are available. Sign 2 reads YIELD POINT—ENTER FRWY AT SPEED OF TRAFFIC. This emphasizes the separation point of the planning (waiting) phase from the acceleration phase of a merge maneuver. It also makes it clear that drivers should not enter slowly and must plan to accelerate before crossing into lane 1.

Although site A has a long acceleration area, the same basic treatment as that illustrated for site B can be used. Figure 5 shows the details. Even with the extended gore striping and solid line out from the taper, a considerable range of crossing points into lane 1 is provided. Narrowing of the lane near the gore will channel vehicles more directly into the acceleration area rather than into lane 1. The yield point remains at the location of the present yield sign, and distinctive triangular pavement markings are also added to reduce the chance of out-of-turn merges and to encourage earlier monitoring of through traffic.

While the gore itself could signal the yield point when the acceleration area is adequate and the use of signs could be reserved for inadequate designs as recommended by MUTCD, a single standard marking seems advisable for reducing the driver's need to process information. Until entrance ramps have a single design standard, it seems necessary to mark all entrance ramps to guide the driver in the execution of a smooth, more uniform maneuver.

Site C is between sites A and B in the degree of restriction of the merge points. In this case the range offered is short, but it is not reduced to the single path seen in site B.

Merge Paths

One further possible remedial treatment is suggested where the geometry or design reduces the choice of acceptable merge paths so that there is essentially a single path. Figure 6 shows the recommended track delineated so that it becomes obvious where the traffic engineers expect merging vehicles to travel. This delineation with merge-path marks should be quite compelling for drivers, since it provides an obvious indication of where the center of the vehicle is to go. When viewed directly ahead as the ramp drivers see it, the marks are perceived as a strong line. Since the marks begin well up the ramp, where there is no question of multilane tracks, the function of the merge-path marks is clearly identified as different from that of lane boundaries.

When the merge-path marks are viewed from an angle, as they are by through drivers, the marks fail to form as strong a line, but their meaning will soon become obvious: Merging traffic will enter here. The "elephant tracks" across the entrance are in the direction of travel for through drivers, so they are perceived as a strong boundary line. The opposite is true from the angle of the merging driver: The path marks determine a strong line and the dashed entrance markings present a weaker boundary, since they are seen from an angle.

Merge-path marks are not necessarily the most practical remedial treatment for a merge site because the yield-point concept is more directly related to current practice. The optimum symbol shape, size, and spacing for path marks must also be investigated. Although site B exemplifies the type of situation that requires one best path, the path marks may also be useful in better designs (such as site A) to reduce the variation among drivers in path choice. While no single ideal path can be shown to be critical in the sense of determining accident frequency, the path marks should encourage better merging performance through a gentle tutorial remainder of the recommended merge tactics. Reduced variability in the behavior of merging drivers decreases the uncertainty for all drivers.

SHAPING MERGING BEHAVIOR

Changing a driver's behavior in any situation also involves changing the expectations of other drivers. For example, drivers have always had the option of stopping farther back on a ramp to allow more room for acceleration. In many cases, a driver will be hesitant to stop at the "proper" point because no one else does. Following ramp drivers might not expect a stop at that point and might run into the stopping vehicle or might go around the stopping vehicle, perhaps assuming that the engine has stalled. If the hesitation point must be moved back from the current yield-sign or gore location to allow room for smooth merging, the point should be marked and other drivers should be prepared for stops at this point by advance warning signs and by prior education.

Erecting special signs only on substandard entrance ramps has the advantage of "custom" treatment, which reduces the likelihood that they will be used routinely to form a standard that does not really apply. Driver confidence in signs has been eroded by the use of signs for the wrong reasons, e.g., ease of law enforcement or problems of liability rather than as driver aids. Where drivers are required to make decisions and commit their vehicles to high-speed merges, they must have confidence in the signs that shape their paths and speeds.

Achieving smoother operations in merging is obviously too broad a job for driver educators alone. Contributions from traffic engineering are essential, especially when costs prohibit reconstruction of inadequate designs. Posting tutorial signs to educate drivers and to shape their behavior to allow smoother interactions in the system may be useful. Legislation and legal expertise are also required to make enforcement more of a rehabilitative and corrective force and less of a punitive one. The laws and codes must be consistent with the requirements of the transportation system as it actually functions. For example, the wording of the Uniform Vehicle Code (5), Section 11-403(c), implies that stopping at a yield sign is always prudent to avoid liability in case of an accident during merging, as though, having stopped, the merging driver can enter the mainstream blindly.

Until drivers know what is expected of them and until they are aided in making judgments that are known to be difficult, there is little hope of bringing about a common, efficient set of behaviors in the merge situation. The recommended tactics must be based not only on what some authority finds most desirable but also on what drivers are willing and able to do under specific circumstances. While the highest design standards are conducive to smooth merging operation, behavior can be shaped to reasonably accommodate less than ideal conditions through an integrated program of education, engineering, maintenance, and enforcement.

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Interaction Analysis as a Tool for Evaluating On-Road Driver Instruction

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One of the persistent difficulties encountered in attempts to improve driver eduction courses has been the lack of a reliable measure of on-road instruction. Accurate description of what actually occurs in the car during training would permit evaluation of a number of aspects of on-road instruction, such as various instructional approaches, the relative effectiveness of teachers with different types of students, student progress through the course, and the role played by student observers. Interaction analysis, which has been used for many years in research studies of instructional processes in the classroom, holds some promise for analysis of this type of instruction.

Although many interaction systems have been devised as research instruments (92 were cited by Simon and Boyer, 1), most are not suitable for large-scale evaluation efforts. The system for the analysis of classroom communication (SACC), an instrument developed as a tool for evaluation of classroom teaching in a large-scale field project (2), was readily adapted for coding one-to-one instruction in the car. The details of the coding procedure can be found in the final report of the California Driver Training Evaluation Study (3). Briefly, there are five major categories of teacher behavior, five major categories of student behavior, and two major categories that refer to the non-task-oriented behavior of anyone in the car. The categories refer to verbal and physical behaviors and feeling tones. There are several gradations in each category, and each behavior is codable into one unique and meaningful category. This technique was used in observing 2500 high-school driver trainees at all stages of learning chosen at random from approximately 15 000 students involved in a controlled study of driver education (2).

The training of the coders is a vital step in building a reliable instrument. Our coders did not have, and should not have had, a background in driver education. They did, however, have to be intelligent and diligent. They were trained in 2 weeks on a half-time basis. In our study, the coder sat in the right rear seat, where he or she soon became inconspicuous to both driver and instructor. In this experiment, there were six coders. The interobserver agreement ranged from 68 to 91 percent for all tests, usually from 80 to 89 percent. The mere statistics do not tell the whole story; disagreements occurred largely in the intensive dimension, i.e., degrees of positive reinforcement, generality of information, and the like. Since this judgment depends to some extent on context and intonation, it is somewhat difficult to standardize. In many of the statistical analyses reported below, judgments were collapsed across the several subgroups of a behavioral category, which had the effect of increasing the reliability further.

In the analysis of the behavioral categories, not only were the individual cells of the matrix analyzed but also some categories were collapsed to create 14 composite categories, e.g., Teacher Positive Affect (all levels), Teacher Control (all types), Noise (all sources), and Total Teacher Talk. Not only were these composite categories more reliably coded, they were also more interesting pedagogically.

The picture of the driving instructor that emerged from the analysis was not very different from that of the classroom teacher (4, 5, 6). The general findings from 100 years of observing teacher behavior in the classroom are that (a) teachers do 80 percent of the talking; (b) students ask very few questions, and those they do ask usually concern the mechanics of the classroom; (c) the kind and level of teacher affect are important; and (d) a teacher's style is extremely difficult to change. One might suppose that teachers of perceptual-motor skills, in a one-to-one relationship, would behave differently and that the students, now engaged in a task that presumably interests them, with individual attention, would also behave quite differently.

This does not appear to be the case. The greatest amount of teacher behavior occurred in Total Teacher Talk, which had a mean of 5.92 statements per minute and a maximum of 36.21 statements per minute! On the other hand, Total Student Talk was only 0.69 statements per minute and consisted largely of specific questions about the task. Since students did not ask

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clarifying questions, the teacher was not aware of misunderstandings. Practicing of a particular skill (defined as several maneuvers of the same sort in sequence, e.g., passing one car, then trying it again and again) was very infrequent in our sample, both for simple skills like backing (Skill Practice 1, 0.08 per minute) and for more complex maneuvers like overtaking and passing (Skill Practice 2, 0.09 per minute). Yet to develop competence in psychomotor skills of even the simplest sort, a great deal of practice is necessary.

One of the more interesting categories was Noise. This refers to events that are not task related and that are clearly distracting to the driver. Noise occurred on the average of 0.81 times per minute, but in one case it occurred 13.27 times per minute (these were discrete events, some of them lasting an appreciable time). It is hard to see how a student could learn much or perform well under such circumstances. Noise 5 (non-task-directed distraction by the teacher) occurred on an average of 0.24 times per minute, although one teacher produced distractions at the rate of 4.09 times a minute. An important improvement in the instruction could be made by taking steps to reduce distraction, including unnecessary talk by the teacher even when it is task related, since there is good evidence that any talk distracts attention from the task and attention is particularly important in the early stages of learning.

The student observers also distracted the driver. Task-related interactions between teacher and student observer occurred at mean rates of 0.12 and 0.11 per minute. There was thus not much involvement on the part of student observers, and it is appropriate to question whether the practice of requiring long hours of observation (often 18 hours) is justifiable. The unoccupied observers contributed significantly to the sheer noise and distraction and were often observed to be studying, sleeping, or commenting on social events. On the other hand, if they were to be more involved in relevant tasks, those tasks would have to be so designed that they would not add to distraction of the driver; i.e., they should not involve questions and answers between teacher and observers.

In comparisons of different types of instructional programs, a number of statistically significant differences were found. There were significant differences in teaching techniques between instructors at public high schools and instructors from commercial driving schools. Public-school instructors talked more, tolerated more noise (distraction) in the car, gave less practice in elementary skills, and received fewer student questions. There was also less positive affect (feeling tone) in the public-school program ($p < 0.001$). These differences should be examined in greater depth to discover whether they are related to student learning, as we hypothesized.

In comparisons of public-school programs using simulators (3 hours of in-car instruction and 12 hours of instruction in the simulator) with those having only in-car instruction (6 hours), significant differences were found in the amount of control exercised by the instructor. The simulator-trained students were subject to more physical control ($p < 0.006$), understandably, since these students have less experience in actual control of the car. The two sorts of programs, although they are often said to be equivalent, are clearly not behaviorally equivalent in the eyes of instructors. The important pedagogical question is whether the highly controlled student learns as much as one who has more freedom. Again, this is a question that can and should be answered experimentally.

It was hypothesized that the tight control restricts the development of important perceptual skills. The data provided clear evidence that instructors treat male and female students differently. Females were subject to more Specific Commands (Control 1), more Physical Control, and more Total Control ($p < 0.001$) in all cases. They received significantly more correctional remarks (Teacher Negative Affect 1 and Total Teacher Negative Affect) but also more Total Teacher Positive Affect. In spite of all this, there was no difference in skill practice, although it would seem females should require more because they enter with less vehicular experience and were rated by their instructors as less skillful. This appears to indicate that lessons were not usually tailored to students' needs even in one-to-one instruction.

A similar conclusion was derived from some limited data on the effect of socioeconomic level. Neither Teacher Negative Affect (largely informational feedback as to errors) nor Total Control showed any difference across socioeconomic levels. In view of the fact that students of low socioeconomic levels had less vehicular experience, lower scores on performance and rating scales, and lower scores on the state's road test, one would expect both more control and more correction of errors. These students should also have received more practice in both simple and complex skills, but they did not.

There was some evidence, however, that teaching techniques were moderately flexible. For all programs except the shortest (3 hours in the car plus 12 hours in the simulator), there was more Total Teacher Talk at the beginning and less toward the end of training. The same thing occurred in Total Control: All programs except the short simulator program had more control early and less late in training and all the differences were highly significant ($p < 0.0001$ or better). However, for the short simulator programs, early and late training were not different. These programs (only 3 hours in the car) were clearly different from all the others in the way the student was handled by instructors. This was borne out by data on Teacher Negative Affect 1 (corrections for information purposes), in which these programs showed no change over time, whereas all other programs did. These data provided strong evidence that the standard simulator program (12 hours plus 3 in-car hours) is not equivalent to 6 hours in the car—nor to still longer programs.

All programs but these short simulator programs tended to have a greater concentration of skill practice in the early training hours. This consisted largely of practice in simple skills. There was very little practice of complex skills in any program at any time. This, too, was a finding of some significance, since psychological research universally shows the necessity for great amounts of practice for mastery of both simple and complex skills. It points to a need for revision of in-car training and enlistment of parents in providing greatly expanded opportunities for the time-consuming practice of skills.

Interaction analysis is a feasible method for obtaining objective data descriptive of the on-road training phase of driver instruction. It yields highly significant differences among programs and students in a number of different behavioral categories. The data are descriptive of instructional strategies, distractions, use of observer's time, student involvement, and changing strategies as the student progresses through the course. The data presented here show that educational prescriptions for the on-road curriculum could be devised and their effectiveness assessed objectively.

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Photographic Analysis of Control Responses of Motorcycle Operators

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The purpose of the research described in this paper was to identify the precise nature of the control responses required of motorcycle operators in turning, stopping, avoiding collisions, and surmounting an obstacle. An earlier analysis of the motorcycle operator's task (1) revealed that there are a number of questions about the nature of the responses required of operators in carrying out these tasks.

METHOD

Two highly experienced motorcycle road racers carried out each of the four maneuvers. Their performance was recorded by two Super 8 cameras, one mounted beside the motorcycle's path of travel and one mounted at the rear of the motorcycle. Super 8 photography was found to offer an inexpensive means of recording a wide array of operator and vehicle responses. The equipment proved extremely durable, surviving a number of falls without damage.

Cameras

The first camera was mounted on a tripod in such a position as to keep the operator and motorcycle suitably framed during each maneuver. In turning maneuvers, it was positioned close to the axis of the turn. It recorded the motorcycle's position on the path and its pitch angle; front- and rear-wheel rotation (locked versus rolling); the operator's body position (seated versus standing), body angle, and foot position (on or off pegs); and the motorcycle's deviation from its path.

The second camera was mounted on a lightweight frame that extended 1 m (3 ft) to the rear of the motorcycle. It was focused on a display panel that was mounted directly behind the operator. The display panel held a set of pointers, each of which was connected to one of the vehicle's controls. The position of the pointer indicated the position of the corresponding control. The operator's upper body, the motorcycle's speedometer, and the horizon were also captured by the rear camera. In all, the rear camera recorded the positions of the front and rear brakes, the throttle position, the clutch position, the steering angle, the velocity, the motorcycle's roll angle, and the operator's body angle and body position.

Maneuvers

Each maneuver was performed by each operator on a moderate-sized (500-cc) and on a small-sized (100-cc) motorcycle. To allow for filming problems, each run was performed three times. The process of data reduction involved reviewing each selected film frame by frame and measuring operator and vehicle responses. All responses were plotted along a common timeline to provide a graphic profile of each maneuver.

The maneuvers performed were as follows:

Turning

Turning maneuvers involved a series of 90-deg curves with radii of 3, 6, 9, and 15 m (10, 20, 30 and 50 ft). Each curve was taken at a specific speed. In each case, the speed was set as close as possible to the maximum at which the curve could be negotiated. Turning maneuvers were performed on both wet and dry surfaces.

Stopping

The stopping maneuver consisted of a series of straight-line braking exercises performed at 40 and 61 km/h (25 and 38 mph), over both dry and wet pavement. Each maneuver was performed by using three different techniques for applying the rear brake:

1. Locked. The rear wheel was locked and the motorcycle brought to a skidding stop.
2. Controlled. The rear brake was applied as firmly as possible without locking the rear wheel.
3. Modulated. The rear wheel was alternately locked and released.

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Avoiding Collisions

In a collision-avoidance maneuver, the operator approached a barrier through a chute of traffic cones. On reaching the end of the chute, he was to make a quick turn to avoid the obstacle. The operator was free to use any combination of braking and turning.

Surmounting an Obstacle

The maneuver to surmount an obstacle took place along the edge of an asphalt surface where there was a 10.2-cm (4-in) drop-off to a paved shoulder. A series of barriers forced the operator to drive onto the paved shoulder and then return to the asphalt surface. The arrangement was designed to require the operator to approach the asphalt surface at the smallest angle at which it could be safely surmounted.

RESULTS

Maneuver profiles varied considerably from one trial to the next. The intraindividual variability was as great as that between individuals. However, sufficient commonality was found across trials and riders to support the following statements of general findings.

Turning

Turning a motorcycle involves achieving a close coordination between the motorcycle's angular velocity and the roll angle. Both motions are controlled almost entirely through adjustment of the steering angle. It is particularly noteworthy that neither the operator's body angle nor body position was substantially involved in producing the motorcycle roll required to maintain balance through a turn. Approximately half of the turns were initiated through a "countersteer," that is, a slight deflection of the front wheel away from the direction of the intended turn. The countersteer was generally about 2 deg in amplitude, with durations ranging from ⅛ s to almost a full second. Where no countersteer appeared, it was hypothesized that the required roll developed out of the normal roll oscillations that characterize straight-line operation.

