CONCLUSIONS

The following statements serve to sum up this analysis of alignment and superelevation.

1. Highway alignment is definitely a causal factor in highway accidents: Curves surprise drivers. This leads to driver error and accidents. The sharper the curve, the higher the accident rate. Sharp curves in the middle of long segments that do not have speed-impeding environments are the worst curve-related safety problem.

For 3R programs to be effective, the locations that have alignment discontinuities associated with them should be identifiable. This identification might come from an analysis of highway plans, accident statistics, or over-the-road inventory techniques.

2. Design speed for a curve is not a limiting speed that is indicative of the maximum safe operating speed of the curve: The method used by most states to distribute the maximum superelevation throughout the range of intermediate curve radii has weakened the relationship between design speed and the limiting speeds suggested through the laws of physics. Because different states employ differing rates of maximum superelevation, the same curve can have different design-speed values in different states.

3. Tying 3R improvements to design speeds on curves can lead to inequities between states: Because the same curves can have different design speeds, depending on the maximum permitted superelevation, the adoption of a uniform policy for rehabilitation based on design speeds would be inconsistent. States that have lower e_{max} standards will show higher design speeds for a given curve than those states that have higher e_{max} standards.

Therefore, an analysis of the highway system that compares design speeds of curves to adjacent sections and a standard that attempts to improve situations with large disparities would penalize states that have high maximum permitted superelevation. Those states would show higher deviations from a uniform design-speed policy for an identical roadway section simply by virtue of their design policy.

4. Surprise curves and other geometric conditions that lead to improper average running-speed transitions need to be remedied; however, comparisons of design speeds are not the appropriate measures. The disparity between the maximum safe speeds as derived from the standard curve formula and that of the design speed is large. Therefore, comparisons of design speeds are not appropriate. However, some means of determining the impact of individual geometric elements on average vehicular speed performance must be developed and applied.

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Effect of Shoulder Width and Condition on Safety: A Critique of Current State of the Art

CHARLES V. ZEGEER AND DAVID D. PERKINS

A critical review was conducted of available studies on the effect of shoulder width and condition on safety. A set of criteria was established for use in evaluating the reliability of the conclusions reported in past studies on this subject. Most studies based conclusions on the analysis results of pre-1955 accident data and only two of them considered the effect of shoulder width on related accident types (run-off-the-road and head-on accidents). Several studies did not control for the effect of intersections and differing roadway alignment (tangent or curved sections) on rural highway accident rates. Wider shoulders were found to be associated with safer conditions in the studies that were judged most reliable. Shoulder stabilization was effective in reducing accident rates on two-lane roads, particularly on identified high-accident sections. Shoulder widening was found to be cost effective on high-accident sections that had shoulder widths less than 1.2 m (4 ft). In particular, sections of rural two-lane roads that had six or more run-off-the-road or head-on accidents per 1.6 kilometer per year were likely to result in benefit/cost ratios greater than one. Shoulder widening was not cost effective, however, for low-volume roads (less than 1000 vehicles/day) that had a low frequency of accidents. Shoulder paving or stabilization is generally desirable from a safety standpoint, although its cost-effectiveness is not well established. Rural winding highway sections and sharp horizontal curves were recommended as the best

candidates for shoulder improvements, particularly those that have a high incidence of run-off-the-road and head-on accidents. Shoulder widths of 1.8-2.7 m (6-9 ft) are recommended for rural, two-lane roads.

Rural highways typically account for a disproportionately high percentage of injury and fatal accidents. Consequently, rural highways present a continual challenge to highway safety engineers who are responsible for the selection of cost-effective highway safety improvements. Countermeasure selection is usually based on past experience and documented results of project evaluations and research studies.

The effect of most rural highway improvements is generally consistent and well documented. For example, deslicking projects reduce wet-weather accidents, lane-widening projects [i.e., to 3.4 or 3.7 m (11 or 12 ft)] reduce run-off-the-road accidents, and removal of fixed roadside obstacles on horizontal curves results in fewer fixed-object accidents. The effect of such highway improvements is generally accepted when consistent results are documented in the literature.

A considerable amount of inconsistency exists in the literature concerning the safety effects of shoulder width and condition. Several major studies conclude that accidents increase with increasing shoulder width for certain conditions. Other studies report inconclusive results or no relationship between shoulder width and safety. Others report that wider shoulders result in a safer roadway in terms of run-off-the-road and other accident types. Some studies conclude that wide shoulders are necessary for recovery by vehicles that run off the edge of the roadway. Others argue that wide shoulders encourage leisure stops that result in rear-end accidents, particularly at night on Interstate routes. Faced with conflicting results from past research, today's safety engineers must decide which conclusions to believe.

The purpose of this study was to critically review and critique many of the research studies related to highway shoulders to obtain a better understanding of the effect of shoulder width and condition on safety. This knowledge will assist the highway safety engineer in making informed decisions regarding the selection of cost-effective, shoulder-related improvements. First, we reviewed current shoulder design standards. Next, a set of criteria was defined for evaluating past studies. These criteria were used to identify the strong points and deficiencies of each study and to evaluate the reliability of study conclusions.

CURRENT SHOULDER-WIDTH STANDARDS

Design standards for shoulder widths on rural highways are addressed in the 1965 American Association of State Highway Officials (AASHO) Blue Book. AASHO recommends 3.7-m (12-ft) lanes with usable 3.0-m (10-ft) shoulders on two-lane roads. However, because of high construction costs, 3.0-m shoulders are not always feasible, so minimum and desirable standards were developed by AASHO for various ranges of traffic volumes. For very low-volume roads [average daily traffic (ADT) of 50-250], a 1.2-m (4-ft) shoulder is the suggested minimum, and the desirable width is 1.8 m (6 ft), as shown in Table 1 (1). Minimum shoulder widths are 1.8 m for ADT of 400-750, 2.4 m (8 ft) for design hourly volume (DHV) of 200-400, and 3.0 m (10 ft) for higher volumes. Desirable shoulder widths are 3.7 m (12 ft) for a DHV greater than 400 (1).

Table 1. Design widths for shoulders on two-lane rural highways.

