Design Consistency and Driver Error

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Geometric design consistency appears to be a major factor affecting accident rates on rural highways, yet little assistance that enables engineers to design roadways consistent with driver expectations is available. AASHTO instead focuses primarily on individual elements, basing guidelines on functional classification, volume, and design speed. The methods that have been presented in the literature for quantitatively assessing design consistency are focused in two primary directions, speed consistency and driver workload. Speed consistency consists of analyzing predicted speeds on a highway and striving to keep those speeds within a narrow range. Several major research studies have provided methodologies for deriving and analyzing predicted speeds. Workload consistency for geometric design, however, has been the focus of only one major research study, receiving an examination by Messer et al. in 1981. In their study they developed procedures that assign subjective workload ratings for features along the roadway, depending on the type and severity of features, the sequence of features, and the proximity to other features. Some 19 rural two-lane highways in Texas were analyzed to derive relationships between the workload ratings provided by the procedure of Messer et al. and the accident records on those roadways. It was concluded that roadway sections with either high workload magnitudes or large positive changes in workload were associated with high accident rates when compared with accident rates on other sections on the study roadways. A final conclusion was that the driver workload procedure of Messer et al. represents a viable tool for use in the examination of design consistency.

Roadway designers are faced with many choices in the design or rehabilitation of a roadway. The designer must meet or exceed the requirements placed by engineering guidelines and standards, choosing, in some cases, which requirements will be met. The designer must then request design exceptions for those requirements not met. One of the requirements placed on the designer is to meet driver expectancies (*1*). Given the vague guidance provided in this area, most of the designer's attention is usually directed toward the clear-cut requirements for discrete elements of the design, neglecting an overall examination of the driving environment. When today's designer attempts to reconstruct segments of old routes as needs dictate and money becomes available, attention must be placed on the issue of driver expectancy so that inconsistencies are not built into the highway system.

DESIGN CONSISTENCY

Highway designers are vitally concerned with building the most efficient, most cost effective, and safest highways possible. To increase the safety of a highway, however, the engineer must know which portions of the roadway merit improvement. The necessity for accident prediction by the transportation engineers was pointed out by Dart and Mann when they stated, "Unless accidents can be predicted above the level of chance, the processes that cause accidents cannot be understood with any degree of confidence" (*2*). Accidents do not occur in the same locations every year, though, and patterns in accident occurrence are difficult to understand and quantify, confounding the engineer's attempts to provide a safer driving environment.

Little need would exist for accident study and analysis if drivers could readily assess the risks that they encounter as they drive. A British study by Watts and Quimby (*3*), however, compared the risks encountered with the drivers' perceptions of those risks and found that wide discrepancies existed between the objective and subjective risk levels. This discrepancy was later confirmed by Philput (*4*) using U.S. drivers. Because drivers do not appear to be capable of accurately assessing the risks they encounter by driving along a roadway, they are not able to adequately modify their driving behaviors accordingly.

Driver Expectancy

Expectancy, in general, can be stated to represent a set of possible probabilities regarding a given situation (*5*). Those probabilities are subjective and based on learned and experienced events. Expectancy is a known determinant of reaction time, signal detection, and vigilance. Because the driving task involves all these factors, attention must be placed on the driver's expectancies. An operational definition of expectancy has been given by Ellis (*6*):

> Driver expectancy relates to the observable, measurable features of the driving environment which:
> (1) Increase a driver's *readiness* to perform a driving task in a particular manner, and
> (2) Cause the driver to *continue* in the task until it is completed or interrupted.

This definition attempts to narrow expectancy from the general view of the psychology profession to the viewpoint of the transportation engineer.

Speed Differential

A driver's expectancy of a specific situation is formed by his or her experience, both long term and short term (*6*). Long-term expectancy has been termed *a priori expectancy*, and short-term expectancy has been termed *ad hoc expectancy* (*7*). Expectancy influences many of the decisions encountered in the driving task. Some researchers have examined design consistency in an attempt to provide a consistent roadway design. One method of examining the consistency of a roadway design is to check various surrogate measures. Although several surrogates are available (*8*), one mea-

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sure that appears useful is speed differential along the roadway. This particular measure of operation has the advantage of being both easily measured and easily simulated, permitting the simulation of roadways under study and the measurement of speeds along existing roadways for research purposes. Several methodologies have been developed for use in analyzing speed differential. These techniques generally focus on reducing or limiting the severity of speed differential along the roadway.

Lamm et al.