Most operators leaned their bodies slightly in the direction of the intended turn as they began the turn. The small amount of leaning involved, coupled with the fact that it did not appear to be closely correlated with the roll of the motorcycle, suggests that it had little direct effect on the motorcycle's roll angle. It may only reflect the operator's anticipation of a turn. A similar phenomenon occurred in ending the turn, where there was a slight reduction in the body angle, just as the motorcycle began its return to an upright position. This change in body angle could not have helped in any way to straighten up the motorcycle.

Once a turn is initiated, stability is maintained by coordinating velocity and steering angle so that the outward force of the turn counters the gravitational force acting upon the operator. Variations in steering, throttle application, and braking were observed during turns. The frequency and amplitude of these variations were less for the two experienced riders than among novices attempting the same maneuvers.

The motorcycle is brought back to an upright position by adjusting the steering angle so as to achieve a high rate of turn and an excessive outward force. In large-radius turns, ending the turn was associated with a definite change in the steering angle. In turns with a short radius, the necessary steering angle was attained through a continuation of the original steering input. In other words, the operator started to come out of the turn as soon as he was in it.

Stopping

The shortest stopping distance was achieved by maximum application of the rear brake to the locked position and controlled application of the front brake. The sooner and more firmly the front brake was applied, the shorter was the stopping distance. There was no support for the theory that the rear brake should be applied before the front brake. In most instances the rear brake was applied first, slightly ahead of the front brake, but this appeared to be a result of the operator's and vehicle's control mechanisms rather than the result of any attempt to apply one ahead of the other.

Modulating application of the rear brake or controlling it to prevent the rear wheel from locking produced longer stopping distances. This was true regardless of initial velocity or the degree of surface friction. Because the rear wheel contributes less than 30 percent of the braking power, it did not appear likely that differences in application of the rear brake could account for the observed differences in stopping distance. The results were attributed to the fact that locking the rear wheel allows the operator to devote total attention to adjustment of the front brake and thus produces better application of the front brake.

Surprisingly, stopping distances on dry pavement were not appreciably different from those obtained when the surface was wet. It is hypothesized that caution in application of the front brake resulted in stopping distances on dry surfaces that were above the minimum obtainable. When the surface was wet, it became unnecessary to reduce the level of brake application.

Avoiding Collisions

In attempting to avoid an obstacle in the path of the motorcycle, operators turned and braked simultaneously. Slowing the motorcycle allowed more time to achieve a greater turning arc and thus a greater change in lateral position.

The greatest danger in braking during an obstacle-avoidance maneuver was locking of the rear wheel. This did not occur among the expert riders but was observed among nonexperts performing the maneuver. When the rear wheel is locked in a turn away from an obstacle, the operator is forced to turn toward the obstacle in order to maintain balance. In the case of a real obstacle, such as an automobile, such a turn could be extremely hazardous. It appears advisable to avoid use of the rear brake entirely during the collision-avoidance maneuver.

Surmounting an Obstacle

Surmounting an obstacle in the motorcycle's path requires (a) a quick application of the throttle to achieve a rearward weight shift and thus reduce the load on the front wheel and (b) rising on the foot pegs to keep from being thrown from the seat as the rear wheel strikes the obstacle. The motorcycle must be kept upright to avoid capsizing.

When the obstacle is parallel to the path of the motorcycle (e.g., a curb), the motorcycle must approach the obstacle at a sufficient angle to allow the front wheel to climb the obstacle. With an obstacle 10.2 cm (4 in) in height, the minimum safe angle of attack was found to be 35 to 45 deg. In a few instances, the obstacle was surmounted at angles as small as 20 deg. However, in such instances, the rear wheel was dragged sideways for a short distance. When it did finally climb the obstacle, it caused the motorcycle to lurch ahead. In one instance, this caused a fall. No attempts were made to climb the obstacle at an angle less than 20 deg. Had such an attempt been made, it is likely that the front wheel would have been deflected sideways rather than climbing the obstacle. The result would have been a loss of steering control resulting in an immediate fall.

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Differential Effect of Bicycle Lanes on Ten Classes of Bicycle-Automobile Accidents

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Bicycle lanes are being proposed or established in a good many communities in the United States. Although proponents commonly cite improved safety as a justification for the lanes, their contribution to the reduction of bicycle-automobile accidents is the subject of some debate. As a means of evaluating their effect, the accident experience revealed in police records over a 4-year period in Davis, California, a city with a long-standing system of bicycle lanes, was used as a data base. Accidents were classified in a 10-class system. The relative frequency of accident classes in Davis was compared with that in Santa Barbara, a comparable community without bicycle lanes. The same comparison was made of accidents within Davis on streets with bicycle lanes versus those without them. Three accident classes that were judged to be uninfluenced by the presence or absence of bicycle lanes were used as a standard for comparing the effect of bicycle lanes on the frequency of accidents in other classes. The results showed lower accident rates for bicycle lanes in six classes and higher rates in one class. Overall the frequency of accidents influenced by the presence or absence of bicycle lanes was reduced by 51 percent, and the frequency of all accident types combined was reduced by 29 percent on bicycle lanes, demonstrating a positive effect of bicycle lanes on safety.

Separate facilities for bicycle travel on city streets are a relatively recent development in the United States. The lanes are usually established for a variety of purposes, including facilitating multimodal traffic flow in the streets, reducing disputes about the right-of-way, and encouraging bicycle use. One of their usual justifications is the reduction of automobile-bicycle collisions. Although European experience has shown bicycle facilities to be useful in this role, their effectiveness has been challenged in the United States.

Like many motorists, many experienced bicyclists consider themselves experts in traffic engineering as it applies to their vehicles. Considerable folklore about bicycle lanes and bicycle operation has evolved from personal experiences and observations and cursory analysis of accident statistics. But the factors affecting traffic operations are often quite complex, and their assessment generally requires sophisticated analysis.

The central criticism of bicycle lanes is the claim that they are ineffective in reducing (or, worse yet, that they increase) all types of accidents between bicycles and motor vehicles except for rear-end and sideswiping collisions. While this contention might seem to have merit in a superficial intuitive assessment, there are equally compelling intuitive arguments that bicycle lanes are beneficial in preventing several other types of accidents. But to date neither the critics' nor the proponents' contentions have been backed by sound statistical evidence positively demonstrating the effectiveness or ineffectiveness of bicycle lanes in relation to various types of accidents between bicycles and motor vehicles.

METHOD

One of the best sites in the United States for studying the effect of bicycle lanes on bicycle-automobile interactions is Davis, California, which has many miles of heavily used bicycle lanes integrated into a street network. Since it also has many streets of all functional types that lack bicycle lanes, it is possible to compare streets that have bicycle lanes with streets that do not but that are shared by the same population of motorists and bicyclists. And because of the relatively long-standing experience with bicycle lanes and the high levels of bicycle travel on all types of streets, enough relevant accident data have accumulated to permit meaningful statistical analysis.

Smith (1) cited the dramatic overall decline in bicycle-automobile accident rates in Davis following the installation of the bicycle lanes as evidence that the lanes enhance safety. This paper presents an analysis of the impact of bicycle lanes on particular accident types in an attempt to substantiate that overall finding and to discover how bicycle lanes contribute to safety.

The analysis of bicycle-automobile accidents in general has acquired considerable sophistication in recent years. Consequently, we are able to use an excellent classification scheme developed by Cross (2) in a study of bicycle-automobile collisions in Santa Barbara, California. Our general approach has been to analyze the Davis bicycle-automobile collisions in terms of the categories created by Cross and then to compare the frequency of these accident types (a) in Davis versus in

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Santa Barbara and (b) on streets in Davis with bicycle lanes versus on streets in Davis without bicycle lanes.

An important feature of the Cross analysis is the assignment of fault. This does not necessarily mean "fault" in the criminal or legal sense, but rather a determination of the particular maneuver or "critical behavior" that caused the accident. Since most accidents are caused by maneuvers by one or the other of the participants, it is usually possible to assign fault in this sense to either the bicyclist or the motorist. In practice most accident-causing maneuvers do violate some traffic regulation and therefore correspond to a legal definition of fault. The goal of this categorization system, however, is not to determine legal liability, but to determine the behavioral causes of accidents.

The materials analyzed were the police reports on all the 177 bicycle-automobile collisions reported in the city of Davis from 1970 through 1973. Not all accidents reported in police accident records can be classified according to the Cross scheme. Certain events (e.g., collisions in supermarket parking lots) fall outside its scope and also outside the scope of our interest. Since the assignment of responsibility was a central feature of this analysis, certain other incidents were also excluded, i.e., those that occurred at least in part because of the decreased visibility of an unlighted bicycle at night. More than half (8 out of 14) of these accidents were technically a violation of the bicyclist's right-of-way by a motorist turning left. However, since the motorist can hardly yield the right-of-way to a bicyclist he cannot see, no fault was assigned in these incidents. With nonclassifiable and low-visibility accidents excluded, a total of 145 accidents for which responsibility could be assigned remained from the 177 recorded collisions between bicycles and motor vehicles.

RESULTS

The accident data from Davis were categorized according to the Cross system, and these categories were further subdivided into the circumstances under which the accident occurred (with or without bicycle lanes) and by age classes of the bicyclist involved. These data are given in Table 1.

Although Davis has both class 1 and class 2 bicycle lanes, only four of the accidents, all at intersections, were associated with a class 1 bicycle lane (a right-of-way designated for the exclusive use of bicycles). In Davis there are two types of class 2 bicycle lanes: (a) protected, which is next to the curb with parking between it and the automobile travel lane and (b) unprotected, which is next to the automobile travel lane with parking between it and the curb. There is only one block of the protected type, and only two accidents were associated with it. Consequently, the accidents associated with bicycle lanes occurred almost entirely on unprotected class 2 bicycle lanes.

Inherent in the Cross categories is the assignment of fault to either the bicyclist or the motorist. The bicyclist is at fault in accident types A, C, D, and E, and the motorist is at fault in types B, F, G, H, I, and J. Williams (3), in a study of bicycle-automobile accidents in Maryland, observed that the proportion of accidents that are the bicyclist's fault declined as the age of the bicyclist increased. This was also true in Davis: 71 percent of the accidents involving bicyclists age 11 or younger were the cyclist's fault. This declined to 50 percent among those 12 to 17, 29 percent among those 18 to 24, and 21 percent among those 25 and older.

To compare the accident data for Davis with the Santa Barbara data analyzed by Cross, we converted the frequency of each type of accident in the Davis sample to a percentage of the total, as shown in Table 2. This comparison suggests that there are some important discrepancies between Santa Barbara and Davis in the relative frequency of different accident types. The Davis data summarize experience both on and off bicycle lanes.

Since the bicycle lanes may influence the relative frequency of accident types, the percentage of accidents by type on and off the bicycle lanes was compared in Table 3 (based on the 145 classifiable accidents). All accidents that involved a bicyclist on a street with bicycle lanes were counted in the bicycle-lane category even if they occurred at an intersection where the bicycle lanes are interrupted. An accident that occurred at an intersection where the street in the bicyclist's direction of travel had a bicycle lane on one side of the intersection but not on the other was categorized as bicycle-lane related if the bicyclist entered the intersection from the street segment with a bicycle lane but counted as not related to bicycle lanes if the bicyclist entered from the other street segment.

Table 3 shows that accidents of certain types occur relatively more frequently on streets without bicycle lanes than on streets with bicycle lanes. It is also clear that overtaking and sideswiping are not the only accident types affected. Relative frequency, however, is not the critical question. The more important question is: Is there a change in the absolute frequency of certain types of accidents on streets with bicycle lanes compared with streets without bicycle lanes?

This is a difficult question to answer. It would be helpful, of course, to know the relative number of kilometers traveled by both bicycles and automobiles on streets with bicycle lanes and on streets lacking them. One could then compare the absolute rates of accidents per kilometer traveled in each situation. But even if we had such data, they would not be conclusive because the bicycle lanes are not placed on the streets randomly, as an unbiased comparison would require. Instead they are generally placed on the streets where the perceived need is greatest because of a combination of high density of both modes of traffic and features that enhance through travel; i.e., they are on arterials and secondary streets. An alternative approach would be to compare accident data for a particular street before and after bicycle paths were established. Very few such data are available, and their interpretation is complicated by the fact that the lanes change the structure of the user population.

There does appear to be one other way to estimate the effect of bicycle lanes on the absolute rate of particular accident types. This approach is based on the assumption that the bicycle lanes have no effect whatever on the frequency of certain types of accidents. These "neutral" accident types can then be used as a standard for comparing the relative frequency of other accident types on and off the bikeways. If a nonneutral type of accident occurs half as frequently as the neutral accidents off the bicycle lanes (e.g., 6 accidents and 12), but occurs as frequently as the neutral accidents on the bicycle lanes (12 and 12), then we would say that the rate of the nonneutral type of accident has doubled on the bicycle lanes. If, on the other hand, that type of nonneutral accident occurs only one-fourth as often on the bicycle lanes as the neutral accidents (3 and 12 versus 6 and 12 off the bicycle lanes), then we would say that its rate was cut in half by the bicycle lanes.

The first step in this approach is to develop the standard, i.e., to determine the neutral accident types. This determination is now a matter of judgment, which may or may not be sustained by later empirical research. Three accident types appear to be neutral (that is, the presence of the bicycle lanes should not affect their occurrence): bicyclist's failure to stop or yield at a controlled intersection (type C), motorist's failure to stop or yield at a controlled intersection (type G), and improper left turn by a motorist (type H).

If these accident types are in fact neutral, their rate of occurrence on the bicycle lanes can be equated with their rate of occurrence off the bicycle lanes by determining the difference between the percentages of neutral accidents on and off the bicycle lanes and then multiplying all accident types on the bicycle lanes by the difference factor. In this case the neutral accidents formed a lower percentage of the accidents off bicycle lanes than of the accidents on bicycle lanes; this indicated that nonneutral accidents generally occurred at a lower rate on bicycle lanes. To find out how much their rate was reduced, we divided the percentage of neutral accidents occurring off the bicycle lanes by the percentage occurring on the bicycle lanes. The neutral accidents proved to be only 71 percent as great a part of the total accidents off bicycle lanes as they were of the total accidents on bicycle lanes.

The frequencies of particular types of accidents on bicycle lanes were equated with accidents off bicycle lanes by multiplying their percentages by the equating factor, 0.71. For example, accident type E (bicyclist on the wrong side of the street) constituted 7.25 percent of all the classifiable accidents occurring on bicycle lanes. Its relative frequency was corrected for the lower expectation of accidents on streets with bicycle lanes by multiplying it by the correction factor, 0.71. The result is $7.25 \times 0.71 = 5.15$. Table 4 was generated from Table 3 in this fashion. Comparison of accident type E on and off the bicycle lanes leads to the prediction that for every 18.4 such accidents without bicycle lanes one would expect 5.15 with bicycle lanes.

Table 4 indicates that the nonneutral accidents are reduced by slightly more than half overall by the bicycle lanes, but that the magnitude and direction of change vary from one type of accident to another. The statistical reliability of this difference was examined by comparing the incidence of neutral and nonneutral accidents on and off the bicycle-lane streets as given in Table 5. This yields a chi-square value of 3.74 ($df = 1$, $p < 0.06$), which establishes that nonneutral accidents are relatively less common on streets with bicycle lanes than on streets without them. It also provides an opportunity to estimate the magnitude of the reduction of accidents by bicycle lanes. The neutral accidents on bicycle lanes are 61 percent of the total accidents on bicycle lanes. Therefore one can estimate the impact of bicycle lanes by reducing the number of nonneutral accidents that occurred on streets without bicycle lanes enough to make the neutral accidents 61 percent of the total. To produce this effect it is necessary to reduce the nonneutral accidents off bicycle lanes by 22, from 43 to 21. Nonneutral accidents are thus reduced 51 percent, and both classes of accidents combined are reduced 29 percent by bicycle lanes (Table 5).

DISCUSSION

Evaluation of the causes of this difference is not a completely straightforward task. Accident types have been shown to be related to the age of the bicyclist (2, 3). If it were the case that the bicyclists involved in accidents on and off the bicycle lanes came from different age groups, then a difference in accident types could be the result of having riders of different ages in the two situations. In fact, Lott and Lott (4) have shown that bicyclists aged 25 and older are more inclined to modify their travel routes to use bicycle paths than are those 18 to 24 years old.

Since older bicyclists are most commonly involved in neutral accidents, this raises the possibility that the greater number of neutral accident types is merely a reflection of the fact that older bicyclists are more likely to ride on bicycle lanes. Table 1 reveals, however, that the number of neutral accidents is a larger part of the total number of accidents on streets with bicycle lanes than on streets without bicycle lanes for all groups except those 25 and older.

Since the difference in accident types is not a function of the bicyclist's age, it seems likely to be a function of the facilities themselves. The statistical reliability of this difference was examined by using a $K \times 2$ analysis of the accidents on bicycle lanes versus accidents off bicycle lanes (i.e., a $K \times 2$ analysis of the accident-type subtotals in Table 1, taking into account the information in the footnote). The chi square was 16.42 ($df = 8$ and $p < 0.05$). Since these differences are reliable, it is appropriate to proceed with an analysis of the reasons for them.