Current ADT	Design Hourly Volume	Usable Shoulder Width (m) Minimum	Usable Shoulder Width (m) Desirable
50-250		1.2	1.8
250-400		1.2	2.4
400-750	100-200	1.8	3.0
	200-400	2.4	3.0
	>400	3.0	3.7

Note: 1 m = 3.28 ft.

According to AASHO, shoulders should be usable at all times, regardless of weather conditions. Shoulders on high-volume roads should be stabilized or paved whenever possible. Where the side slopes are steeper than a 4:1 ratio, the shoulder should be 0.6-1.8 m (2-6 ft) greater than the dimensions given in Table 1. Whenever possible, full shoulder widths should be carried across bridges to reduce the chance of a vehicle hitting the bridge structure (1).

CRITERIA FOR EVALUATING PAST STUDIES

To evaluate past studies on shoulder improvements, criteria were defined and used as a basis for determining the reliability and validity of the conclusions of each study. The criteria established include the following:

1. Type of data analysis and statistical testing performed,
2. Reliability of the accident data sample,
3. Characteristics of roadway sections used, and
4. Accident types used in the study.

If a study fails to satisfy any one of these criteria, serious questions may arise as to the validity of the study's results.

Analyses and Statistical Testing

Two types of analysis were used in past studies to evaluate the relationship between shoulders and traffic accidents. These include the following:

1. Analysis of traffic accidents before and after a change has been made in the highway shoulder and
2. Comparative analysis of traffic accidents for various shoulder-width characteristics.

Both analyses are valid when used properly. An awareness of potential problems and an understanding of the limitations of each analysis technique are essential to proper interpretation of study results.

The before-and-after analysis is used to determine the cause-and-effect relationship between shoulder improvements and accidents. The effect of a shoulder improvement can be assessed by comparing accident data before and after the improvement only when the shoulder improvement is the sole physical change on the highway section. The change in accident experience can then be attributed to the improvement, all else being approximately equal.

There are several potential problems with the use of before-and-after analysis. For example, accident data at a location are random and several years of both before and after data are necessary to increase the reliability of the accident sample. However, as the analysis period is increased, other factors may be introduced that influence accidents (e.g., changes in traffic volumes and traffic mix). Also, to obtain an adequate sample of highway distance for which the only improvement is a shoulder improvement is very difficult, since improvement projects often include other simultaneous improvements, such as delineation, skid treatment, realignment, and improved drainage—all of which affect accident experience. Finally, some construction-related accidents may result from lane closures or traffic stoppages and should be omitted from the analysis.

Other limitations of the before-and-after technique are that accident experience may change because of (a) random fluctuation in accident experience, (b) a change in the character of the highway system other than the shoulder improvement, or (c) the regression-to-the-mean phenomenon. Properly designed analysis techniques can minimize the adverse effects of these limitations. Problems associated with chance variations in accidents may be minimized by performing statistical tests of significance on the observed change in accident experience between the before and after periods. Statistical tests such as Poisson test and chi-square test (2) may be used to assess whether the accident change is a result of chance or some specific change in the environment (assumed to be the shoulder improvement) at a selected level of statistical confidence. The confounding effect of changes to the highway system (other than the improvement) and regression to the mean can be miminized by the use of control sections when practical.

The second and more common type of analysis involves selection of a large sample of highway sections where both geometric and accident data are known. We refer to such an analysis as a comparative analysis. Sections that have similar geometrics are grouped together and accident data are compared for different shoulder widths and conditions. One advantage of this method is that a large data base may be used without relying on improved sections. One or two years of accident data are usually adequate if a large number of similar sections are combined into each group. Also, volume changes may be minimal, since a shorter analysis period is required than for a before-and-after analysis.

Despite these advantages, there are several disadvantages of this type of analysis. For example, no two highway sections are exactly alike and, therefore, grouping sections of similar characteristics obviously does not consider all possible differences in geometrics or volumes. Another problem involves the difficulty of handling extensive geometric and accident information for large distance samples.

Some of the studies used regression techniques to perform comparative analyses. This involves developing linear or nonlinear relations by using accident measures as dependent variables and shoulder characteristics (with other variables) as independent variables. However, as in the before-and-after approach, statistical tests must be performed to determine the significance of the observed relationship. This includes testing both the slope of the relationship and the correlation between the dependent and independent variables for statistical significance. Researchers have also used a variety of other analysis approaches, which range from correlation techniques to analysis of variance. Each approach must be accompanied by appropriate statistical testing techniques to facilitate interpretation of results and ensure validity of findings.

Neither analysis method is perfect; however, either can produce reliable results if the limitations and potential problems of each method are fully understood and steps are taken to minimize these shortcomings.

Reliability of Accident Data Sample

The reliability of the accident data sample is important in any safety study. Two of the major questions to be answered on data reliability are (a) How current are the accident data? and (b) What is the sample size used? Outdated accident data can give results that may not be totally appropriate when applied under current roadway and traffic conditions. For example, several major shoulder-related safety studies were conducted in the 1950s. Studies that are 25-30 years old may not reflect current driver attitudes, vehicle characteristics, highway speeds, average traffic volumes, delineation characteristics, gasoline availability, or traffic mix. Also, many roadway safety standards have changed considerably in recent years. Such changes have been made in the design of guardrails, shoulder slopes, lane widths, clear zones, pavement striping, highway signing, placement of fixed objects, and other highway features. Older study results may still be valid today in many cases; however, more credibility can be commanded by a properly designed study if recent accident data are used.

The size of the data sample is also important to ensure reliable conclusions. A larger sample size is generally possible for a comparative analysis than for a before-and-after study. However, with either analysis technique, several hundred kilometers may be considered a minimum to ensure consideration of a variety of different highway conditions. One must also remember that sections that had no accidents should not be arbitrarily excluded from an analysis, since this could lead to biased and erroneous results.

Highway Data Characteristics

The reliability of analysis results is improved if sample highway sections are selected that have basic similarities, such as number of lanes, section length, and highway classification. For example, sections of two-lane and four-lane roads should not be combined for analysis purposes. Traffic operations are considerably different on two-lane roads than on four-lane roads, so the effect of shoulder improvements on safety could be different. Comparison of unequal lengths of highway segments could also cause instability in data summaries. A more desirable procedure would be to use sections of equal length, where all geometric and volume characteristics can be recorded separately for each section.

Care should also be exercised in choosing the type of sections. Sections that contain major intersections should not be included, because intersection accident data can distort the effect of shoulders on safety. For example, higher-class roads normally contain wider shoulders and more major intersections than lower-class roads. An analysis of accidents might initially indicate that roads with wider shoulders (higher-class roads) result in higher total accident rates than roads with narrow shoulders. The true explanation may be that the wide-shouldered roads are associated with higher rates of intersection-related accidents and higher traffic volumes.

Highway sections that contain sudden changes in geometrics (transition sections) should also be omitted from the data base because they may adversely influence the accident data. Such transitions include abrupt changes in lane width, shoulder width, median width, pavement type, clear recovery area, area type (suburban, rural, or urban), traffic volume, and the number of lanes (lane drop). Sample sections should generally be homogeneous, so the corresponding accident data for each highway segment represent a single combination of traffic and highway conditions.

The data set should also include representative characteristics of rural roads, since urban streets normally use curbs and gutters instead of shoulders. Representative sections should not include only tangent sections. This is because shoulders are logically more useful for vehicle recovery after the vehicles leave the highway, and vehicles are more likely to leave the highway on curves than on tangents. Thus, the use of only tangent sections will not represent the full benefit of shoulders on rural highway sections.

The purpose of shoulder improvements can largely determine the resulting safety benefits that will occur. If a before-and-after analysis is used, the results may vary greatly, depending on whether or not the shoulder improvement is in response to an observed safety deficiency. If the shoulder is widened on a section primarily for operational reasons and few or no related accidents occur annually before the improvement, then the improvement is not likely to be a cost-effective means of accident reduction. If, however, shoulders are widened in response to a disproportionately high number or severity of run-off-the-road accidents, then the improvement will probably result in an acceptable safety benefit.

Selection of Accident Types

One of the major problems with past studies is that they fail to use accident types that are related to shoulder width and condition. For example, logic dictates that shoulder

Table 2. Summary of information for various major studies.

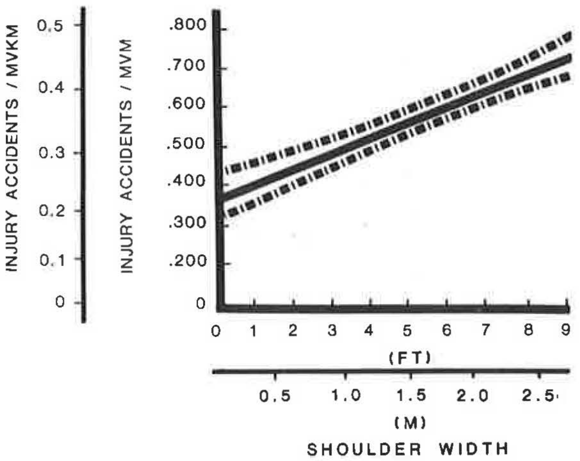
Study	State	Analysis Period	Sample Size	Controlled Variables	Analysis and Statistical Testing	Accident Variables
Billion and Stohner (3)	NY	1947-1955	1753 accidents	Number of lanes, pavement width, speed restrictions, location, intersections excluded, sections with roadside structures excluded, alignment, grade, and shoulder width	Comparison of average accident expectancy with actual accident experience for combinations of shoulder width, grade, and alignment. Chi-square used to test significance of actual accident experience	Ratio of percentage of total accidents to percentage of total travel
Stohner (4)	NY	1952	9299 accidents on 14 075 km	Number of lanes, pavement width, traffic volume, location, and shoulder width	Development of graphical relationship of accidents versus shoulder width by pavement width, no statistical analysis performed	Fatal + injury accidents per million vehicle-km and property-damage accidents per million vehicle-km
Perkins (5)	CT	1951-1954	16 672 accidents	Number of lanes, location, pavement width, shoulder type, and shoulder width	Analysis of trends between accidents and shoulder widths	Total accidents and total accidents per kilometer
Belmont (6)	CA	1948	1333 accidents on 858 km	Number of lanes, pavement type, grades, speed limit, intersections excluded, sections with roadside structures excluded, traffic volume, shoulder type, and shoulder width	Regression analysis, F-test used to test statistical difference of developed relationship	Total accidents and total accidents per kilometer
Head and Kaestner (7)	OR	1952-1954	554 km	Number of lanes, shoulder type, sight restrictions, lane width, speed restrictions, alignment, grade, traffic volume, number of driveways, and shoulder width	Statistical significance of slopes and partial correlation coefficient tested	Total accidents per kilometer, injury accidents per kilometer, and property-damage accidents per kilometer
Blensly and Head (8)	OR	1959	557 km	Number of lanes, lane width, sight restrictions, alignment, grades, shoulder type, traffic volume, number of driveways, and shoulder width	Simple and partial correlation techniques and analysis of variance and covariance, F-test used to test statistical differences	Total accidents, injury accidents, and property-damage accidents
Zeeger and Mayes (9)	KY	1976	16 912 accidents on 25 488 km	Number of lanes, lane width, shoulder width, traffic volume, access points per kilometer, and functional classification	Types of accidents found to relate to shoulder width were run-off-the-road and opposite direction, average accident costs were computed for related accidents, accident rates were computed for various shoulder widths for sections of similar geometrics, and calculation of percentage of accident reduction due to wider shoulders	Property damage, total accident rates, all accident severities, and rates of run-off-the-road and opposite direction accidents
Rinde (10)	CA	1964-1974	230 km, 37 projects	Number of lanes, surface width, traffic volume, and shoulder width	Chi-square statistical distribution testing, comparison of accident rates for similar sections, and before-after study	Property damage, injury, and fatality, specific accident types, accidents by movement preceding collison, and total accident rates
Belmont (11)	CA	1951-1952	1122 sections	Number of lanes, surface width, shoulder width, vehicle speed, level tangents, paved shoulders, and lane width	Least-squares fit and confidence levels computed	Injury accident rate

improvements influence run-off-the-road accidents but probably not right-angle accidents. Many past studies have only considered total accidents in the evaluation of shoulder width and condition. For example, consider a rural highway sample that has 1000 accidents/year before shoulder widening, of which 20 percent (200 accidents) involve run-off-the-road accidents. After shoulder widening, suppose traffic volumes and total accidents increase by 10 percent to 1100 accidents/year, but run-off-the-road accidents decrease to 100. Although run-off-the-road accidents decreased by 50 percent, the total accidents and traffic volume each increased by 10 percent. If the run-off-the-road accidents are not considered, the conclusion is made that the total accident rate did not change. Thus, the true effect of shoulder widening on related accidents may go undetected.