Table 4 reveals that the expected accident rate is lower on bicycle lanes in all but one type of nonneutral accident (type D). In some cases the reason for this difference seems obvious. For example, the number of accidents in which the motorist overruns the bicyclist from behind (type F) is generally expected to be reduced by bicycle lanes and it was. In fact the only accident of this type on the bicycle lanes occurred when the motorist, intending to turn right, merged into the bicycle lane ahead of the intersection.

The class of accidents in which bicyclists leave a driveway or alley into the path of the motorist (type A) is also greatly reduced. Probably this is because the painted line keeps the motorist off part of the travel lane and at the same time demarks the area in which the bicyclist must change directions to avoid entering the motor vehicle lanes.

The reduction of instances in which a motor vehicle goes from a driveway or alley into the bicyclist's path (type B) probably has a different cause. In practice bicyclists ride near the left margin of the bicycle lane, considerably farther to the left than they would on the same street without a bicycle lane. This increases the distance at which they and the operator of a car leaving a driveway or alley can see each other. In moving vehicles, distance is time and increased time increases the chance that one or both operators will be able to avoid a collision.

This same characteristic of bicycle-lane riding will, of course, reduce the number of accidents caused by drivers opening their car doors into the path of bicyclists (type J). This accident type is completely missing in Davis, both on and off bicycle lanes. The reason may be that in Davis the bicycle lanes are established on the busiest streets, where the problem would be most severe. Since the lanes give the riders room to get around even an opened door without leaving the bicycle lane and the pattern of riding tends to keep them in such a position that they need not even maneuver to be clear of the opened door, the rate of accidents from this cause should be low; a reduction to zero is quite reasonable.

The reduction in the number of accidents caused by wrong-way riding (type E) raises a point at which the intuition of people imagining how riders would behave in bicycle lanes is almost invariably in conflict with the facts of their behavior. The reduction in accidents caused by wrong-way riding seems to have a simple explanation. Bicyclists ride on the wrong side of the street much less frequently if there are bicycle lanes (5). When the incidence of wrong-way riding declines, the incidence of accidents caused by that maneuver will surely decline also, as it has in Davis.

In evaluating the magnitude of the decline in this case,

Table 1. Bicycle-automobile accidents in Davis from 1970 to 1973 by age groups of bicyclists.

	Streets With Bicycle Lanes					Streets Without Bicycle Lanes				
Accident Type	<11	12 to 17	18 to 24	>25	Total	<11	12 to 17	18 to 24	>25	Total
A Bicyclist exited driveway into path of motorist	1	0	0	0	1	3	1	2	0	6
B Motorist exited driveway into path of bicyclist	0	1	1	0	2	0	1	2	0	3
C Bicyclist failed to stop or yield at controlled intersection	2	3	2	1	8	1	2	3	0	6
D Bicyclist made improper left turn	4	1	1	4	10	2	1	1	0	4
E Bicyclist rode on wrong side of street	1	2	2	0	5	3	3	8	0	14
F Motorist collided with rear of bicyclist	0	0	1	0	1	1	2	3	0	6
G Motorist failed to stop or yield at controlled intersection	1	2	5	7	15	0	2	8	3	13
H Motorist made improper left turn	2	3	6	8	19	0	2	6	3	11
I Motorist made improper right turn	1	0	5	2	8	1	1	8	0	10
J Motorist opened car door into bicyclist's path	0	0	0	0	0	0	0	0	0	0
Total	12	12	23	22	69	11	15	41	6	73

Note: In four accidents, two type G (off bicycle lanes) and two type H (one off and one on bicycle lanes), the bicyclist's age was unknown; these accidents are not reported in this table. One type G accident associated with bicycle lanes involved a male and a female bicyclist, both 18, and so is reported twice.

Table 2. Percentage of accidents by type in Santa Barbara and Davis.

Accident Type[a]	Santa Barbara	Davis
A Bicyclist exited driveway	8.6	3.9
B Motorist exited driveway	5.7	2.8
C Bicyclist not stop/yield	8.3	7.9
D Bicyclist improper left	11.2	7.9
E Bicyclist wrong side	14.3	10.7
F Motorist overtake bicyclist	4.1	3.9
G Motorist not stop/yield	7.8	16.4
H Motorist improper left	12.7	18.1
I Motorist improper right	11.2	10.2
J Motorist opened car door	7.2	0.0
K Other	8.6	18.1

[a] Abbreviated from Table 1.

Table 3. Percentage of accidents by type on streets with and without bicycle lanes.

Accident Type[a]	With Bicycle Lanes	Without Bicycle Lanes
A Bicyclist exited driveway	1.45	7.89
B Motorist exited driveway	2.90	3.95
C Bicyclist not stop/yield	11.59	7.89
D Bicyclist improper left	14.49	5.26
E Bicyclist wrong side	7.25	18.42
F Motorist overtake bicyclist	1.45	7.89
G Motorist not stop/yield	20.29	19.74
H Motorist improper left	28.99	15.79
I Motorist improper right	11.59	13.16
J Motorist opened car door	0.00	0.00

[a] Abbreviated from Table 1.

Table 4. Expected rate of nonneutral accidents on streets with and without bicycle lanes.

Accident Type[a]	With Bicycle Lanes	Without Bicycle Lanes
A Bicyclist exited driveway	1.03	7.89
B Motorist exited driveway	2.06	3.95
D Bicyclist improper left	10.29	5.26
E Bicyclist on wrong side	5.15	18.42
F Motorist overtake bicyclist	1.03	7.89
I Motorist improper right	8.23	13.16
Total	27.79	56.57

[a] Abbreviated from Table 1.

Table 5. Incidence of neutral and nonneutral accidents on streets with and without bicycle lanes and estimated reduction of nonneutral accidents.

			Without Bicycle Lanes			
	With Bicycle Lanes		Actual		Estimated Reduction	
Accident	Number	Percent	Number	Percent	Number	Percent
Neutral	42	61	33	43	33	61
Nonneutral	27	39	43	57	21	39
Total	69	100	76	100	54	100

Table 6. Percentage of accidents caused by improper left turns by bicyclists in Santa Barbara and Davis.

		Davis	
Accident Subtype	Santa Barbara	With Bicycle Lanes	Without Bicycle Lanes
D1 Bicyclist hit oncoming motorist	26	0	25
D2 Bicyclist hit from behind while crossing in front of motorist at intersection	16	60	25
D3 Bicyclist turned into path of motorist	58	40	50

one must note a peculiarity of the data on this accident type. Fault and cause sometimes become separated. This occurred in two accidents in which the bicyclist was entering a signalized intersection coming from the "wrong way" (legal but unexpected direction, i.e., the driver's right) on a two-way, class 1 bicycle lane. The bicyclist had a green signal but was hit by a car turning right from the intersecting street during the car's red-signal phase. Fault was assigned to the car driver in both cases, but the accident appeared at least in part to be caused by wrong-way riding imposed by the two-way bicycle lane.

The reduction in rate of accidents caused by improper right turns by motorists (type I) is somewhat more difficult to interpret. Bicyclists in Davis are required to yield the right-of-way to all vehicles within or approaching an intersection, but in practice motorists nearly always yield to through bicyclists before turning right at an intersection. This may help to explain the decreased accident rates caused by vehicles turning right (type I) on streets with bicycle lanes. Perhaps a bicycle-lane stripe causes motorists to treat a right turn as a lane change, which requires a check for traffic in the lane to their right. Or the stripe may serve as a reminder that bicyclists may legitimately share the roadway. Whatever the cause, it is clear that bicycle lanes reduce right-turn accidents.

The improper left turn by bicyclists (type D) is the one accident type that our analysis shows is increased by bicycle lanes. For this accident type we have made a more detailed analysis, again following the general approach of Cross, of the incidence of different subtypes of this general type of accident. As Table 6 reveals, the predominant subtype is D3, in which the cyclist tries to make a turn at an intersection from the bicycle lane through the automobile lane. This type of turn is illegal under the ordinances that govern riding on the bicycle lanes in Davis. Nevertheless, the greater frequency of this type of accident suggests that bicyclists take advantage of the protection afforded by the lanes all the way to the intersection and then make a quick and convenient, but dangerous and illegal, left turn.

SUMMARY

We believe that the data reported here confirm the already cited evidence (1) for a large overall reduction in accidents between bicycles and automobiles in Davis following installation of bicycle lanes. The fact that our analysis conforms to the expectations of that overall finding increases our confidence in our decision to base a major part of our analysis on the concept of the neutral accident type.

But while we feel that this decision was justified as a conservative approach to the question of the effect on safety of bicycle lanes, we believe that it led to an underestimation of the magnitude of that effect. For example, we note that in Santa Barbara bicyclists running into open car doors was an important class of accidents, accounting for 7.2 percent of all the bicycle-automobile accidents that occurred there. Yet in Davis there were no such accidents either on or off the bicycle lanes. Consequently our analysis leads to the conclusion that bicycle lanes have no effect on that class of accidents, but we believe that the fact that bicycle lanes have been established on high-risk streets means that they have virtually eliminated that class of accidents.

However, this technique had the advantage that it not only revealed an overall decline, but also showed which accident types are most affected and in which direction so that there is an empirical basis for modifying the design or use of the lanes.

It is very important, of course, that other approaches to this important question be used. As more and more bicycle lanes are established, there will be more and more opportunity to study their effect. It is our hope that the future will see a steady growth of empirical studies of the safety impact of bicycle lanes.

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Location of Pedestrian Grade Separations: A Priority Ranking System

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Pedestrian grade separations provide a means of reducing conflicts between vehicular and pedestrian traffic, thus increasing the efficiency and safety of the transportation system. While some attempts have been made to use economic analysis to justify the construction of pedestrian facilities, a systematic approach has generally been lacking.

This paper proposes an approach that rates alternate sites and lists them in a priority order. This priority ranking system requires a minimum number of measurements and gives a uniform system for comparison of sites. Recommended locations are divided into two categories: (a) those at which pedestrian activity exists, e.g., where pedestrians are observed crossing at grade on the roadway, and (b) those at which pedestrian activity is not possible, e.g., a controlled-access roadway.

The factors included in the ranking system were chosen after aspects of existing and proposed locations for pedestrian grade separations were observed. The importance of each of these factors in relation to the others was subjectively determined and a weighting factor was used to give the desired relationships. We believe that this system presents a workable method of evaluating pertinent field data for locations at which pedestrian grade separation is under consideration.

The factors used to warrant the need for a pedestrian grade separation at a site where pedestrian activity exists are

1. The relationship between volumes of vehicular and pedestrian traffic, with a peak-hour average delay factor applied;
2. The amount of time a pedestrian needs to cross the roadway compared with the maximum time available to pedestrians during green and yellow signals at a signalized site, or the actual sight distance compared with the desirable sight distance at a nonsignalized site;
3. The number of school children;
4. The distance to the nearest alternate crossing, considering the type of protection there; and
5. A judgment value.

The factors used to warrant the need for a pedestrian grade separation at a site where pedestrian activity is not possible are

1. The generation of trips by pedestrians;
2. The distance to the nearest alternate crossing considering the type of protection there; and
3. A judgment value.

We have developed a procedure that explains how all field data should be collected to obtain consistent results. These field data can be processed either manually or by computer. The manual method uses prepared graphs and charts to determine a point score for each factor and a final point score that ranks the priority of each proposed location of the pedestrian overpass.

The second method uses three computer programs that were developed from the manual method as an easy and convenient way to process the data. The first program computes peak-hour pedestrian delay at signalized intersections from the field data, the second computes the priority ranking score for each location from the field and delay data, and the third formats and prints the scores by priority ranking and serves as a data file designed to accept additional scores and rerank the previous locations accordingly.

ACKNOWLEDGMENT

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Descriptions of the manual method, complete with a user's manual, and of the computer programs, with the actual listings, are included in the final report of this project, which can be obtained from the authors, Division of Research and Development, New Jersey Department of Transportation, 1035 Parkway Avenue, Trenton, New Jersey 08625.

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Pedestrian Accidents in Kentucky

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When a pedestrian is hit by a motor vehicle, he is usually injured or killed; there is no protective cushion to absorb the impact. The high concentration of pedestrians in urban areas coupled with heavy vehicle traffic often results in large numbers of pedestrian accidents. In rural areas, there are considerably fewer pedestrians but traffic speeds are higher, and, therefore, accidents are more often fatal.

Pedestrian fatalities have increased in the United States from about 7800 in 1960 to approximately 10 500 in 1973 (1). There are 120 000 pedestrian accidents each year. Total traffic accidents in the United States number about 17 million annually with about 56 000 fatalities. Thus, pedestrian accidents account for less than 1 percent of the total traffic accidents nationwide but more than 18 percent of all fatal traffic accidents. Figures released by the National Safety Council in 1974 show that total accident costs from pedestrian accidents amount to more than $1.2 billion annually (using $3400 per injury and $82 000 per fatality).

In 1973, there were an estimated 1500 pedestrian accidents in Kentucky; 167 pedestrians died in these accidents, giving a pedestrian death rate of 5.2 deaths per 100 000 population. The national rate is 5.0 (1). The pedestrian death rate in Kentucky has exceeded the national rate in 9 of the 14 years from 1960 to 1973. The number of pedestrian deaths in Kentucky has varied between 129 and 167 annually since 1960 (2). Total costs for pedestrian accidents in Kentucky amounted to more than $18 million in 1973.

Kentucky is a predominantly rural state. Since 1960, most pedestrian fatalities have occurred in rural areas. However, only 342 out of an estimated 1500 pedestrian accidents in Kentucky in 1973 occurred on the rural state-maintained highway system. Nearly 30 percent of all rural pedestrian accidents were fatalities, whereas only 4 percent were fatalities in urban areas. There were virtually no property-damage-only pedestrian accidents reported.

To obtain information on rural pedestrian accidents, files of rural accidents reported by state police for 1972 and 1973 were searched. To study pedestrian accidents in urban areas, data were obtained directly from the local police departments of cities—Louisville, Lexington, Covington, Owensboro, Bowling Green, Paducah, Ashland, Newport, and Frankfort. The populations of these cities range from about 362 000 (Louisville) to about 22 000 (Frankfort). The accident information was analyzed to determine the major causes and patterns of pedestrian accidents.

HUMAN FACTORS

Many traffic accidents result from errors in human judgment. Research indicates that about two out of every three pedestrians killed in traffic accidents violated a traffic law or committed an unsafe act (3). Thus, a reasonable approach to reducing traffic accidents of any kind is to analyze the nature and possible causes of human error and seek to remedy them. The human factors considered were the effect of the ages of the pedestrian and the driver, pedestrian action preceding the accident, and the cause of the accident.

The ages of pedestrians killed in traffic accidents were plotted against percentage of occurrence. Pedestrian fatalities were highest for ages under 9 and over 64. Most people killed in traffic accidents in Kentucky are between the ages of 15 and 44, which corresponds to the age range of the vast majority of drivers (4). The large percentage of deaths of very young pedestrians results from their lack of understanding of traffic dangers. The high percentage of fatalities among elderly pedestrians results from reduced mobility and failing eyesight or hearing. A plot of the annual fatality rate for ages of pedestrians from 1 to 75 years resulted in a U-shaped curve.

The most frequent pedestrian action preceding the fatal accidents involved crossing the street (69 percent). As expected, walking with traffic causes three times as many pedestrian fatalities as walking against traffic (15 to 5 percent). Standing, lying, or playing in the roadway was associated with 11 percent of the pedestrian fatalities.

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Most pedestrian fatalities were the fault of the pedestrian (69 percent). A large percentage of fatalities (25 percent) involved children under 10 playing in or running across the street. Although a national study (3) indicated that about 23 percent of all pedestrians killed in accidents had been drinking, only 5 percent were so identified in Kentucky. It may be important to note also that, although 20 percent of all pedestrian fatalities occur at intersections, only 3 percent of them resulted from an illegal crossing of the intersection. The major driver fault was speeding or reckless driving (12 percent). Inattentiveness was a factor in 9 percent of the cases, and drinking caused 4 percent of the fatalities. The influence of alcohol, therefore, was responsible for about 9 percent of the pedestrian fatalities, compared with about 17 percent of all traffic fatalities in Kentucky.

ENVIRONMENTAL FACTORS

Environmental conditions associated with fatal pedestrian accidents are of particular importance because they give the engineer information that may be helpful in deciding which physical characteristics of the roadway may contribute to pedestrian fatalities. Particular environmental conditions considered here are road defects, road character, weather and light conditions, type and class of road, and area or county in which pedestrian fatalities are most prevalent.

Of the 321 reports of fatal pedestrian accidents that we examined, only 12 indicated any road defect that could have contributed to the accident. Of the 12 road defects, 5 were defective shoulders and 2 were road construction zones. One defect was described as holes, ruts, or bumps in the roadway. Other defects included a dirt road and mud, sand, and other loose material on the road surface.

The most common characteristic of locations of fatal pedestrian accidents was a straight, level roadway (41 percent). Other types with appreciable numbers of fatalities were intersections (20 percent), straight roads on a grade (14 percent), and alleys and driveways (13 percent). The remaining fatalities occurred on curves (8 percent), in parking lots (2 percent), and at interchanges and bridges (1 percent each).