RESEARCH FINDINGS: SHOULDER WIDTH VERSUS SAFETY

Past research to investigate the relation between highway shoulder width and traffic accidents has resulted in a variety of conclusions. Some research findings indicate that accidents increase with increasing shoulder width; others conclude that accidents decrease with increasing shoulder widths. Other studies conclude that no detectable relation exists or that relation exists only for certain ranges of traffic volume. This section provides a brief description and critique of selected research publications. The validity of each study was measured against the criteria discussed previously. To facilitate the evaluation of past research efforts, information on several of the research studies is summarized in Table 2.

Figure 1. Injury accident rates for various shoulder widths.



The studies are classified into three general categories:

1. Studies that indicate adverse safety effects of wider shoulders,
2. Studies that indicate unclear or no effects of wider shoulders, and
3. Studies that indicate improved safety effects of wider shoulders.

Such classification schemes are not totally appropriate for several of the studies because some study results give different conclusions for various volume ranges or number of lanes.

Studies That Indicate Adverse Safety Effects of Wider Shoulders

One of the first major research studies that concluded that accidents increase with increasing shoulder width was a 1954 report by Belmont (6) in California. Three ranges of shoulder widths were tested against total accident frequency: shoulders less than 1.8 m (6 ft), 1.8-m shoulders, and shoulders greater than 1.8 m. The study concluded that accident rates were significantly lower with paved 1.8-m shoulders than with wider-paved shoulders for traffic volumes greater than 5000 vehicles/day. Accident data included about 1300 accidents (1948 data) on 858 km (533 miles) of two-lane tangents (6).

A critical review of this study resulted in the following weaknesses:

1. Roadway sample consisted of only tangent sections,
2. Accident types were analyzed without testing related accident types,
3. Accident data are now outdated (more than 30 years old), and
4. Most volume ranges were limited with respect to roadway sample sizes.

The regression equations developed in the study resulted in r^2 values that were quite high (0.82-0.90), and a considerable number of variables were controlled. However, the weaknesses mentioned above limit the reliability of the conclusions.

Another study that reported adverse safety effects of wider shoulders was a 1960 study by Blensly and Head in Oregon (8). Based on simple correlation procedures, the authors concluded that total and property-damage accident frequency increased with increasing shoulder widths for all volume ranges studied. Another analysis approach (partial correlation procedures) resulted in a similar finding in the 2000-2999 ADT range. Analysis of variance and covariance also yielded similar results. The sample included 557 km (346 miles) of rural two-lane tangents.

Although rather sophisticated analyses were performed, several study limitations were observed. For example, only tangent sections were used. Comparisons were performed on only two groups of shoulder widths [1.2 m (4 ft) or less and 2.4 m (8 ft) or greater]. The effects of shoulders between 1.2 and 2.4 m were not reported. Also, no consideration was given to specific, related accident types, and the accident data are now outdated.

A later study by Belmont in 1956 used 1951 and 1952 accident data to develop an equation of the relationship between shoulder widths and injury accident rates as shown in Figure 1. The figure shows that wider shoulders are associated with higher injury accident rates (11).

Several observed study limitations include the following:

1. Use of only straight and level tangent sections,
2. Outdated accident data, and
3. Failure to analyze specific related accident types.

Also, only injury accident rates were used and may result in limited usefulness of study conclusions, since accident severity is usually related to vehicle speeds at the time of impact and may not be a good substitute for shoulder-related accidents.

Studies That Indicate Mixed or No Effects of Wider Shoulders

Several studies reported mixed effects or no effect of shoulder width on accidents. One such study was completed in 1956 by Perkins (5) in Connecticut by using a sample of more than 16 000 accidents for 1951-1954. His analysis considered accident numbers on roads that have pavement widths of 4.3-7.3 m (14-24 ft). Control variables included pavement width, shoulder width and type, number of lanes, and other locational information. No significant relation was found between accident rate and shoulder width for any volume category.

The analysis included a large accident sample but failed to consider several important factors, such as (a) effect of related accident types, (b) influence of volumes on accidents, and (c) other important geometric variables that affect accidents. Also, accident data used are nearly 30 years old.

A study completed in 1956 by Head and Kaestner (7) provided mixed results on the effect of shoulder width on accidents. A sample of 554 km (344 miles) of highway in Oregon that has gravel shoulders was analyzed by means of accident data from 1952 to 1954. The statistical significance of regression coefficients and partial correlation coefficients was tested for total, injury, and property-damage accidents per kilometer for various ADT groups. Accident frequency was found to be unrelated to shoulder width for low-ADT groups (less than 3600). However, for ADT groups of 3600-7500, total accidents were reduced for wider shoulders, as shown in Figure 2 (7).

This study included an extensive statistical analysis and controlled for 10 variables. Intersection accidents were omitted and various accident severities were considered, all of which add credibility to the results of the study. The possible weaknesses of the study were that (a) specific accident types were not considered, (b) the accident data are outdated, and (c) accidents per kilometer were used instead of accidents per million vehicle kilometers.

Studies That Indicate Positive Effects of Wider Shoulders

Several past studies conclude that shoulder widening reduces various types of accidents. One study, by the Institute of Transportation Engineers (formerly Institute of Traffic Engineers), was completed in California in 1955 and showed an accident rate of 213 (accidents per hundred million vehicle kilometers) on roads that have no shoulder and 165 on roads that have shoulders of 2.4 m (8 ft) or more, as shown in Figure 3 (12,13). Details of the study were not

Figure 2. Predicted total accidents from shoulder width and ADT.