A summary of weather and light conditions showed that most (52 percent) pedestrian fatalities occurred during daylight hours (46 percent on dry pavements and 6 percent on wet pavements). Lighted streets accounted for only 12 percent (7 percent on dry and 5 percent on wet pavements) and dark street conditions existed during 36 percent (28 percent on dry and 8 percent on wet pavements) of the fatal pedestrian accidents. Dry highway surfaces were reported in 81 percent of these accidents.

The percentage of fatalities by type of location (rural, small urban, and large urban) and number of lanes was also determined. Two-lane roads accounted for 75 percent of these fatalities, and about 61 percent were in rural areas. Interstate highways and parkways accounted for 9 percent even though pedestrians are prohibited on these facilities.

TIME FACTORS

The relationship between the time of day and the percentage of fatal pedestrian accidents in Kentucky was also determined. The greatest percentage of occurrences was noted at approximately 4:00 p.m. and the smallest at 4:00 a.m. However, there was a large increase in pedestrian fatalities between 7:00 and 8:00 p.m., corresponding either to dusk or early nighttime hours when the pedestrian is particularly hard to discern. Much of the pedestrian activity normally subsides after 10:00 p.m.

The relationship between the day of the week and the percentage of pedestrian fatalities shows a broad peak from Wednesday through Saturday, with the lowest percentages of pedestrian fatalities on Mondays and Tuesdays. The exposure of school children to motor vehicles before and after school on weekdays, combined with weekday pedestrian shopping trips, tends to smooth the curve of pedestrian fatalities over the week.

PEDESTRIAN ACCIDENT CONCENTRATIONS

The urban pedestrian accidents in 1972 and 1973 included 1650 that occurred in the nine largest cities in Kentucky. In the larger cities there are large numbers of accidents due to congestion. There were more than 20 000 traffic accidents within the city limits of Louisville in 1973, compared with about 30 000 accidents reported over the entire rural highway system in Kentucky by state police in 1973. There were 476 pedestrian accidents in Louisville in 1973, compared with 342 over the statewide rural highway system.

The annual number of pedestrian accidents is shown in Figure 1 as a function of population by city. The plot shows a uniform increase in pedestrian accidents as population rises from 22 000 to 360 000. As can be seen, a straight line closely represents six of the nine cities. Covington and Newport, therefore, have a more serious pedestrian accident problem than the other cities. The annual rates of occurrence for pedestrian accidents per 100 000 population also showed Newport (208) and Covington (169) to be high in relation to the other cities. Paducah showed a slightly lower pedestrian accident rate for its population.

The 120 Kentucky counties were divided into nine groups by population. The number of fatalities per county, the average population of the counties in each group, and the fatality rates for each of the groupings were computed. The rate of fatal pedestrian accidents decreases with increasing population because of the high percentage of deaths in predominantly rural counties. The higher vehicle speeds in pedestrian-related accidents on rural roads present a greater likelihood of a fatality. Because of the large number of pedestrian accidents in urban areas, combined with a high risk that any pedestrian accident will result in a fatality, the pedestrian death rate was highest in Jefferson County, the most highly populated. The average annual number of pedestrian fatalities increased from about 0.5 in sparsely populated counties to about 40 in Jefferson County, which has a population of more than 600 000 (Figure 2).

COUNTERMEASURES

Because of the random occurrence of pedestrian accidents and their low numbers compared with other types of accidents, cost-effective countermeasures are not always possible. The pedestrian accident problem must be handled in the planning stages of highway networks instead of being treated only after a concentration of such accidents is noted at a particular location. Some measures that have been used successfully in reducing the potential for pedestrian accidents include

1. Prohibition of vehicle parking,
2. Designation of one-way streets,
3. Improvements in overhead street lighting,
4. Use of crosswalks,
5. Installation of pedestrian signals,
6. Use of pedestrian barriers,

Figure 1. Relationship between annual number of pedestrian accidents and population in major Kentucky cities.

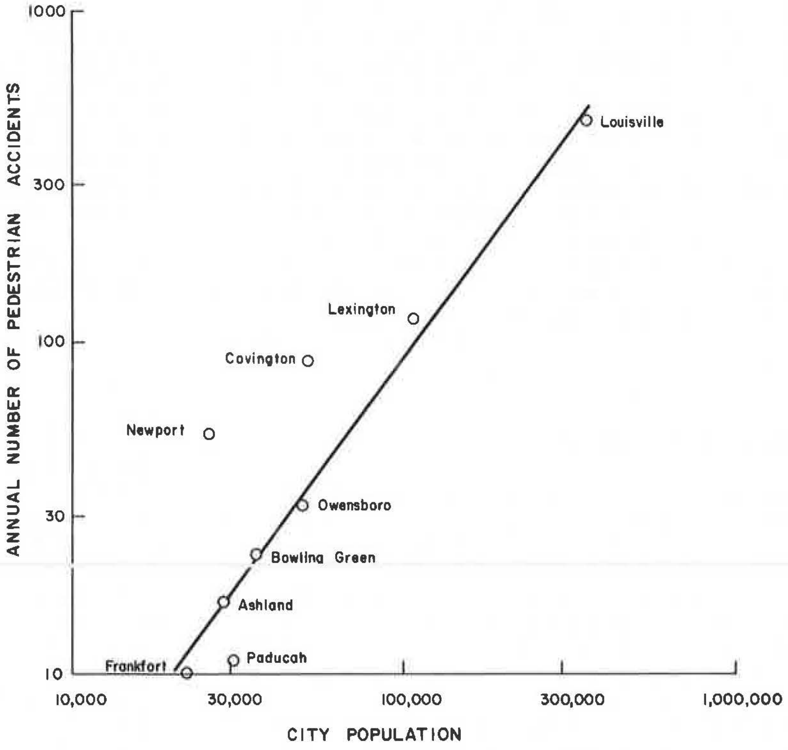
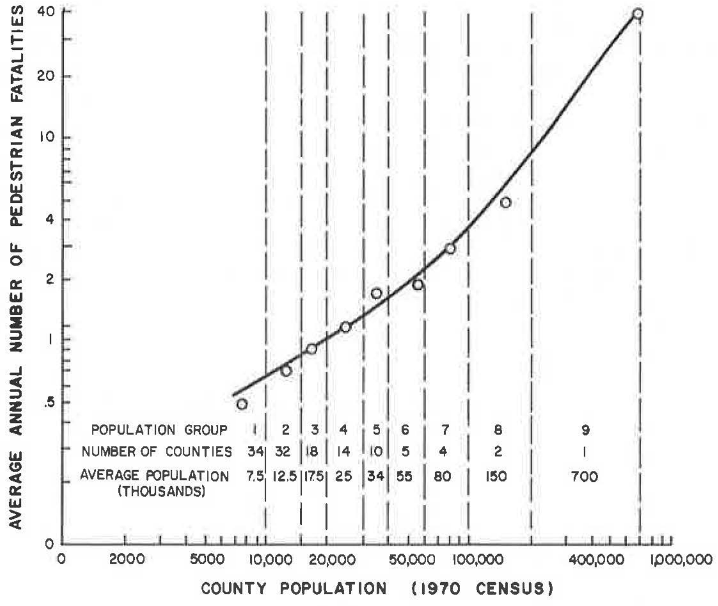


Figure 2. Relationship between county population and average annual pedestrian fatalities.



7. Prohibition of pedestrians (on Interstate highways),
8. Improvements in driver regulations,
9. Installation of pedestrian refuge islands,
10. Use of reflectorized apparel for pedestrians,
11. Installation of special pedestrian signing and markings,
12. Widening of shoulders (in rural areas),
13. Installation of sidewalks,
14. Grade separation of crossings,
15. Construction of pedestrian malls,
16. Construction of playgrounds (in urban areas),
17. Conducting of pedestrian education programs, and
18. Increased enforcement of pedestrian and driver regulations.

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Analysis of Some Characteristics of Pedestrian Travel

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As serious attempts are made to alleviate the problem of congestion in the central business districts, it becomes apparent that knowledge of pedestrian travel behavior is very important. This paper describes a pedestrian travel survey for the central business district of Chicago and analyzes the results. The factors that affect trip-length distributions and time of travel are described; comparisons are made with other urban centers.

A downtown business area is viable only if it can absorb many people while minimizing conflicts among them: closeness without congestion. The typical central business district (CBD) today is highly congested, and proposals are being evaluated to alleviate this condition.

Pedestrians are a major component of the problem and the focus of recent proposals, but little is known about pedestrian travel behavior. Although mathematical models exist to predict vehicular travel, pedestrian travel has been ignored. Many of the latest suggestions for transportation in the CBD (moving walkways, personal rapid transit) compete with walking; if ridership for these alternatives is to be reliably predicted, better information on pedestrian travel must first be obtained and analyzed.

This paper analyzes a little-known but extensive survey of Chicago's CBD in 1963. These data represent the most comprehensive pedestrian travel survey yet done and provide significant insights into an area that has been little studied.

DATA COLLECTION

Characteristics of Chicago's Loop

The CBD of downtown Chicago, the Loop, is an intensely developed and congested area. The total number of person-vehicle trips to the CBD each day has remained at about 450 000 over the past 15 to 20 years. Of these daily trips to the Loop, 27 percent are made by rapid transit, 18 percent by suburban railroad, 26 percent by bus, and 29 percent by automobile (1).

Automobiles compete for about 19 000 parking spaces in the Loop, and the remaining vehicles must be parked in the fringe-area lots contiguous to the Loop or on the street. The number of people making walking trips to the Loop, i.e., trips solely by walking and involving no other mode, is not known. However, it is known that about 1 percent of the people employed in the Loop walk to work.

In 1965, employment in the Loop was estimated to be about 304 000 (2). In addition to being an employment center, Chicago's CBD is also a major retailing area with more than 1200 ground-floor businesses and 1 million m^2 (11 million ft^2) of retail floor space. By 1966, there were nearly 3.7 million m^2 (40 million ft^2) of total office space in the Loop. Actual and committed construction by 1971 increased the total by an additional 2.4 million m^2 (26 million ft^2) (3).

It seems curious, then, with this expansion of the base that the total number of person-vehicle trips has remained constant. There are three possible explanations. First, office space is used less intensively than retail and service space; therefore, increases in office-building space may be offset by decreased shopping activity. Second, new office space might be used at a less intensive level. Third, with the greater number of residences to the north of the Loop, more people may be walking or riding bicycles.

The Pedestrian Survey

The pedestrian survey was conducted by the Chicago Area Transportation Study (CATS) using 36 people from various city departments as interviewers (4, pp. 32-53). The survey was taken during the period from 7:00 a.m. to 7:00 p.m., with each interviewer collecting a predetermined number of interviews. These interviews were collected randomly along 98 stations consisting of one side of a street about three blocks in length for each hour in the time period.

The survey collected data for each station by hour, including the purpose of the trip, the direction of travel, and whether the respondent was coming from work. The

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interviewer also obtained addresses for the origin and destination of the trip. The total number of people interviewed was 11 632. The sample rates for each station were based on pedestrian volume counts done by regular traffic counters the previous year.

These sampling techniques produced a sample that was uniformly distributed across the Loop area; i.e., it included an approximately equal number of interviews at each station. This distribution has two beneficial effects from a statistical standpoint. First, it ensures that blocks with low volumes on the edge of the Loop are not ignored; i.e., if a uniform sample were taken, very few trips from low-volume areas would be sampled, thus producing a possible bias. Second, when the sample is expanded, there will be a tendency to equalize the percentage of standard error of expansion across blocks. That is, if one takes a certain sample percentage from a low-volume location and an equal percentage from a high-volume location and expands both, the expansion for the low-volume location will have a larger percentage of standard error than that for the high-volume location. If larger percentages in low-volume areas and smaller percentages in high-volume areas are surveyed, the expansions should have a smaller variance in the percentage of standard error than if a uniform sample were taken for the entire area (the problems in obtaining a uniform sample, should one want it, would be nearly insurmountable with sidewalk interviews in a location such as Chicago's Loop).

The expansion of the sample of pedestrian trips to represent the total number of such trips in the Loop area takes into account two factors: the sample rate and a correction for trip length.

The sample-rate expansion factor in this survey varies for each survey station. The sampling varied according to the volume of pedestrians at that particular station. The sample-rate expansion factor is simply the reciprocal of the sample rate; i.e., if 1 of every 200 people was questioned, the expansion factor would be 200. This factor was coded for each trip on the basis of its station location, hour of interview, and direction of travel.

A second factor is necessary because a random sample of pedestrians on sidewalks, as done by CATS, will not yield the proper distribution of trip lengths. Consider a trip of one block in length and another of two blocks; the two-block trip has twice the "life" and therefore (everything else being equal) twice the probability of being sampled. This means that the sample taken in the Loop contains an overrepresentation of long trips. Therefore, this sample must not only be multiplied by the sample-rate expansion factor but must also be adjusted for length bias.

To correct the trip-length bias, it is necessary to adjust the number of trips within a specified length range by their probability of being intercepted. The size of the length range depends on the data. Therefore, starting with the first length range, e.g., 0 to 91.4 m (0 to 300 ft), each successive range is then divided by its probability of being sampled relative to the first length range; e.g., 91.4 to 182.9 m (300 to 600 ft) is divided by 2, 182.9 to 274.3 m (600 to 900 ft) by 3, and so on. However, this technique alone would have the effect of reducing the number of trips in various length ranges and would therefore yield the proper distribution but not the correct total for each range. To keep the total the same, a constant must be included with each term, as shown in the following equation:

$$X_p = Y_{1p}C_p + (Y_{2p}C_p)/2 + (Y_{3p}C_p)/3 + \ldots + (Y_{np}C_p)/n \qquad (1)$$

where

X_p = total number of walking trips in the sample for purpose p;
$Y_{1,2,3,\ldots,np}$ = total number of trips sampled at length $L = 1, 2, 3, \ldots, n$ for purpose p; and
C_p = constant for purpose p.

If the trip-length intervals $1, 2, 3, \ldots, n$ are of equal length, Y_2 has twice the probability of being sampled as does Y_1, Y_3 has three times that of Y_1, and so forth. Dividing by the successive probabilities $1, 2, 3, \ldots, n$ ensures that trips are assigned their proper proportion. The constant (which is solved from the sample data for each purpose) is required so that the two sides of the equation remain equal.

Combining the sample-rate expansion factor and the length-correction factor gives the following final expansion:

$$T_{ijbtdp} = t_{ijbtdp} \times E_{btd} \times C_p/L_m \qquad (2)$$

where

T_{ijbtdp} = number of expanded trips from point i to point j derived from interviews in block b, during hour t, going in direction d, for purpose p;
t_{ijbtdp} = sampled trip from point i to point j derived from interview in block b, during hour t, going direction d, for purpose p;
E_{btd} = expansion factor for block b, time t_n, and direction d;
C_p = length-correction constant for purpose p; and
L_m = length range m of trip.

In the application of the above equation, trips were grouped into increments of 91.4 m (300 ft) so that the cell sizes of the length-increment groups to be expanded were large enough to maintain information about short trips. As the trip length approaches zero, the theoretical length-correction factor would approach infinity; clearly, small increments are to be avoided.

The technique described here for trip-length correction can generally be applied to any situation in which sampling is performed on a random basis from a process with a predictable variability in its life, length, time, and so forth. This method must be applied if a true distribution is to be obtained. Thus, the expansion technique developed here could be applied whenever travel data are collected by sampling trips in progress, such as in cordon or roadside-interview methods.

DATA ANALYSIS

Trip-Length Distribution by Purpose

The expanded trips total more than 2.6 million. Since about 450 000 person-vehicle trips have destinations in the Loop, that figure amounts to about 5.8 pedestrian trips for each vehicle-trip destination, or 3.8 trips other than those relating to vehicles. At first glance, this seems too high, and a critical look at the expansion follows. A pedestrian trip is defined as any walking trip made outside of a building. After each stop, a new pedestrian trip is begun. Thus, a lunch trip that includes a stop at a retail store and then a return to work would be counted as three separate pedestrian trips.

Figure 1 plots the trip-length distribution for the total expanded sample. Distance is a very important factor in describing a pedestrian trip. This figure represents the total pedestrian trips for the entire day (7:00 a.m. to 7:00 p.m.) and for all areas of the Loop (including trips with origins or destinations outside of the Loop itself).

The numbers and percentages for each trip purpose are shown below.

Purpose	Number	Percent
Work	581 646	22.2
Home	428 446	16.3
Shopping	372 938	14.3
Work-related business	475 256	18.7
Personal business	403 279	15.5
Social-recreation	281 531	10.7
School	76 173	2.3
Total	2 619 269	100.0

The work trips are the greatest, with the workplace forming the focal point of CBD pedestrian travel. This category includes the morning trip to work and also trips returning from lunch and so forth throughout the day. The work-related business trips and personal business trips together comprise 34.2 percent of the total; this percentage reflects the importance of the face-to-face communication that is often mentioned as a primary activity in the CBD.