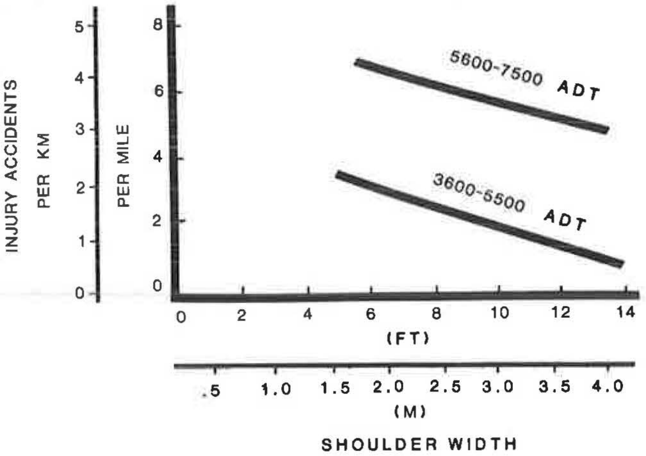
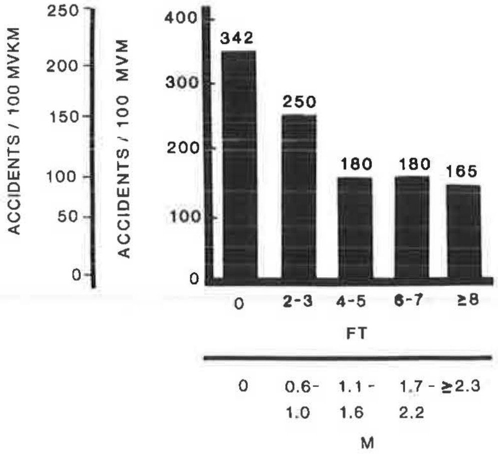


Figure 3. The effect of shoulder width on accidents.



available for review and critique.

A study by Stohner was completed in 1956 for 14 081 km (8746 miles) of two-lane rural highways in New York State that had more than 9000 accidents (1952 data). Rates were used for property-damage and injury plus fatal accidents. Results showed that the accident rate decreases with increasing shoulder width, particularly for property-damage accidents (4).

This study analyzed a large highway-length sample and used a classification scheme for grouping similar highway types for analysis purposes. Although intersection accidents were included in the data, the author noted that the study results were dependent on an equitable distribution of intersections (and other geometric features) in each grouping. Related accidents were not analyzed, and the data base is now quite old.

In 1957, Billion and Stohner published a paper that included 1753 accidents that occurred from 1947 to 1955 in New York State (3). Numerous variables were controlled for rural two-lane highways that have 6.1-m (20-ft) pavements. Shoulders of 1.5-2.1 m (5-7 ft) in width were found to be safer than 0.9- to 1.2-m (3- to 4-ft) shoulders under all conditions of vertical and horizontal alignment. Wide shoulders [2.4 m (8 ft) or more] had a lower accident incidence than did narrow- or medium-width shoulders on poor alignment. No statistically reliable relationships were found for level tangents or grades of more than 5 percent.

The study controlled for several variables. The control for 6.1-m lane width isolated the analysis to sections where wide shoulders are probably more likely to be beneficial. The study does not include analysis of specific related accident types but does include various accident severities. Also, the accident data are now outdated.

One of the more prominent studies on the effect of shoulder width on accidents was a study by Rinde in 1977 (10). The before-and-after technique was used to evaluate 37 shoulder-improvement projects on rural two- and three-lane roads in California, which included 230 km (143 miles) of shoulder widening on existing alignment. The accident rates were reduced by 16 percent for shoulder widening widths of 8.5 m (28 ft) [less than 3000 annual average daily traffic (AADT)], by 35 percent for 9.8 m (32 ft) (less than 5000 AADT), and 29 percent for 12.2 m (40 ft) (more than 5000 AADT). Reductions for 9.8 and 12.2 m were statistically significant at the 95 percent confidence level.

Summaries of accidents were also made for specific accident types as shown in Table 3 (10). Head-on accidents decreased by 50 percent, and hit-object accidents were reduced by approximately 25 percent. Significant accident reduction was not observed for rear-end, overturn, and sideswipe accidents. The total accident rates were higher for wider pavement widths due to the greater number of intersections and driveways on sections that have wide pavements (10). This finding is consistent with studies that report adverse effects of wider shoulders.

Generally, this study presents a very good analysis of the effect of shoulder widening on safety. Some of the strong points of this study include the following:

1. Various related accident types (run-off-the-road and head-on incidents) were analyzed,
2. The analysis used relatively recent accident data (1964-1974 data),
3. Control of several influencing variables, and
4. An analysis to determine which accident reductions were statistically significant due to shoulder widening (at the 95 percent confidence level).

The length of highway was somewhat small [230 km (143 miles)] but, as was discussed earlier, very large samples are usually not possible in a before-and-after analysis, since samples are selected from highways where widening has been completed.

A study of the effect of lane and shoulder widening on safety on rural two-lane roads was performed by Zegeer and Mayes in Kentucky in 1979 (9). A comparative analysis was conducted on more than fifteen thousand 1.6-km (1-mile) sections for which geometric data, traffic information, and accident data (including numbers, severity, types, and rates) were available. The roadway sections were classified by AADT, functional class, the number of access points per kilometer, lane width, and shoulder width. No sections were used that contained major intersections or other transitional characteristics. Sections were compared where the only known difference was in shoulder width. Optimal shoulder widths were found to be 2.1-2.7 m (7-9 ft), and wide shoulders were found to be associated with fewer run-off-the-road and opposite-direction accidents. On wide shoulders, accidents were observed to be 6-21 percent lower for these two accident types, depending on the width of shoulders, as shown in Table 4 (9). The average accident costs (National Safety Council costs in terms of 1976 dollars) for the run-off-the-road and opposite-direction accidents were $5569/accident, compared with $2199 for other accident types.

The strong points of the study included the following:

1. A large sample size was used [more than 24 000 km (15 000 miles) of data and about 17 000 accidents],
2. Specific accident types were used in the analysis (including run-off-the-road and head-on accidents),
3. Numerous important classification variables were controlled (including lane width, access control, ADT groups, functional classification, number of lanes, and area type),

Table 3. Effect of shoulder widening on various accident types.

Collision Type	8.5-m Pavement; AADT<3000			9.8-m Pavement; AADT<5000			12.2-m Pavement; All AADT		
	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Head on									
Frequency	3	2		32	19		29	14	
Rate	0.10	0.5	-50	1.04	0.50	-52[a]	0.14	0.6	-57[a]
Rear end									
Frequency	2	2		10	4		80	71	
Rate	0.6	0.5	-17	0.32	0.10	-69[a]	0.37	0.29	-22
Hit object									
Frequency	37	35		34	20		137	112	
Rate	1.19	0.87	-27	1.10	0.52	-53[a]	0.64	0.46	-28[a]
Overturn									
Frequency	13	18		10	18		61	41	
Rate	0.42	0.45	+7	0.32	0.47	+47	0.29	0.17	-41[a]
Sideswipe									
Frequency	1	8		14	14		43	37	
Rate	0.03	0.20	+567[b]	0.45	0.37	-18	0.20	0.15	-25

Notes: 1 m = 3.28 ft.
Accident rates are expressed in terms of accidents per million vehicle miles (1.6 million vehicle kilometers).

[a] Statistically significant decrease.
[b] Statistically significant increase.

Table 4. Percent reduction in related accident types due to wider shoulders.

Shoulder Width (each side)		Reduction in Run-off-the-Road and Opposite-Direction Accidents (%)[a]
Before Widening (m)	After Widening (m)	
0	0.3-0.9	6
0	1.2-1.8	15
0	2.1-2.7	21
0.3-0.9	1.2-1.8	10
0.3-0.9	2.1-2.7	16
1.2-1.8	2.1-2.7	8

Note: 1 m = 3.28 ft.

[a] Opposite direction includes head-on accidents and sideswipes between vehicles of opposing direction.

4. Recent accident and geometric data were used, and
5. Intersections, nonhomogeneous sections, and transition sections were eliminated.

Expected accident reductions were also used to determine accident benefits for various degrees of shoulder widening.

ECONOMIC ANALYSIS OF SHOULDER WIDENING

The economic effectiveness of shoulder-widening projects is a function of improvement costs and derived accident benefits. If shoulder widening has no effect or a negative effect on safety, the expected benefits will be zero or negative. Therefore, the only studies that might be expected to include a meaningful economic analysis are those where shoulder widening was found to improve safety.

One study of the cost-effectiveness of various accident countermeasures was the 1976 National Highway Safety Needs report by the U.S. Department of Transportation (14). In this report, 37 types of safety improvements were listed in priority order by cost-effectiveness, as given in Table 5 (14). For each improvement type, the corresponding fatalities forestalled were given with corresponding improvement costs and dollars per fatality forestalled.

The most cost-effective improvement was found to be mandatory safety-belt usage, which would only cost an estimated $500/fatality forestalled. The least cost-effective project was improvement of the roadway alignment and gradient, at a cost of $7.7 million/fatality forestalled. Paving or stabilizing shoulders was found to be next to last in terms of cost-effectiveness, at $5.8 million/fatality forestalled. Based on this study, shoulder improvements do not appear to be a cost-effective improvement in terms of reducing traffic fatalities per dollar spent (14).

The information from this study is based on nationwide estimates; however, only fatalities were included as benefit items. Shoulder improvements were apparently not found to have much effect on fatalities in this study. Because of the rare, random nature of fatal accidents, such an accident sample is probably not the most desirable for comparing the relative merits of various improvement types. Further, information was not available concerning the author's assumptions to adequately evaluate the study results.

Very different results were found in another study of safety benefits from improvements by Hall in 1978 (15). A total of 23 different improvement types were ranked from best to worst by benefit/cost ratio, as shown in Table 6 (15). The top-priority improvement was shoulder widening or improvement, which had a benefit/cost ratio of 28.83. The least cost-effective project was bridge widening, which had a benefit/cost ratio of 0.41. The computed annual reduction in accidents for shoulder widening or improvement was 29 percent for all accidents, 20 percent for injuries, and 41 percent for fatalities.

Although the details of the data were not readily available, the shoulder-improvement projects evaluated for this study were possibly high-accident sections before improvement, since benefit/cost ratios were of such a high magnitude. Such high benefit/cost ratios may not be possible for shoulder widening on a random sample of highway sections. However, this study illustrates that shoulder improvements can be very cost effective, dependingl8n the sections selected for widening.

A third study by Zegeer and Mayes in Kentucky in 1980 included an economic analysis related to various shoulder widths (9). Costs for shoulder widening were computed based on a large number of past statewide construction costs and adjusted to 1976 dollars. For every 0.6 m (2 ft) of widening on each side of the road, average costs were nearly $24 000/km ($38 000/mile). Costs for widening shoulders by 1.8 m (6 ft) (each side of road) were found to be about $56 000/km ($90 000/mile). All costs were itemized and represent average values for the generally rolling and hilly terrain found in Kentucky.

As discussed earlier, wider shoulders were found to be associated with from 6 to 21 percent lower rates for run-off-the-road and opposite-direction accidents (depending on amount of widening). This information was used to compute expected benefit/cost ratios from shoulder widening. The expected benefit/cost ratios for such improvements were a function of annual number of related (run-off-the-road and opposite-direction) accidents. Plots were made of benefit/cost ratios for shoulder widening projects that have from 1 to 20 such accidents per year [Figure 4 (9)]. For example, for a 1.6-km (1-mile) section of road that has 10 accidents/year, the widening of 0.6-m (2-ft) shoulders to 1.5 m (5 ft) (each side of road) would be expected to result in a benefit/cost ratio of about 1.8. Benefit/cost ratios of greater than 1.0 were expected for the widening of sections that have narrow shoulders and 6 or more related accidents per 1.6 km per year. The magnitude of such benefit/cost ratios appears to be quite reasonable for high-accident sections, and the expected economic effectiveness of shoulder improvements from this study was found to lie between the results of the Highway Needs study (14) and the Hall study (15).

SHOULDER STABILIZATION AND SAFETY

The effect of shoulder stabilization on safety has been addressed in several studies, with somewhat different results. Accident data were collected before and after shoulder stabilization in Ohio and Oregon, as reported by

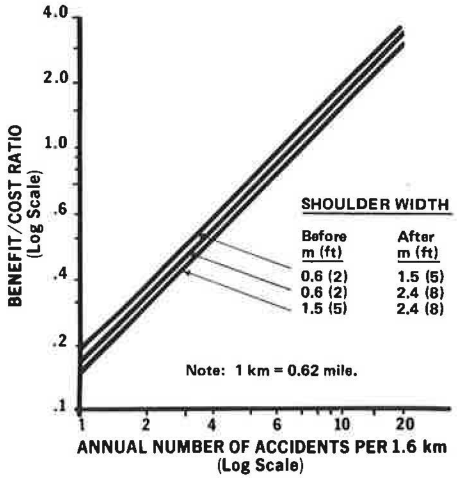
Table 5. Ranking of countermeasures by decreasing cost-effectiveness in present-value dollars—10-year total.