The reliability of the data expanded by trip purpose can be assessed in several ways. In 1966, about 304 000 persons were employed in the Loop (3), and about 70 to 80 percent of office employees left their office buildings during midday for lunch (5). Therefore, about 528 000 pedestrians could be expected to go to work either from vehicular transportation terminals at the beginning of the workday or from lunch at midday. This number would be reduced by absenteeism and increased if workers made other trips during the day. Overall, the surveyed and expanded number of 582 000 in the table appears to be quite reasonable.

Trips home can be checked in a similar way. It is estimated that about 450 000 people leave the Loop each day; the table lists 428 000 home trips. These would be included in the 450 000, except for persons returning to hotels. However, home does not necessarily have to be the destination for a person leaving the Loop, so these figures are inconclusive. Tabulating the data another way gives 340 000 trips home for Loop workers, a number that is clearly too high since only about 304 000 people are employed there (and not all of those would be there on a given day). The employment figures given were for 1966 and, since the survey was taken in 1963 and employment has presumably grown (office space has), there were probably fewer employees in 1963, making this comparison somewhat worse. The possibility that the expansion of trips could be 10 to 15 percent too large should be considered and the results interpreted with that understanding. In the absence of better information, these numbers must tentatively be accepted.

The number of trips to school seems to be unreasonably large and should be viewed with suspicion. A check of the unexpanded data revealed that a small number of school trips in locations with high expansion factors make up a substantial portion of this total. Such a large expansion of only a few trips is likely to lead to error, and the value is probably much lower. Since school trips represent only a small percentage of total travel, the effect of this expansion was ignored.

The curve in Figure 1 assumes the familiar form of a vehicular trip-length distribution, i.e., only a few very short trips followed by a quick peak, reflecting either a lack of ability to survey very short trips, the possibility that destinations are so spaced that a minimum distance must be traveled to go from one to another, or the possibility that many short trips are captured within buildings. The median trip length for this curve is about 296 m (970 ft); a block in downtown Chicago is about 137 m (450 ft). Fewer than 1 percent of those interviewed were walking farther than 1.6 km (1 mile); the north-south length of the Loop is about 1.2 km (0.75 mile). Figure 2 shows the median trip lengths for various purposes. It demonstrates how short shopping trips (which include lunch trips) and social-recreation trips are, which reflects the compact nature of shopping areas; this effect is common and will be discussed later.

Trips home are the longest, perhaps because many of these are to parking lots and transit stations, some of which are on the periphery of the Loop. Work, work-related business, and personal business trips have very similar median lengths, probably reflecting the similarity in type of destination.

Trip-Length Distribution by Time of Day

Figure 3 plots the median trip length by time of day for all trips. Curiously, trips are relatively short very early in the morning and then gain in length from 8:00 to 10:00 a.m. as the majority of workers converge on the Loop. Early-morning trips may be shorter because of the greater availability of parking and taxis. The coffee-break trips at 11:00 a.m. and 2:00 p.m. are fairly short (perhaps because of the limited time available for them); midday (lunchtime) trips are somewhat longer. Toward evening, trips again gain in length, possibly reflecting the trip to the transportation terminals for home.

Distribution of Trips by Time of Day

Figure 4 shows total trips as they vary by time of day. This plot is characteristic of similar plots done for vehicular traffic that show pronounced peaking in the morning and evening with another peak at midday. The major difference is that the maximum peak occurs in the evening for vehicular traffic instead of at midday as shown here. The buildup of nonworkers, combined with the workers' lunch hour, produces the effect shown. The sharp peak during midday reflects the multiplicity of trips for Loop employees that are related to lunch, i.e., trips to the bank, recreation walks, and so on.

Loop Workers Versus Others

People who work in the Loop may have travel characteristics that are different from those who do not. To test this hypothesis, the sample was divided into these two classes, and each was analyzed separately. Figure 5 displays the median trip length for workers and for others by purpose. This figure shows the importance of trip purpose in the analysis. While the difference for total trips is not great, workers do have a tendency toward longer trips. This difference probably reflects the multiplicity of short shopping trips nonworkers might make and the dominance of the trips to work and to home for the worker. In addition, even though employees arrive early in the day, the parking rates for very convenient spaces are high in order to discourage long-term parking and to save space for shoppers. In this light, the difference between the groups may be influenced by other factors than behavioral considerations; i.e., the price structure of parking may create part of the response. Workers make about 68 percent of the trips to the Loop and 57 percent of the Loop pedestrian trips; therefore, workers on the average make fewer pedestrian trips than nonworkers.

Most worker-related trips are longer because the employment areas are spread over the entire Loop and have poorer access to transit than do shopping areas. Workers' social-recreation trips are shorter, reflecting the walk-after-lunch trip. Their personal business trips

Figure 1. Trip-length distribution, all purposes.

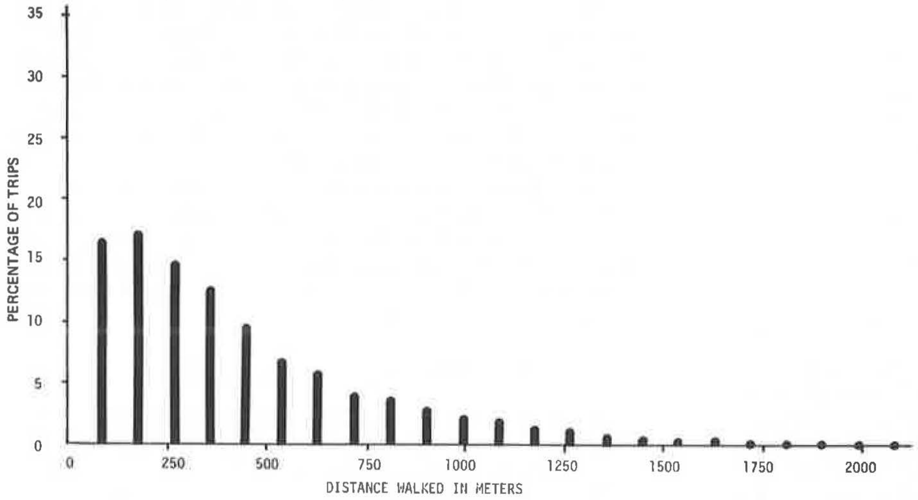


Figure 2. Median walking distance by purpose.

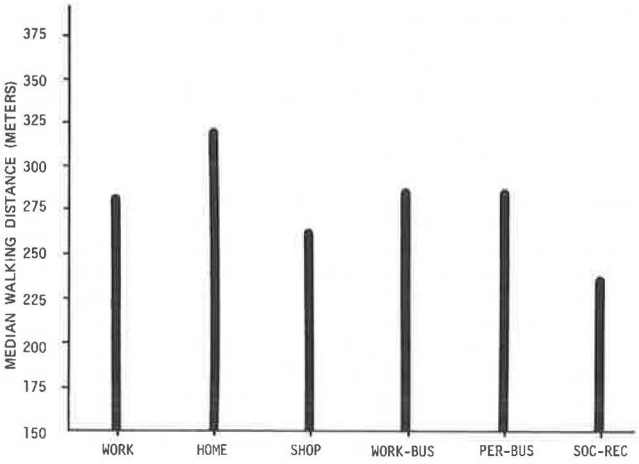


Figure 3. Median trip length by time of day, all purposes.

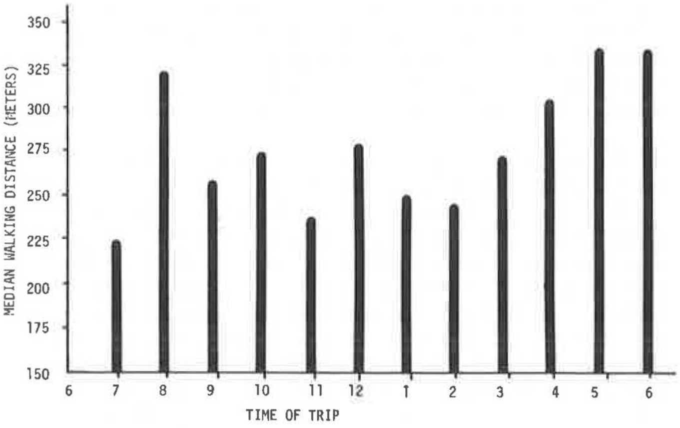


Figure 4. Number of trips by time of day, all purposes.

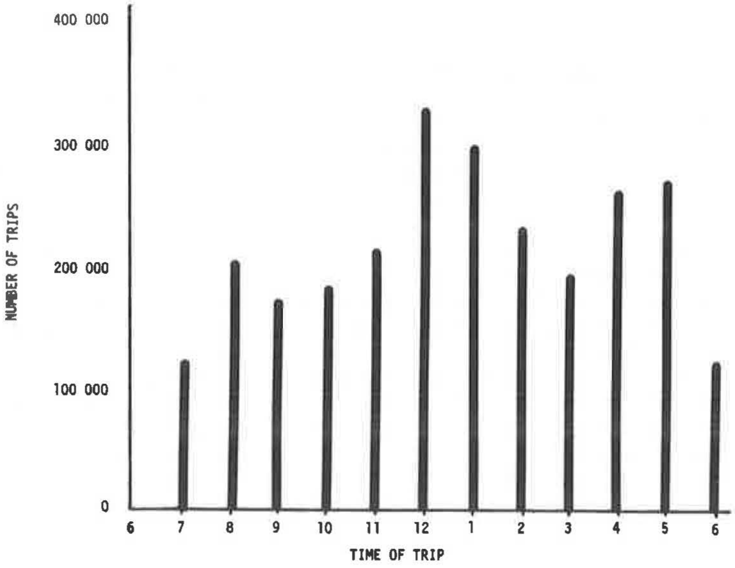


Figure 5. Median trip length by purpose for Loop employees and for others.

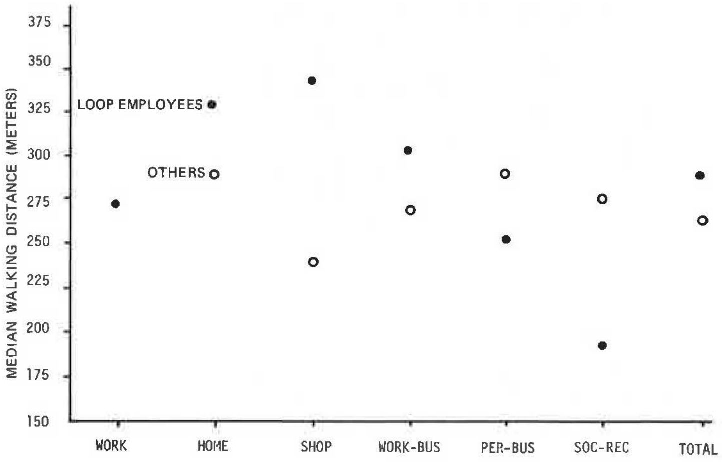


Figure 6. Percentage of trips by time of day for Loop employees and for others, all purposes.

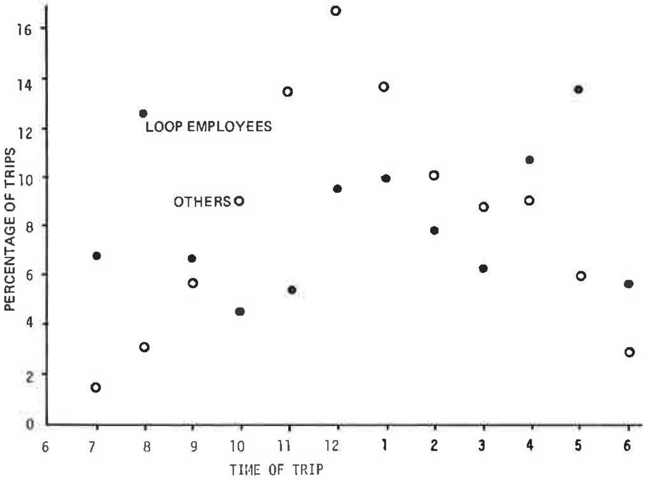
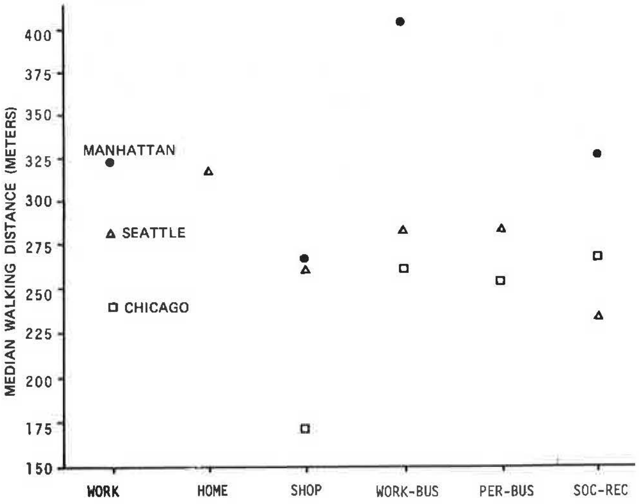


Figure 7. Median trip length by purpose for three cities.



are shorter, because the financial and government offices are in the same area as the offices where most of them work.

The difference in the generation of trips by time of day for workers and for others is shown in Figure 6. The Loop workers show peaks in the morning, at midday, and in the evening as one would expect. The nonworkers' trips build to a peak at midday, then appear to become far fewer, and generally disappear before the office rush hour at 4:00 to 6:00 p.m.

This analysis suggests that trip purpose is an important factor in describing the trip-length distribution and that, while differences between workers and nonworkers exist, the reason for much of this difference is the structure of the Loop; i.e., the transit facilities are near shopping, which promotes shorter trips.

COMPARISONS WITH PEDESTRIAN TRAVEL ELSEWHERE

The majority of pedestrian travel studies to date have dealt almost exclusively with egress from various transportation modes or terminals, usually parking facilities. Two studies have been done that are somewhat similar to the one analyzed here. One dealt with Seattle (6) and the other with Manhattan (7). Seattle is not nearly so dense as Chicago and has two downtown centers (one retail and one financial) separated by about nine blocks. Travel in Manhattan is unique.

Figure 7 compares the median trip length for Chicago, Seattle, and Manhattan by purpose. Trips in Manhattan for every purpose are longer. The numbers for Seattle are for building-to-building trips only. Since trips to parking facilities in Seattle are fairly short, these median lengths would be even lower if these trips were included. This indicates that trips in Seattle are generally shorter than those in Chicago.

In general, comparisons are very difficult to make, and any conclusions reached must be considered tentative. Until standard survey methods are developed, reliable comparisons cannot be made. One of the major dissimilarities is always the definition of trip purposes; standardization in this factor alone would make comparisons much easier.

CONCLUSION

The pedestrian exhibits travel characteristics that are very similar to and probably as predictable as those for travelers by other modes of transportation. We have outlined and analyzed several major aspects of pedestrian travel. We hope that insight gained from this article can be applied to planning in CBDs. This type of information is also required for the development of possible analytic models to predict future travel or probable response to new technologies. The information presented here was originally developed for use in a gravity-distribution model (4). This calibrated pedestrian distribution model was then used to test various assumptions about situations in which there was a choice between walking and riding a moving sidewalk.

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Factor Analysis of Pedestrian Accidents

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Factor analysis was used to investigate more than 1000 pedestrian accidents reported in Maryland from 1970 to 1973. The Maryland accident record system was searched to select 120 sections of roadway that were potentially hazardous to the pedestrian. Data collected at these study sites from field examinations and photologs were then combined with data obtained from the accident record system and subjected to factor analysis. The factors that contribute to making certain locations hazardous to pedestrians relate to traffic conflicts, road conditions, nighttime illumination, the physical condition of both the pedestrian and the driver, and the pedestrian's lack of regard for his own safety. The usefulness of factor analysis in identifying hazardous locations is illustrated with a hypothetical example.

One of the most urgent problems facing the traffic engineer today is how to provide safe and efficient pedestrian movement. The interaction between pedestrians and vehicles on or adjacent to roadways results in delay and a less orderly flow for both types of traffic. Past operational practices seem to have assigned a higher priority to keeping the vehicles moving, giving concomitantly less emphasis to the pedestrian. The feeling was that, if the flow of vehicles could be maintained, the pedestrian would somehow fit into the environment and make his own way. However, with increased volumes of vehicular and pedestrian traffic, conflicts between pedestrians and vehicles have increased and forced those concerned with the community, including the engineer, planner, politician, and psychologist, to consider or reconsider techniques to promote a safer mixing of modes.

Accident data presented by the National Safety Council (1) indicate that pedestrian injuries and fatalities tended to decrease between 1937 and 1961. This trend was reversed and pedestrian accidents increased from 1962 to 1972. Despite a 2 percent decrease in 1973, the 10 500 pedestrian fatalities in that year accounted for almost 19 percent of all highway fatalities. In comparison with nonpedestrian traffic fatalities, the percentage of pedestrian fatalities that occurred in urban areas was considerably higher (64 percent versus 25 percent). National statistics also indicate that more than 54 percent of the pedestrian fatalities occur at night. Of the 2.1 million traffic injuries reported each year, approximately 7 percent are received by pedestrians. In Maryland, of the more than 328 000 traffic accidents reported in a 4-year period (1970 to 1973), fewer than 2 percent (6268) involved pedestrians. These comparatively small percentages are misleading since injuries to pedestrians are generally more severe than those to occupants of vehicles.