Countermeasure	Fatalities Forestalled	Cost ($000 000s)	Dollars per Fatality Forestalled
Mandatory safety belt usage	89 000	45.0	506
Highway construction and maintenance practices	459	9.2	20 000
Upgrade bicycle and pedestrian safety curriculum offerings	649	13.2	20 400
Nationwide 88-km/h (55-mph) speed limit	31 900	676.0	21 200
Driver improvement schools	2 470	53.0	21 400
Regulatory and warning signs	3 670	125.0	34 000
Guardrail	3 160	108.0	34 100
Pedestrian safety information and education	490	18.0	36 800
Skid resistance	3 740	158.0	42 200
Bridge rails and parapets	1 520	69.8	46 000
Wrong-way entry avoidance techniques	779	38.5	49 400
Driver improvement schools for young offenders	692	36.3	52 500
Motorcycle rider safety helmets	1 150	61.2	53 300
Motorcycle lights-on practice	65	5.2	80 600
Impact-absorbing roadside safety devices	6 780	735.0	108 000
Breakaway sign and lighting supports	3 250	379.0	116 000
Selective traffic enforcement	7 560	1010.0	133 000
Combined alcohol safety action countermeasures	13 000	2130.0	164 000
Citizen assistance of crash victims	3 750	784.0	209 000
Median barriers	529	121.0	228 000
Pedestrian and bicycle visibility enhancement	1 440	332.0	230 000
Tire and braking system safety critical inspection, selective	4 591	1150.0	251 000
Warning letters to problem drivers	192	50.5	263 000
Clear roadside recovery area	533	151.0	284 000
Upgrade education and training for beginning drivers	3 050	1170.0	385 000
Intersection sight distance	468	196.0	420 000
Combined emergency medical countermeasures	8 000	4300.0	538 000
Upgrade traffic signals and systems	3 400	2080.0	610 000
Roadway lighting	759	710.0	936 000
Traffic channelization	645	1080.0	1 680 000
Periodic motor vehicle inspection, current practice	1 840	3890.0	2 120 000
Pavement markings and delineators	237	639.0	2 700 000
Selective access control for safety	1 300	3780.0	2 910 000
Bridge widening	1 330	4600.0	3 460 000
Railroad-highway grade crossing protection, automatic gates excluded	276	974.0	3 530 000
Paved or stabilized shoulders	928	5380.0	5 800 000
Roadway alignment and gradient	590	4530.0	7 680 000

Table 6. Safety benefits of improvements.

Improvement	Annual Reduction (%)			Benefit/Cost Ratio
	Accidents	Injuries	Fatalities	
Shoulder widening or improvement	29	20	41	28.83
Installation of striping or delineators	13	20	46	26.49
Skid treatment and grooving	48	30	74	20.12
Installation or upgrading of traffic signs	23	33	27	15.03
Signing or marking	0	42	35	14.94
Installation or improvement of median barrier	3	6	91	13.73
Localized lighting installation	9	9	73	13.24
Installation or improvement of road edge guardrail	13	15	59	10.97
Flashing lights replacing signs only, railroad crossing	94	93	99	9.41
Signs and striping combination	24	26	27	8.60
Breakaway signs or lighting supports	35	44	100	7.25
Traffic signals installed or improved	18	32	49	6.36
Skid treatment and overlay	17	27	30	6.09
Automatic gates replacing signs only	99	99	100	5.44
Channelization, including left-turn bays	23	29	65	3.94
Pavement widening, no lanes added	25	38	87	3.68
Sight distance improved	31	38	36	2.97
Traffic signals installed or improved and channelization, including left-turn bays	31	35	50	1.78
Automatic gates replacing active devices	81	75	96	1.13
Horizontal alignment changes (except to eliminate highway grade crossing) and vertical alignment changes	21	32	69	0.91
Replacement of bridge or other major structures	44	60	47	0.90
Lanes added without new median	17	11	31	0.80
Widening existing bridge or other major structures	65	74	33	0.41

Figure 4. Expected benefit/cost ratios from widening 0.6-m shoulders.



Jorgensen (16). Stabilization of shoulders in Oregon was conducted as routine improvements on highways that have low accident rates, and accidents were found to actually increase on two-lane roads (91 percent) and also on roads that have more than two lanes (52 percent). The number of injuries and fatalities also increased, although accident variances were quite high (16).

In Ohio, the results were quite different for two-lane roads. This was due primarily to the fact that shoulders were stabilized on sections that had high numbers of accidents, high accident rates, and high percentages of run-off-the-road and head-on accidents. Accidents were reduced by 38 percent, and there was a 46 percent reduction in injuries and fatalities (16).

Based on the results of data from Ohio and Oregon, the effectiveness of a shoulder stabilization project (or perhaps any improvement project) depends on the need for improvement from a safety standpoint. Reductions in accidents are not likely to result when such improvements are implemented on sections that had few or no accidents before improvement. When stabilization projects were selected where the greatest needs existed (as in the Ohio sites), then a reduction in accidents and injuries is very likely.

Another study was conducted by Heimback and others in North Carolina in 1974 (which used 1966 to 1969 accident data) to investigate the cost-effectiveness of paved shoulders on rural primary highways (17). Accident experience was compared between highway sections that were similar in all respects, except for the presence or absence of a paved shoulder. A sample of 3054 homogeneous roadway sections on rural, two-lane roadways was used. Results showed that paved shoulders of 0.9-1.2 m (3-4 ft) were the safest. Shoulder paving was found to sometimes be cost effective (benefit/cost ratio of 1.0 or greater) on two-lane roads but not on four-lane roads. The study assumed paving costs of $1200-$8800/km ($2000-$14 000/mile) (both sides of the road), service lives of 7-21 years, an economic rate of return of 6-12 percent/year, and a traffic growth rate of 5-8 percent/year.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to determine the effect of shoulder width and condition on highway safety through a critique of past research studies. A set of criteria was established for use in evaluating each study in terms of reliability and validity. Studies were classified according to their general findings of the effect of shoulder width on accidents. Three studies were evaluated where wider shoulders were associated with increased accidents. These studies dealt primarily with tangent sections and the results should not be generalized for all alignments.