A more realistic indication of the problem is given by the severity index, the ratio of fatal plus injury accidents to total accidents. In Maryland the severity index is 0.32 for all traffic accidents and 0.99 for pedestrian accidents. In other words, virtually all reported pedestrian accidents involve a fatality or an injury. Another indicator of the seriousness of pedestrian accidents is the fatality index, the ratio of fatal to total accidents. The fatality index for pedestrian accidents in Maryland is 0.083, approximately 10 times higher than the index for all other accidents. These characteristics are summarized in Table 1.

The objective of the research reported in this paper was to evaluate pedestrian accidents in order to develop effective countermeasures. The study procedure included the use of Maryland's accident record system to identify sections of roadway in Maryland that have conditions that were apparently hazardous to pedestrians. The statistical techniques of factor analysis were subsequently used to identify and investigate the factors that are associated with pedestrian accidents.

To aid in understanding the pedestrian problem and in determining the elements that contribute to pedestrian accidents, the data were dealt with in five categories: the driver, the environment, the pedestrian, the roadway, and the vehicle. A failure or breakdown within any of these five categories could contribute to a pedestrian accident. This pedestrian accident, described as a pedestrian-vehicle conflict, was defined as the actual accident resulting from a collision between one or more pedestrians and vehicles.

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*Mr. Dickinson was with the University of Maryland when this research was performed.

SELECTION OF STUDY SITES

Before collecting our data, we had to select study sites that were potentially hazardous to the pedestrian. Using three criteria, we determined these sites from the accident data contained in the Maryland Department of Transportation accident record tapes for the period 1970 to 1973. First, we identified sections of roadway that had a high number of recorded pedestrian accidents per kilometer of roadway type within each county and determined the countywide ratio of pedestrian accidents to total length of roadway of each type. Second, we looked for pedestrian accidents that clustered along certain routes, since in some instances there were recurring accidents at the same location, although the number of accidents per kilometer was not significant. Third, we looked for consistent identifying characteristics of pedestrian accidents on certain types or sections of roadway, e.g., midblock accidents, bus-stop-related accidents, accidents involved with turning.

Computer programs were written to identify on the record tapes accidents that involved pedestrians and to create, for each of the 4 years, tapes that contained only pedestrian accidents. The three criteria were then applied to the records on the shorter tapes to select the study sites. This process yielded a total of 120 sections of roadway selected for field examination. Although the study sites were located in 16 of Maryland's 23 counties, most of the study sites were in the more urbanized counties, which had higher frequencies of pedestrian and vehicle conflicts. The study sites are identified below according to type of roadway.

Type of Roadway	Percentage of Maryland Roadways	Number of Study Sites
Interstate	1.4	3
U.S.	3.6	24
State	17.7	77
County	69.2	16
Municipal	8.1	0
Total	100.0	120

COLLECTION OF DATA

To make certain that the maximum amount of data was obtained at each of the study sites, a pedestrian field survey form was developed and filled out for each of the 120 sections of roadway. An example of this form, showing the type of information collected, is presented in Figure 1.

Before the study sites were investigated in the field, we located each accident site by using a listing that noted the milepost number for each accident. At the reported location of each pedestrian accident, we observed conditions that may have contributed to the conflicts. This information was used later in recommending remedial action or policy changes designed to improve the unsafe environment. The conditions we observed included improper use of shopping center entrances, driveway exiting problems, poor location of crosswalks and bus stops, restricted sight distance, extremely wide intersections, misuse of pedestrian crosswalks, poor or nonexistent sidewalks, and extremely poor maintenance. These conditions were recorded on the pedestrian field survey form and photographed for future reference.

After visiting about half of the accident sites, we concluded that filming the sections of roadway would be very useful since it would permit us to view and review the study sections on film, accident by accident. With the assistance of the Maryland Department of Transportation, we filmed approximately 483 km (300 miles) of roadway on one-directional photologs to capture the 101 study sections that were located on state and U.S. highways. Although the photologs posed several problems, they did provide the opportunity for a detailed examination of each accident location. The film presented the situation that would normally be observed through the driver's eye. It also permitted us to obtain measurements directly from each film frame.

FACTOR ANALYSIS

The data collected in this study were treated under three headings: general pedestrian accident characteristics within Maryland, pedestrian accident characteristics at the study site locations, and factor analysis of the pedestrian accident data. The analysis and results of the first two are presented in a separate report (2); the third is discussed here.

The primary emphasis in previous analyses of accident data has involved tabulations and cross tabulations of two or more variables. Although this type of analysis is necessary, it promotes the theory of a single cause of accidents. Studies have shown that there are many interrelated variables that contribute to accidents; summary statistics, annual reports, and tabulations indicate the scope of pedestrian accidents rather than provide an adequate description. Thus, there is a need to apply the methods of multivariate analysis that are congruent with a multiple-causation theory of accidents. Factor analysis, one of these techniques of multivariate analysis (3, 4), was used in this study. This statistical procedure has been used extensively in social science research (5, 6). Like any other statistical procedure, it is a valuable tool if used correctly.

The most significant virtue of the technique with respect to this work is its ability to explain the relationship among many variables. For example, if a predictor variable correlates with a criterion variable, factor analysis tells "why" the correlation exists, in terms of which factors account for the correlation. Thus, certain relationships are explained in terms of more basic concepts, which in turn help to explain the overall problem.

In this research, factor analysis was used to search for meaningful relationships among the many variables associated with pedestrian accident data. By determining the relationship between groups of variables and more basic factors, we can achieve a clearer understanding of the pedestrian problem. The greater insight into the problem provided by this technique can then be used to develop realistic types of countermeasures or remedial actions for reducing hazardous conditions and establishing a safer environment for the pedestrian.

Data on the pedestrian accidents at the study sites, together with information on the design and operating characteristics of the roadways, were analyzed by using the BMDO3M, a factor-analysis computer program (7). A detailed analysis was performed on the 243 pedestrian accidents that occurred during the 4-year period at the 26 study sites in Prince George's County, near Washington, D.C. Using data from the accident record system, we categorized 1090 pedestrian accidents at the 120 study sites according to five types of land use. The six classifications used and the number of variables analyzed for each are identified below.

Classification	Variables Analyzed
Prince George's County	23
Manufacturing-industrial land use	21
Shopping-business land use	22
Residential land use	22
School-recreational land use	20
Open country	22

Table 1. Selected Maryland accident statistics (excluding Baltimore City).

		Pedestrian Accidents							
		Total							
Year	All Traffic Accidents	Number	Percent	Fatal	Fatalities	Injury	Injuries	Severity Index[a]	Fatality Index[b]
1970	74 005	1366	1.8	114	116	1249	1288	1.00	0.083
1971	82 650	1584	1.9	136	138	1437	1512	0.99	0.086
1972	79 950	1603	2.0	139	139	1435	1513	0.98	0.087
1973	91 030	1715	1.9	132	132	1538	1588	0.97	0.077

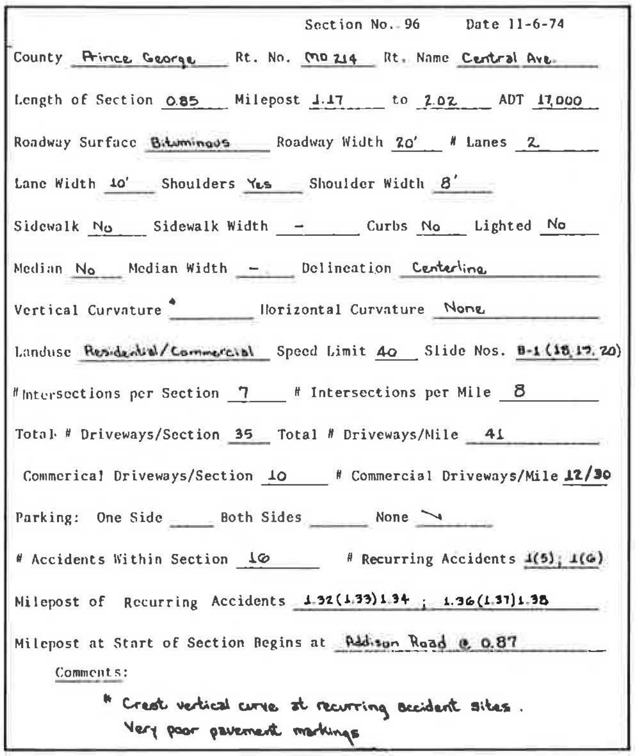
[a] (Fatal + injury accidents)/total pedestrian accidents.
[b] Fatal accidents/total pedestrian accidents.

Table 2. Variables and their values.

Number	Description	Value	Number	Description	Value
1	Lane width	Numerical	13	Good weather (versus bad)	Dichotomous
2	Number of lanes	Numerical	14	Daytime (versus night)	Dichotomous
3	Sidewalk width	Numerical	15	Weekend (versus weekday)	Dichotomous
4	Median width	Numerical	16	Summer (versus nonsummer)	Dichotomous
5	Speed limit	Numerical	17	Dry surface (versus not dry)	Dichotomous
6	Commercial driveways per kilometer	Numerical	18	Good road (versus bad)	Dichotomous
7	Residential driveways per kilometer	Numerical	19	Pedestrian normal (versus not normal)	Dichotomous
8	Intersections per kilometer	Numerical	20	Driver normal (versus not normal)	Dichotomous
9	Average daily traffic of vehicles	Numerical	21	Intersection (versus nonintersection)	Dichotomous
10	Parking (versus no parking)	Dichotomous	22	Peak period (versus off-peak)	Dichotomous
11	Average daily traffic of pedestrians	Numerical	23	Accident score[a]	Numerical
12	Shoulder width	Numerical			

[a] Accident score: 3 = fatal, 2 = injury, 1 = property damage only.

Figure 1. Pedestrian field survey form.



Section No. 96 Date 11-6-74
County Prince George Rt. No. MD 214 Rt. Name Central Ave.
Length of Section 0.85 Milepost 1.17 to 2.02 ADT 17,000
Roadway Surface Bituminous Roadway Width 20' # Lanes 2
Lane Width 10' Shoulders Yes Shoulder Width 8'
Sidewalk No Sidewalk Width – Curbs No Lighted No
Median No Median Width – Delineation Centerline
Vertical Curvature * Horizontal Curvature None
Landuse Residential/Commercial Speed Limit 40 Slide Nos. B-1 (18, 17, 20)
Intersections per Section 7 # Intersections per Mile 8
Total # Driveways/Section 35 Total # Driveways/Mile 41
Commerical Driveways/Section 10 # Commercial Driveways/Mile 12/30
Parking: One Side ____ Both Sides ____ None ✓
Accidents Within Section 16 # Recurring Accidents 1(5); 1(6)
Milepost of Recurring Accidents 1.32(1.33)1.34 ; 1.36(1.37)1.38
Milepost at Start of Section Begins at Addison Road @ 0.87
Comments:
* Crest vertical curve at recurring accident sites.
Very poor pavement markings

Factor analysis was applied separately to each of the categories.

The variables used in the investigation were obtained from both the coded accident records and the field studies. Approximately half of the variables had numerical values, while the remainder were dichotomous. The use of dichotomous values was dictated by the nature of some of the variables, which had to be coded as 0 for a favorable condition or 1 for an unfavorable condition. Previous research (5, 8) has used this dichotomous structure to increase the sensitivity of factor-analysis programs in detecting variations within the data. The variables that were analyzed are shown in Table 2.

The initial factor analysis was conducted by using data for the study sites in Prince George's County. This was the only area in which information was available for variable 11, pedestrian average daily traffic (ADT). This variable was important because, as volumes of pedestrian and vehicular traffic increase, the potential for accidents also increases. With assistance from county personnel, the pedestrian ADT was obtained for each of the 26 study sites within Prince George's County.

The correlation matrix for the 23 variables, which is used as input to the factor-analysis program, is shown in Table 3. The coefficients appear reasonable in both sign and magnitude. For example, variable 2, number of lanes, is positively correlated with variable 9, vehicle ADT, and negatively correlated with variable 7, residential driveways per kilometer. These correlations suggest that the accidents occurred on roadways that have good design features. These facilities are characterized by higher vehicular speeds, greater volumes of traffic, and lower numbers of residential driveways. Variable 11, pedestrian ADT, is positively correlated with variable 3, sidewalk width, and negatively correlated with variable 5, speed limit. Not surprisingly, variable 13, good weather (versus bad), is highly correlated with variable 17, dry surface (versus not dry). Variable 19, pedestrian normal (versus not normal), is not significantly correlated with any of the remaining variables.

Factor Matrix

The correlation coefficients shown in Table 3 were used to develop a factor matrix. This matrix shows the correlation between each of the 23 variables and the developed factors, which were selected by the computer program in a stepwise manner, depending on the amount of variance between variables that is explained. For example, the first factor selected would explain the maximum variance between each of the variables, while the second factor, orthogonal to the first, would explain the largest possible amount of the remaining variance. Each factor has an eigenvalue, which is the sum of the variance of each variable explained by a factor. The process continues until all the variance is explained. At this point the number of independent factors equals the original number of variables.

Interpretation of a matrix this size is difficult because of the number of elements. To simplify the interpretation, eigenvectors that explain an insignificant amount of variation can be eliminated. In addition, it is often worthwhile to rotate the remaining factors to ensure a more meaningful interpretation. Since a certain amount of explained variation for each variable is lost by elimination of some of the factors, rules have been established for determining which factors should be selected for rotation (3, 9, 10). The rotated factor matrix for the pedestrian accident data is presented in Table 4, which shows the coefficients of correlation between each variable and factor. These coefficients are also referred to as factor loadings. Although it is not shown in the table, the total variance of each variable (communality) remains constant during rotation of the factor matrix.

Describing the Factors

The traffic engineering interpretation of the rotated factor matrix can best be illustrated through an example. Factor I has the highest eigenvalue. The loadings on this factor varied from +0.88 to -0.75. The larger positive loadings indicate that certain variables were highly positively correlated with factor I; i.e., the accident locations were characterized by wider shoulders, medians, and lanes and by higher speed limits. Several variables exhibit a strong negative association with the accident data, indicating that the locations were characterized by infrequent occurrence of intersections and commercial driveways, limited availability of sidewalks, and low volumes of pedestrian traffic. Table 4 also indicates that there was little correlation between factor I and the remaining variables.

The variables that were negatively correlated with factor I provide as much information about the accidents as those that were positively correlated. The finding that certain variables (11, pedestrian ADT; 6, commercial driveways per kilometer; 3, sidewalk width; and 8, intersections per kilometer) were negatively correlated with this factor suggests that these accidents occurred away from urban or built-up areas. This is supported by the finding that other variables (12, shoulder width; 5, speed limit; and, to a lesser degree, 4, median width; and 9, vehicle ADT) were positively correlated with factor I. In view of these conditions, the factor was described as open roadway without pedestrian facilities (a description not unique to us), primarily on the basis of the factor loadings. The loading of the accident score also indicates the existence of more severe injuries among these accidents, which would occur in the more open suburban areas with lower traffic volumes and a lesser number of points of interference between the pedestrian and vehicle.

A similar approach was followed in characterizing and identifying the nine remaining factors. Although the second factor also refers to features of the roadway, this factor is characterized by multilanes, wider medians, higher speed limits, and higher vehicle ADT. It is also characterized by a negative loading on variable 7, residential driveways per kilometer. Factor II was thus described as pedestrian-restricted high-speed roadway.

The third factor clearly refers to the weather at the time the accident occurred (note the extremely high loadings found on variables 13 and 17). Factor III was referred to as weather.

The fourth factor is characterized by higher loadings on variables 14, daytime (versus night), and 22, peak periods (versus off peak), which is consistent with the correlation found between those two variables (Table 3). Factor IV was therefore described as traffic density. For this factor, the accident score had a loading of 0.30, reflecting a greater severity of injury during peak periods.

Factor V had unusual factor loadings. Its negative association with medians (variable 4), as well as a high correlation with parking (variable 10) and somewhat smaller loading for weekend accidents (variable 15), seemed to relate this factor to a restricted or impeded area, such as a vehicle terminal area. The lack of peak-period accidents and the positive loading for pedestrian ADT strengthen this association. Therefore, factor V was described as roadway impedance (friction).

The sixth factor was associated with a high positive loading on lane width (variable 1) and smaller positive loadings on both pedestrian ADT (variable 11) and the condition of the pedestrian (variable 19), which indicate association with some type of crossing. The negative loading on variable 8 (intersections per kilometer) suggests that these crossings occurred away from intersections. With this in mind, factor VI was described as pedestrian crossing.

The seventh factor clearly represents the alcohol problem. This interpretation is a result of the negative loading of variable 19 and the high positive correlation of variable 20. Factor VII was described as the drinking pedestrian.

The eighth factor presented a problem in interpretation. It was associated with nighttime accidents that occurred during nonsummer months (variables 14 and 16) and showed a tendency for the presence of residential driveways and the absence of commercial driveways (variables 7 and 6). Analysis of the correlation matrix (Table 3) substantiated the description of factor VIII as season.

Factor IX was associated with a high loading on variable 18, good road (versus bad), apparently indicating that these accidents largely occurred on good pavement surfaces. The factor loading for variable 15 also showed a higher occurrence of weekend than weekday accidents. Neither the factor matrix nor the correlation matrix assisted in establishing the exact nature of this factor. The most reasonable description of factor IX was road condition.

Factor X had the lowest eigenvalue above the selected base of 1.0 and was the most difficult to describe. The three most notable characteristics were the positive loading for commercial driveways per kilometer (variable 16), the high positive loading for intersection versus nonintersection (variable 21), and the negative loading for pedestrian ADT (variable 11). The first two reflect the merging, diverging, and crossing of traffic streams. Assigning major importance to these two variables, we described factor X as potential conflict points.

Approximately 75 percent of the variance among the original 23 variables was explained by these 10 independent factors.

Factor	Description
I	Open roadway without pedestrian facilities
II	Pedestrian-restricted high-speed roadway
III	Weather
IV	Traffic density
V	Roadway impedance (friction)
VI	Pedestrian crossing
VII	Drinking pedestrian
VIII	Season
IX	Road condition
X	Potential conflict points

Although some of them were easily described, several factors, especially those with low eigenvalues, were difficult to describe because they contained few variables

Table 3. Correlation coefficients for variables.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	1.00																						
2	0.33	1.00																					
3	-0.32	0.08	1.00																				
4	0.24	0.28	-0.26	1.00																			
5	0.16	0.49	-0.47	0.24	1.00																		
6	-0.07	0.30	0.19	-0.19	-0.11	1.00																	
7	0.01	-0.60	0.02	-0.27	-0.47	-0.45	1.00																
8	-0.36	-0.04	0.49	-0.29	-0.55	0.44	0.04	1.00															
9	0.19	0.70	-0.10	0.53	0.68	-0.02	-0.54	-0.26	1.00														
10	0.30	0.32	-0.22	-0.29	0.38	-0.02	-0.18	-0.06	0.18	1.00													
11	0.05	0.16	0.32	-0.27	-0.39	0.20	-0.01	0.19	-0.19	0.14	1.00												
12	0.19	0.23	-0.56	0.39	0.52	-0.50	0.05	-0.60	0.34	0.04	-0.40	1.00											
13	0.15	0.05	-0.11	-0.06	0.11	-0.05	-0.01	-0.21	0.02	0.15	0.04	0.06	1.00										
14	-0.02	0.04	0.04	-0.01	0.09	0.05	-0.11	-0.01	0.08	-0.03	—	—	0.10	1.00									
15	0.15	0.10	-0.05	-0.13	0.11	0.03	-0.07	-0.01	0.12	0.23	0.05	0.04	0.06	-0.03	1.00								
16	-0.01	0.02	0.01	-0.04	0.03	0.09	-0.11	-0.02	0.01	-0.06	0.06	-0.05	0.01	0.18	-0.04	1.00							
17	0.17	0.07	-0.15	-0.04	0.13	-0.05	0.01	-0.23	0.05	0.13	—	0.08	0.87	0.09	0.08	0.01	1.00						
18	0.04	0.02	0.05	-0.05	-0.03	0.04	0.04	-0.02	0.05	0.07	0.01	0.02	0.10	-0.02	0.08	-0.05	0.12	1.00					
19	0.10	0.02	-0.02	0.08	0.02	0.09	-0.12	-0.04	-0.02	-0.07	0.07	0.01	-0.05	0.20	-0.03	0.09	-0.01	-0.09	1.00				
20	—	—	0.11	-0.03	-0.08	-0.07	0.05	0.12	-0.02	-0.01	0.10	-0.08	-0.01	0.16	0.06	0.03	-0.02	-0.03	-0.08	1.00			
21	0.03	0.06	-0.15	0.07	0.17	0.05	-0.03	-0.12	0.13	-0.03	-0.27	0.14	-0.12	0.07	-0.03	-0.03	-0.04	0.03	-0.01	—	1.00		
22	-0.04	0.02	0.07	0.03	—	0.03	-0.04	0.02	0.03	-0.06	0.04	-0.05	0.03	0.47	-0.10	-0.05	0.02	-0.08	0.17	0.01	0.04	1.00	
23	0.07	0.02	0.09	-0.09	0.11	-0.13	-0.06	-0.13	0.14	0.01	0.01	0.13	—	0.10	0.07	-0.01	-0.02	0.05	0.08	0.06	-0.01	0.10	1.00

Note: A dash in the matrix denotes zero correlation.

Table 4. Rotated factor matrix.

	Factor									
Variable	I	II	III	IV	V	VI	VII	VIII	IX	X
1	0.23	0.12	0.11	-0.05	0.13	0.85	0.04	0.04	0.02	0.05
2	-0.20	0.86	0.06	-0.02	0.12	0.31	0.06	0.07	-0.02	0.01
3	-0.07	—	-0.06	0.05	-0.18	-0.20	0.19	0.08	0.10	-0.20
4	0.38	0.46	-0.09	-0.04	-0.63	0.24	0.06	0.08	0.04	-0.01
5	0.61	0.63	0.07	0.07	0.29	-0.12	-0.07	-0.04	-0.06	0.13
6	-0.65	0.30	—	0.02	0.09	—	-0.32	-0.22	—	0.26
7	0.11	-0.82	0.02	-0.08	-0.05	0.09	0.19	0.20	0.02	-0.01
8	-0.75	-0.11	-0.19	—	0.02	-0.24	0.05	0.03	-0.02	0.01
9	0.29	0.86	-0.01	0.02	-0.04	0.02	0.11	0.08	0.11	0.02
10	0.09	0.20	0.10	-0.03	0.82	0.18	—	0.14	-0.11	-0.02
11	-0.52	-0.06	0.03	0.04	0.18	0.37	0.07	-0.04	—	-0.44
12	0.88	0.03	—	-0.01	-0.06	-0.02	-0.01	0.02	0.08	0.05
13	0.08	0.01	0.94	0.05	0.06	0.03	—	-0.01	0.03	-0.10
14	-0.01	0.06	0.11	0.79	0.01	-0.05	0.17	-0.22	0.02	0.11
15	0.04	0.08	-0.02	-0.08	0.53	0.07	0.10	-0.06	0.34	-0.05
16	-0.01	-0.04	0.03	—	-0.03	-0.02	0.07	-0.90	-0.05	-0.03
17	0.10	0.02	0.94	0.05	0.04	0.07	-0.02	-0.02	0.06	-0.01
18	-0.09	-0.01	0.18	-0.14	0.03	0.01	-0.05	0.08	0.80	0.19
19	—	-0.01	-0.13	0.43	-0.11	0.36	-0.44	-0.28	0.02	-0.10
20	-0.10	-0.03	-0.04	0.13	0.03	0.07	0.85	-0.12	—	0.02
21	0.12	0.05	-0.12	0.11	-0.02	0.06	0.05	0.03	0.09	0.83
22	-0.06	0.02	0.04	0.82	-0.07	-0.02	-0.03	0.23	-0.09	0.01
23	0.24	0.09	-0.17	0.30	0.06	—	0.06	-0.02	0.51	-0.37

Note: A dash in the matrix denotes a zero factor loading.

Table 5. Specific values and factors selected for hypothetical location.

Variable	Value	Factor Selected	Variable	Value	Factor Selected
1	3.7 m	I, VI	13	0	III
2	6	II, VI	14	1	VIII
3	—	V, VI, X	15	0	V, IX
4	6.1 m	I, II, VI	16	1	VIII
5	88.5 km/h	I, II, V	17	0	III
6	—	I, VII	18	0	IX
7	—	II	19	0	IV, VI
8	1.9	I, III, VI	20	0	VII
9	30 000	I, II	21	0	X
10	1	IX	22	1	I, V, IX
11	25	I, X	23	3	I, IV, IX
12	3.1 m	I			

Note: 1 m = 3.3 ft; 1 km = 0.6 mile; variables 10 and 13-22 are dichotomous.

with high loadings. The absence of more definitive information made their description less meaningful.

The factor-analysis techniques were subsequently applied to pedestrian accident data for all 120 study sites classified by land use. Information on pedestrian ADT was not available for study sites outside of Prince George's County, so this variable was not included in the analysis. The findings of this analysis are presented in a separate report (2).

Using the data from the 26 study sites in Prince George's County, we found that wider shoulders, higher speed limits, wider medians, greater numbers of lanes, and higher vehicle ADT characterized accident locations in nonurban areas. The absence of sidewalks, residential driveways, commercial driveways, intersections, and pedestrians substantiated these interpretations.

To apply these findings to subsequent accident investigations, one must consider both the factors and their associated variables. For example, two related areas of concern, based on recorded accident data, were factor I, open roadway without pedestrian facilities, and factor II, pedestrian-restricted high-speed roadway. The analysis showed that both factors were negatively correlated with pedestrian ADT. For a pedestrian accident to occur, however, a pedestrian must have been present. Since specific accidents lose their identity in the factor-analysis process, it was not possible to determine whether the accidents associated with factors I and II occurred on controlled-access roadways. If they did, stricter enforcement is required to keep pedestrians off these roadways. If they occurred on other roadways, better pedestrian safety education programs, coupled with engineering countermeasures, may be warranted.

As we expected, variables that have direct application to engineering solutions clustered around factors I and II. The lack of engineering-related problems may also suggest that other variables should be included in future investigations. If the factor analysis reflected a clustering of variables concerned with horizontal or vertical curvature around a particular factor, this might indicate that locations with poor sight distance contribute to the occurrence of pedestrian accidents. Further investigation could be made at such locations and, if necessary, countermeasures developed and implemented that could be as minor as removing excessive foliage or shrubbery, restricting pedestrian movement, or providing advance warning to motorists or as major as a complete redesign and construction.

Factors characterized by variables related to the environment or human behavior demonstrate the need for other types of action to provide for a safer pedestrian environment. Cases in which either the pedestrian or the driver was not in normal condition and that also exhibit positive correlation with such other variables as daytime (versus night) and summer (versus nonsummer), as in factor VIII, indicate a need for nonengineering forms of remedial action. These might involve more stringent enforcement of the law concerning both the drinking driver and the drinking pedestrian, as well as safety education programs.

Factor analysis identifies the variables that are associated through many incidents. An examination of these variables leads to the interpretation of a particular problem area. By investigating these problem areas, it is possible to determine which variables in the field should be considered in developing adequate solutions. Taking this process one step further, factor analysis can be used for improving specific locations. For example, assume that recorded accident data indicate that a particular location in Prince George's County is potentially hazardous. The information presented in this study could then be used to determine what the problems are and what effort can best be made to solve them. By using the 10 factors developed from the Prince George's County factor analysis, it may be possible to categorize this particular location under one or more of these factors. Engineering personnel could then select the variables that were highly correlated with this interpreted factor, and these variables would warrant special consideration in planning improvements for the specific area.

Applying the Factor Analysis

A simplified scheme for applying the findings of this research would initially consider the values of the 23 original variables. The average values (both numerical and dichotomous) of these variables would be compared with those at the specific location under consideration. Table 5 presents values for a hypothetical location. The lane width at this location is 3.7 m (12 ft). Since the average lane width for the accident data was 3.4 m (11.2 ft), a factor from Table 4 would be selected that had a high loading on variable 1. Factors I and VI fit this criterion for selection. The number of lanes at the specific location (6) is also larger than the average for the accident data (4.6). Again, we select a factor that has a high loading on variable 2. This criterion is met by factors II and VI. The third line in Table 5 shows that there is no sidewalk at our hypothetical location. Factors V, VI, and X have high negative loading on variable 3, indicating the negative association between pedestrian accidents and sidewalks. This same process is continued for the remaining 20 variables (average values for Prince George's County data for the numerical variables: 4 = 3.5 m, 5 = 56.3 km/h, 6 = 17.5, 7 = 11.1, 8 = 8.1, 9 = 26 730, 11 = 460, 12 = 0.6 m, 23 = 2.05), including the dichotomous variables. For example, since the value for variable 22 shows that the accidents occurred during the off-peak periods, we select factors I, V, and IX, which have negative loadings for this condition.

Table 5 identifies the factors selected for each of the 23 variables. The selection frequency for each factor is then determined. In this example, factor I was selected 10 out of the 23 times and factor VI was selected 6 times. The remaining factors were each chosen less frequently. Since all of the variables have equal weighting, the specific location would then be classified under factor I, open roadway without pedestrian facilities. Table 4 should be reexamined, considering the variables that were highly loaded on factor I, to determine their relevance to the specific location. The appropriate variables can then be used to develop countermeasures for reducing hazards to pedestrians.

CONCLUSIONS

This study determined that there were many factors that make certain locations hazardous for pedestrians. Most of these unsafe conditions were related to areas of traffic conflicts, nighttime illumination, and intoxicated pedestrians and drivers. Even though implementation of the recommended countermeasures would help create a safer pedestrian environment, a stricter observance of existing controls is an integral part of this safer system. A characteristic common to many of the accidents was the pedestrian's lack of attention to his own safety, as reflected by the fact that nearly 80 percent of the reported accidents cited the pedestrian as the cause. The pedestrian's attitudes must be altered so that the maximum benefit can be obtained from engineering. The forms of remedial action that the engineer can implement on a large scale can only ameliorate, rather than solve, the problem of pedestrian accidents.

The factor analysis used in this research was shown to be a useful method for studying the problem of pedestrian accidents. The solutions developed in the original study (2) were based on the results of factor analysis along with a knowledge of traffic conditions at the locations. Because factor analysis lies somewhere between a science and an art, different researchers may interpret the results differently. Therefore, it is not appropriate to develop solutions to the problem of pedestrian accidents by using statistical techniques alone. Traffic engineering continues to play an important element in the planning and implementation of remedial action for the specific conditions surrounding hazardous locations. The use of factor analysis simply directs the engineer's attention to the combinations of roadway conditions that are most closely associated with pedestrian accidents.

To increase the effectiveness of factor analysis, especially in this area, which is closely involved with individual behavior, it is recommended that future research include variables that are concerned with the human factors. Analyzing this type of data might assist in explaining the factions of pedestrians who are involved in accidents. An examination of the human element would be beneficial not only in research but also in the interpretation of accidents that involve a drinking pedestrian or driver.

Further research should also include a comparable number of variables from each of the five elements involved in pedestrian accidents—the driver, the environment, the pedestrian, the roadway, and the vehicle. In this study, 14 of the 23 variables that were investigated pertained to the roadway. Future analysis should consider reducing the number of roadway variables and increasing those for the four remaining areas. The analyst should thus be in a better position to develop broad-based but workable methods of promoting pedestrian safety.

The potential for using the techniques of factor analysis to develop hazard indexes warrants further attention.

This research investigated only those locations with unusually high occurrences of pedestrian accidents. Future research should also examine locations that were not found to be hazardous. In this way the characteristics of both safe and unsafe locations could be analyzed and compared, so that indexes could be established to determine the relative hazard to pedestrians at different locations. These indexes could then be used to formulate a priority listing of unsafe locations so that corrective measures can be taken to alleviate hazardous pedestrian conditions.

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Abridgment

Simulation of the Effect of Pedestrians on Vehicle Delay at Signalized Intersections

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The vehicle capacity of signalized roadway intersections is dependent on the sequence and timing of several elements that are characteristic of intersections, including pedestrian and vehicle movement. The number of pedestrians and vehicles that jointly use the intersections of many urban roadways is constantly increasing. The pedestrian-vehicle conflict at intersections is becoming a more and more important contributor to vehicle delay and reduction of the capacity of intersections. Unfortunately, many of the methods currently used to calculate the capacity of intersections give little consideration to the effect that pedestrians have on vehicle delay and the capacity of intersections.

The purpose of this study was to determine, through simulation, the effects of pedestrian movement on the flow of vehicles at signalized at-grade intersections. Specifically, the objectives of this study were to develop and validate a computer simulation model to quantify the effects of pedestrian movement on vehicle delay and to suggest possible criteria for the inclusion of a separate pedestrian phase in signal cycles as a method of reducing the delay to vehicles caused by pedestrians.

Three measures of vehicle delay at intersections were computed by the simulation model: the average length of the vehicle queue, the average time the vehicles spend in queue, and the number of vehicles passing through the intersection. These three delay measures were considered to be functionally related to volumes of pedestrian traffic, pedestrian crossing behavior (three types), volumes of vehicle traffic, length of signal cycles, and percentage of turning vehicles.

Because a large number of independent variables were used in the simulation model, the simulation experiments concentrated on two typical categories of intersection operation, ideal and undesirable. The ideal intersection operations had a short signal cycle, a small percentage of turning vehicles, and few illegal pedestrian movements. The undesirable intersection operations had a long signal cycle, a high percentage of turning vehicles, and many illegal pedestrian movements. Both types were two-way, two-lane by four-lane intersections. Simulation runs for each of the two types were used to illustrate the sensitivity of vehicle delay to varying volumes of pedestrian and vehicle traffic.

SIMULATION MODEL

Numerous simulation programs have already been written, but very few consider, let alone incorporate, any form of pedestrian movement. The literature, however, provides a basis for building a simulation model in terms of such previously investigated components as rate of flow of pedestrian traffic, pedestrian gap acceptance, and vehicle arrival rates (1).

For the purposes of this study we developed a detailed simulation program capable of handling the movement of both pedestrians and vehicles at signalized intersections. The model used the problem- and time-oriented general purpose simulation system (GPSS) language and was constructed to tabulate data on all pedestrian-vehicle interactions encountered during the simulation of activity at a two-lane by four-lane signalized intersection (1).