Numerous studies were found where accidents were reduced due to wider shoulders, particularly for moderate- to high-volume sections. Wider shoulders were found to reduce run-off-the-road and head-on accidents considerably. Wider shoulders were generally found to be effective on curves and winding sections.

Shoulder widening was found to be cost effective for sections identified as high-accident sections but probably would not be cost effective for random shoulder-widening projects. Shoulder stabilization was also found to reduce accidents where shoulders were stabilized for safety reasons.

Based on a critique of numerous research studies related to shoulder width and condition, the following recommendations were made.

1. Shoulder-widening projects should not be selected randomly but should be based primarily on the incidence of run-off-the-road and head-on accidents or on the presence of obvious roadway safety problems. Widening should be given more consideration on moderate- and high-volume roads and where related accident numbers are abnormally high.
2. Higher priorities for shoulder widening should be given to horizontal curves and winding sections than to straight, level tangent sections.
3. The potential benefits and costs for each shoulder-widening project should be carefully estimated to select projects that have the greatest potential cost-effectiveness.
4. On rural two-lane roads, the optimal shoulder widths are 1.8-2.7 m (6-9 ft).
5. If cost-effectiveness is of primary concern, the best candidate sections for shoulder widening are those rural, two-lane roads that have shoulder widths less than 0.9 m (3 ft) and six or more related accidents (run-off-the-road or head-on) per 1.6 km per year.
6. Shoulder paving or stabilization is generally desirable from a safety standpoint if conducted properly. Locations that have unstabilized shoulders and a history of shoulder-related accidents should be considered for paving or stabilization.

Not all accident-related research studies can be taken at face value. Some may contain unreliable data or questionable analysis techniques. The four criteria developed in this paper (as well as other appropriate criteria) may be useful in the review of all types of safety-related studies.

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Design of Left-Turn Lanes for Priority Intersections

JOE LEE AND THOMAS MULINAZZI

There is general agreement that a left-turn lane should be warranted on a benefit-cost basis. However, existing documents do not provide accurate techniques for the prediction of the two items that are needed for such an approach—the reduction of delay and the length of the left-turn lane. This study shows that the problem can be solved by using the results of two simulation models. These two models attempt to duplicate the traffic of an uncontrolled approach at a two-lane by two-lane priority intersection. A priority intersection is an intersection at which only the two minor approaches are controlled by stop or yield signs—in other words, the major flow has been assigned priority. One model represents a without-left-turn condition and the other represents a with-left-turn condition. Design charts and tables were produced from these models. These charts and tables are presented in this paper to give the user a systematized guide to design problems for the left-turn lane. Application of the study results are intended for use in Kansas and are limited to a two-lane priority intersection. Although the approach and methodologies reported in the study are considered applicable to other locations and for other purposes, users are cautioned to observe the limits of the study results.

A priority intersection is an intersection at which only the two minor approaches are controlled by stop or yield signs. In other words, it is an intersection at which the major flow is assigned priority. Highway engineers involved with the design of left-turn lanes for priority intersections are confronted by two major design consideration issues. The first issue is to determine the conditions (i.e., approach volumes, left-turn percentages, and accidents) under which a left-turn lane is warranted. The second issue is to determine the appropriate length of the left-turn lane. The questions involved in these two issues are complex because of the randomness with which vehicles arrive at an intersection to make left turns and the incidental number of vehicles that turn left at one time when a left-turn lane is provided. Past research efforts regarding these two issues are relatively inadequate.

REVIEW OF LITERATURE

Failmezger (1) developed a warrant for left-turn-refuge construction based on ratings of many geometric and traffic parameters. However, no analytical rationale was provided. Harmelink (2) calculated the arrival and release rate of a combination of through and left-turning vehicles. He proposed that construction of a left-turn lane is warranted when the probability of having more than one of the vehicle combinations waiting in the system is less than 0.005. However, he failed to consider all the other numerous vehicle combinations, such as two consecutive left-turning vehicles, one left-turning vehicle followed by two through vehicles, and two left-turning vehicles followed by one through vehicle, and he did not explain the rationale behind the selection of the 0.005 probability level.

Hammer (3) suggested that a left-turn lane is warranted from an accident consideration point of view but neglected to consider delay. Shaw and Michael (4) as well as Ring and Carstens (5) employed a more-comprehensive approach for the left-turn-lane problem. Both teams considered the reduction in delay and accidents to be the benefits of a left-turn lane. They then compared the benefits with the construction cost of the left-turn lane to see whether the left-turn lane was justified. The approach was undoubtedly rational for an isolated intersection; however, because they assumed that the delay varied linearly with approach volume, opposing volume, and left-turn volume, they underestimated delays for high-volume ranges. This shortcoming would make their findings applicable only to low and moderate volumes.

Numerous studies of delay caused by left-turning vehicles at signalized intersections (6) have shown that delays increase curvilinearly with increases of left-turn, approaching, and opposing volumes. Delay approaches infinity when volumes are so high that left-turning vehicles could not find enough acceptable gaps in the opposing traffic stream. This characteristic of the delay function seems to point out the need for an accurate method of predicting delay if the use of the benefit-cost approach is to be expanded.

An important problem associated with the consideration of stopped delay is capacity. Once vehicles must stop and wait for their release from an intersection, the lane that they have occupied is temporarily blocked. The longer the delay, the shorter the time that the lane would be open for vehicles to go through the intersection, and the greater would be the reduction in capacity. Because delay varies curvilinearly with volumes, the capacity of the lane may be reduced to less than that of the approaching volume (a total breakdown of traffic) sooner than many people have believed. Even if the critical condition has not been reached, the reduction of capacity would cause the volume-capacity ratio to rise. This would result in the reduction of the level of service for the lane. For many lightly traveled highways, capacity may not be a serious problem. The level-of-service consideration, however, would certainly be of interest to highway engineers.

Because of the emphasis on safety and safety improvements, some left-turn lanes have been warranted based only on a consideration of accident reductions, and