This model was designed to facilitate the input of data. It is quite flexible, partly because of the computer language used in the handling of the five major variables mentioned earlier (volume of pedestrian traffic, volume of vehicle traffic, length of signal cycle, percentage of turning vehicles, and pedestrian crossing behaviors). Any number of these can be held constant or be allowed to vary according to the characteristics of intersections that are to be studied. In this manner, the model can be used to simulate intersections with problems peculiar to traffic flow that cannot be analyzed by conventional methods. The model, therefore, need not be restricted solely to analyzing and quantifying pedestrian-caused vehicle delay.

RESULTS OF THE SIMULATION

Because of the large number of independent variables incorporated in the model, all but two were held constant during the simulation of the ideal and undesirable intersection operations. Only the volumes of pedestrian and vehicle traffic were allowed to vary from one simula-

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tion to another. In general, it was expected that vehicle delay at intersections would increase with an increase in pedestrian or vehicle traffic. The ideal intersection operations were also expected to produce less vehicle delay than the undesirable intersection operations, the characteristics of which were less conducive to smooth pedestrian and vehicle flow.

The volumes of pedestrian and vehicle traffic were varied so as to comprehensively cover a range from no pedestrians and little vehicle traffic to many pedestrians and a high level of vehicle traffic (1).

Pedestrian-caused delay was calculated as the difference between the delay value of the simulation run with no pedestrians and the delay value for a given volume of pedestrian flow.

Results of the simulation runs showed that pedestrian-caused vehicle delay increased steadily until a volume of 300 pedestrians per hour per direction was reached. Between this volume and a volume of 470 pedestrians per hour per direction, there was a sharp increase in vehicle delay. Higher volumes of pedestrian traffic continued to increase the delay, but at a lesser rate (1).

The effects on the undesirable intersection operations compared with those on the ideal operations were as expected. If similar volumes of pedestrian and vehicle traffic were used, the average vehicle delay was greater for the undesirable intersection operations than for the ideal operations.

USE OF PEDESTRIAN SIGNALS

The addition of a pedestrian phase to a traffic signal at an intersection not only provides for safer pedestrian movement, but in some cases also reduces the delay to vehicles using the intersection. Separate pedestrian phases added to fixed-time traffic signals must be of sufficient length to allow pedestrians to make a safe crossing. The inclusion of this phase into the signal cycle ensures that pedestrians will not have to wait longer than one signal sycle before being able to cross the intersection. At the same time, however, unwarranted pedestrian phases in fixed-time signals can unfairly increase the total delay to vehicles at the intersection.

For greatest safety, the minimum pedestrian-caused vehicle delay cited to warrant the use of a pedestrian signal phase should be less than the time required for a pedestrian to cross the intersection; this should decrease the possibility of accidents before the critical volumes of pedestrian and vehicle traffic are reached. A reduction factor applied to the minimum safe crossing time for pedestrians can be used to determine the minimum vehicle delay to warrant the use of pedestrian signals at any particular intersection.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study, which are valid only for intersections that exhibit the same physical and operating characteristics as those simulated, are as follows:

1. Pedestrian-caused vehicle delays increased with an increase in the volumes of pedestrian or vehicle traffic.
2. In every case in which volumes of pedestrian and vehicle traffic were held constant, the undesirable intersection operations showed greater vehicle delay than the ideal intersection operations. Improving the operational characteristics of intersections can therefore reduce pedestrian-caused vehicle delay.
3. Intersection operations that exhibit pedestrian-caused vehicle delays longer than the time required for safe pedestrian crossings would benefit from the inclusion of a pedestrian phase in the signal cycle by reducing delay to vehicles and promoting safe pedestrian movement.

Specific recommendations for future research are as follows:

1. Research should be continued to develop models for pedestrian-caused vehicle delay at other types of intersections.
2. Reduction factors to determine the length of pedestrian-caused vehicle delays that warrant the use of pedestrian signals should be developed. The trade-off between vehicle delay and pedestrian safety must be considered.
3. Consideration should be given to the possibility of developing a set of capacity-reduction factors, based on the use of intersections by both pedestrians and vehicles, to be incorporated into the calculation of intersection capacity.
4. Experimentation with the simulation model should be continued in order to determine the effects on vehicle delay of other variables such as the percentage of turning vehicles and the length of the signal cycle.

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Model of Pedestrian Traffic on a College Campus

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This paper reports on a study that was undertaken to develop and evaluate models that could be used to forecast pedestrian circulation (1). In general the models developed were adaptations of those used in pedestrian planning (2). The study, which was exploratory, was undertaken at Montana State University (MSU). Recent construction on the MSU campus provided an opportunity to evaluate the accuracy of the forecasting procedures. The forecasting models were conceptualized, developed, and tested, but they were not operated in an actual planning context.

SOURCES OF THE DATA

An origin-destination (O-D) survey of 418 students (5.5 percent of the student body of approximately 7600) had been conducted in 1971 as part of a campus planning study. This survey asked students to report all the trips made on a single day that were to, within, or from the campus. The trips were described according to origin, destination, purpose at each end, time at each end, and mode of travel. The survey was conducted throughout the school year from September 1970 to May 1971.

To take maximum advantage of this 1971 survey, it was decided that the best method of calibrating and testing the models was to conduct another O-D survey in 1973 and to develop two independent sets of models, one for each school year. The predictive accuracy of each set could be assessed by exercising the models for one year on the data for the other year. Differences between the two sets of models could be identified and evaluated. Accordingly, an O-D survey was conducted for a 2-week period during the winter quarter of 1973. The design of the survey was similar to that conducted in 1971.

In addition to the O-D data, computerized inventories of campus facilities were obtained for each school year. Data on floor area, number of seats, and other building characteristics were extracted from these inventories.

The primary interest of the study was pedestrian circulation within the campus, but this included students who had walked from or were returning to areas off the campus and students who had parked in campus lots or on streets near the campus and were walking from or returning to their cars. It was decided to develop person-trip generation and distribution models for trips that had at least one end on campus. A proportional post-distribution modal split was used to account for walking trips to or from parking areas.

TRIP GENERATION

The O-D surveys showed that the average daily person-trip rate was comparable for each year. The rate for the winter quarter of 1971 was 7.75 trips per student; for the winter quarter of 1973 it was 7.83. A trip rate of 7.8 was considered adequate for purposes of forecasting. Trip ends were classified according to the type of zone (school or residential) rather than by purpose. This kept intact the small sampled volumes associated with each zone and retained some of the advantages of classifying trips by purpose since each zone was primarily associated with one purpose. The total volume of student trips, which was the product of the size of the student body and the trip rate, was split into trips ending in school zones and trips ending in residential zones.

In forecasting, the proportion of trips ending in each type of zone would be derived from predictions about aggregate changes in trip purposes. The survey data were examined to determine the relationship between changes in trip purpose and changes in the proportion of classified trip ends. Since the overall trip rate was equivalent for the 2 years, the changes in trip purposes indicated that, as students work more, a greater number of trips will be made to residential zones and a smaller number to school zones.

Once the total number of trips ending in school zones and in residential zones was obtained, models were developed to apportion the trips among individual zones. The trips ending at school were apportioned among the individual school buildings according to the characteristics

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*Mr. Ballas was at Montana State University when this research was performed.

of the buildings as described in the MSU inventory of facilities. The mathematical model used was

$$\frac{SV_i}{\sum_i SV_i} = B_0 + B_1 \frac{X_{1i}}{\sum_i X_{1i}} + B_2 \frac{X_{2i}}{\sum_i X_{2i}} + e \qquad (1)$$

where

SV_i = trips ending in school zone i,
X_{1i} = floor area at zone i,
X_{2i} = classroom seats at zone i,
B_0, B_1, B_2 = coefficients to be estimated, and
e = error.

The trips ending in residential zones were apportioned according to the number of students residing in each residential zone and whether the zone was on or off campus. The model was

$$\frac{RV_i}{\sum_i RV_i} = B_0 + B_1 \frac{X_{1i}}{\sum_i X_{1i}} + B_2 X_{2i} + e \qquad (2)$$

where

RV_i = trips ending in residential zone i;
X_{1i} = students residing in zone i;
X_{2i} = dummy variable, 1 if the ith zone is on campus, 0 otherwise;
B_0, B_1, B_2 = coefficients to be estimated; and
e = error.

The coefficients found to work best for each school year were virtually identical. The 1973 coefficients were adopted for the apportionment models for both trip ends since they worked as well with the 1971 data as with the 1973 data from which they were estimated.

TRIP DISTRIBUTION

Once the number of trip ends had been determined for each zone, a gravity distribution model was used to build trip tables. It was assumed that the impedance factors for the distribution model would have to be sensitive to class scheduling as well as travel time and that a special factor would be needed to represent this sensitivity. This factor was called the functional similarity (FS) factor and was an index of the degree to which two zones were used by students with the same academic majors. The FS factors were correlation coefficients computed on the basis of data from the O-D surveys.

Three models for impedance were developed, one for each of the three types of interchanges between the two types of trip ends: school-school (S-S), school-residential (S-R), and residential-residential (R-R). The model structure for each of these three types of interchanges was the same, but three sets of coefficients were estimated. The common model that was used was

$$IF_{ij} = B_{k0} + B_{k1} + FS_{ij} + \frac{B_{k2}}{TT_{ij}^{xk}} + e_k \qquad (3)$$

where

IF_{ij} = impedance factor for zones i and j, which combine into interchange type k;
FS_{ij} = functional similarity factor between zones i and j;
TT_{ij} = mean reported travel time between zones i and j, taken from the O-D surveys;
B_{k0}, B_{k1}, B_{k2} = coefficients to be estimated for interchanges of type k;
xk = parameter for linearization of travel time for interchange type k; and
e_k = error for interchange type k.

The coefficients were estimated from impedance factors obtained empirically by using a simplified gravity model with the sampled O-D tables. The form of this model, which was also used in trip distribution, was

$$PTV_{ij} = \frac{V_i V_j}{IF_{ij}} \qquad (4)$$

where

PTV_{ij} = two-way person-trip volume between zones i and j;
V_i, V_j = total person-trip volume at zone i, zone j; and
IF_{ij} = impedance factor for zones i and j, which combine into interchange type k.

Efforts to construct accurate models of the impedance factors by using a combination of the FS factor and the inverse exponential of reported travel time were generally unsuccessful if the trip included a residential zone. The FS factor was, by definition, most appropriate for S-S interchanges, and the simple correlations between the FS factors and the empirical impedance factors for S-S interchanges were the highest obtained throughout the effort to estimate impedance. But it was apparent that the FS factor was generally inappropriate for S-R and R-R interchanges.

Although the impedance factors were not accurately estimated in every case, it was decided to use them in the gravity model and to estimate the number of trips among the 18 zones in order to evaluate the utility of the work performed to date. The 18 zones that were used were those that were most active in terms of origins and destinations. When the gravity model was used, it accounted for 72 percent of the variance in the 1971 sample of volumes of traffic at the interchanges and 52 percent in the 1973 sample.

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Abridgment

Urban Play Streets: Creating and Operating Part-Time Traffic-Free Zones

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On weekdays during the summer, most inner-city residential streets are crowded with youngsters playing and dodging cars. Their parents are working and the kids on some blocks are using the local playground—the street.

Knoblauch (1) indicated that it is this same group of urban youngsters that is most represented in the pedestrian accident statistics. Blackman (2) indicated that the greatest danger to children comes from their undisciplined, incautious playful behavior near their homes. Backett (3) and Read (4) found that children who were victims of pedestrian accidents came from families with more maternal sickness, less maternal supervision, overcrowded homes, and areas with fewer play facilities than children in a similar group not involved in accidents.

Play streets carefully selected and approved by the residents can be very useful to the traffic engineer as one of a number of safety techniques to be considered for spot reductions of urban pedestrian accidents.

Gold (5), in his book Urban Recreation Planning, indicated that the basic need today is to make the planning process more responsive to the need for outdoor recreation in the inner-city neighborhood. Studies by the National League of Cities and a task force sponsored by the U.S. Department of Housing and Urban Development found that there was little communication between the inner-city resident and the urban recreation planner. These studies recommended that facilities should be geared to meet the needs of the specific neighborhood and community rather than the entire city.

Considerable time (usually years) elapses between the discovery of people's recreational desires and the opening of a new facility. Playgrounds and parks require land and are expensive to construct. The cost of urban land is normally staggering. For example, a plot of 930 m^2 (10 000 ft^2) can cost a million dollars or more, and the typical play street in New York provides more than 1580 m^2 (17 000 ft^2) of recreation area.

The residents of densely populated low-income areas (especially the young and the elderly) have few recreational opportunities since their travel is limited and they do not go to areas having more abundant facilities and opportunities. The play street seems to fill a gap in offering urban recreational opportunities. Each play street can be developed to meet the unique needs of the street population and to suit the local topography.

WHAT IS A PLAY STREET?

The play street is a residential street that is closed to vehicular traffic during specified hours to permit a supervised program of recreational activities to take place (Figure 1). A well-run play street is usually characterized by the presence of large numbers of youngsters and smaller numbers of adults engaged in such diverse activities as games, crafts, dancing, talking, sitting, watching, and so on. The play street is the meeting place and activity center for the neighborhood.

Play streets are generally located in densely populated lower income urban areas. The streets are normally one-way and there are few, if any, commercial establishments except on the street corners. The streets are barricaded with wooden sawhorses. Signs on stanchions or on the barricades are used to indicate the prohibition of through traffic and parking, as well as the hours and days when the restrictions are in effect (Figures 2 and 3). Equipment is normally provided for group street games (volleyball, basketball) and curb or sidewalk games played by one or two youngsters (board hockey). The surface of the typical play street is marked to facilitate many of these games (Figure 4).

Recreation departments in several cities use play streets as sites to temporarily locate mobile recreation vans. The play streets are usually sponsored by block associations and community organizations and provide the physical location for recreational programs for local residents of all ages.

It should be pointed out, however, that simply closing a street to traffic does not create a successful play street. The selection of a play street should include (a) developing recreational programs that have trained leaders, scheduled activities, and recreational

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Figure 1. Philadelphia youngsters play in water from a fire hydrant.

Figure 2. Street barricade signs in New York City.

Figure 3. Roll-out sign used in New York City.

equipment; (b) ensuring that the adjacent streets will be able to replace the traffic capacity lost by closing the street; and (c) ensuring that closing the street will not create parking and delivery problems to the extent that most of the residents will object to the existence of the play street.

The main lesson that has been learned from previous programs is to be sure that the majority of the residents and merchants on the proposed play street are aware that parking problems will exist, are in favor of the play street, are willing to form a community organization to sponsor the play street, and are willing to provide their time for supervision, coordination with the local agencies, and storage of equipment. Successful play-street programs are characterized by community support and a continuation of community activities at times when the roadway is not closed to vehicular traffic (6, 7).

Figure 4. Youngsters play baseball or learn to play basketball.

Very little information has been published concerning play streets. The information on play streets provided here was primarily derived from field surveys of the streets and interviews with the play streets' users, residents, and merchants and with the staff supervising the conduct of the play streets. These surveys were augmented by interviews with city officials in New York and Philadelphia.

First we observed play streets in New York City and Philadelphia. Structured surveys were then developed, two pilot tests were conducted, and 20 New York City play streets were randomly selected for surveys. Interviews with 200 children and 200 residents on 20 New York play streets were conducted. Some 500 observations were made of the number of people using the streets, the number of vehicles driving through the streets, and the number of parked cars. There were typically 272 family dwelling units on a play street and the street was used by 112 people. Among the findings were the following:

Item	Percent
Users who live on the street	67
Users who live within three blocks of the play street	95
Users who play on the play street every day	83
Users who stay home (playing, watching television) when not on the play street	52
Adults who were glad the street is a play street	92
Adults who thought the play street reduces the number of children hit by cars	97
Adults who were not in favor of opening the street to through traffic, even at low speeds	93
Adults who did not own cars	65
Adults who engaged in play-street activities	35
Ages of users:	
Under 15	55
15 to 19	25
Over 19	20
Benefits, as viewed by the staff supervising the play street:	
Social	54
Educational	25
Safety	12
Supervision	9

A detailed description of the survey and the survey results can be found in Reiss and Shinder (8, 9).

SUMMARY

Today's cities house a high concentration of people who do not have access to recreation areas or facilities. These people generally are not mobile and they have a minimum amount of discretionary money. At the same time, local governments have limited money or land available for development and operation of recreational areas. The needs of communities change seasonally as well as from year to year. Local programs should be flexible in order to keep pace with the dynamic situation.

The potential for using "traffic-free zones" to solve these problems is significant. The streets are present in these high-need areas. The use of vehicles in these high-density residential areas is often minimal. The conversion costs are extremely small, since only enough funds to close the street are required.

People who understand traffic operations can play a major role in solving some of the problems. Traffic engineering departments must work together with the departments of social services, law enforcement, planning, and recreation and with the city manager, community organizations, and the residents in order to identify what the community wants and needs and how to meet these requirements in a safe, efficient, economical manner.

Resistance to tax increases, together with a desire for increased services, has played a role in creating urban monetary crises. The use of traffic-free zones merits consideration as a workable solution to some of the social, recreational, educational, and safety problems that exist in cities today.

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