Research has focused on ways of providing a consistent speed environment that conforms to driver expectancies and does not require abrupt changes in operating speed to maintain control of the vehicle. Several different design consistency procedures have been presented in the literature. One of the simpler models was presented by Lamm et al. (*9*). This procedure concentrates on operating speed changes induced by horizontal curvature and tangent length, as well as examination of the change in degree of curvature of horizontal curves along the roadway. The strategy focuses on achieving a consistent horizontal alignment by minimizing abrupt changes in operating speed, while keeping the change in degree of curvature to a minimum.

Leisch and Leisch

A procedure introduced by Leisch and Leisch (*10*) includes the influence of both horizontal curvature and vertical grade. Variations in automobile speeds of more than 10 mph, reductions in design speed by more than 10 mph, and differences in speed between trucks and automobiles of more than 10 mph are to be avoided. The objective of the procedure is to enable the designer to detect areas of the highway alignment that violate these recommendations. Truck speeds are predicted from tabular values presented in AASHO's 1965 *A Policy on Geometric Design of Rural Highways* (*11*), whereas the speeds of automobiles are determined through the use of equations derived from driver characteristics. Leisch and Leisch's (*10*) approach to design consistency considers many operational characteristics of the roadway-driver system.

Switzerland

Switzerland (*12*) uses both a design speed and a project speed for arriving at proposed alignments for highways. The design speed is used in a manner similar to that in which it is used in the United States' AASHTO guidelines (*1*). The design speed provides a minimum design value for various roadway features (i.e., sight distance, horizontal curvature, etc.), whereas the project speed is the "maximum speed expected in a certain roadway section and serves as a test speed to assess adequate sight distances, adequate radii of crest or sag vertical curves. . . ." Switzerland uses a speed model to examine the horizontal roadway alignment, predicting project speeds throughout the alignment. By examining changes in that project speed, abrupt changes in speed as well as speed transitions along the roadway may be detected.

Germany

Germany also uses both a design speed and an operating speed as aids in roadway design (*12*). Operating speed as defined in Germany corresponds to the 85th percentile speed on a facility. An acceptable alignment would have a predicted operating speed that did not exceed the design speed by more than 20 km/hr (12 mph). German designers also use the effects of alignment on speed to deliberately provide a speed transition when passing from high-speed rural areas to low-speed populated areas, introducing curvature that might otherwise be unnecessary. Speed transitions are controlled by examining a "curvature change rate" to ensure that transitions are gradual and safe between adjacent roadway sections. Other checks on horizontal alignment include controls on successive curves, tangent lengths, and the number and severity of curves along stretches of roadway.

Australia

Design consistency research by McLean (*13*) has focused on the differences between design speeds and desired speeds. Desired speed has been defined as the 85th percentile speed measured on tangent sections of roadway within a particular roadway section. For high-speed alignments Australian practice is to continue to provide the conservative design features that have been provided previously, since this practice has proven to be consistent with driver expectations and practices. For low-speed alignments, however, design speed is made to match the 85th percentile speed. Following the preliminary selection of horizontal curve radii, projected speeds are estimated for the curves. Those speeds are then used to specify other parameters for the design.

Summary

All of the methodologies discussed so far have concentrated on treating roadways so that *observed* driver responses (i.e., driver speed changes) conform to specific ranges that have been determined acceptable. A premise implicit in those methodologies, however, is that drivers are able to observe and analyze the roadway in such a way as to arrive at an appropriate speed. If drivers tend to drive too fast on severe curves that follow tangents, however, observation of the speed changes between the two features will result in an underestimation of the design consistency. Watts and Quimby (*3*) established that drivers do not always recognize the risk potential of roadway features; it appears reasonable to question procedures that rely strictly on the results of driver-controlled speed changes. Further examination of consistency and expectancy leads to the workload concept in an attempt to address more directly the influence of the roadway on the driver.

Workload

The driving task imposes work on the driver; this work varies greatly in task difficulty and task frequency. The level of this workload and its effects on driver performance would seem to be greatly affected by driver expectations and driver capabilities. Roadways with inconsistencies in their designs would be expected to violate driver expectancies and impose higher workloads on drivers. An understanding of the basis of workload and its impacts on performance is desirable to analyze design consistency.

Definition of Workload

Workload has been defined by Senders (*14*) as "a measure of the 'effort' expended by a human operator while performing a task, independently of the performance of the task itself." Another definition of workload was given by Knowles (*15*) as consisting of the answer to two questions: "How much attention is required?" and "How well will the operator be able to perform additional tasks?" The definition presented by Knowles seems very appropriate to the driving environment, since it consists of many overlapping tasks, each requiring a portion of the driver's attention. A method of examining the workload demands placed on the driver would appear to be a way of directly arriving at the capabilities of the driver as he or she negotiates a given roadway.

Messer Driver Workload Procedure

A method of evaluating driver workload was presented by Messer (*16*) and Messer et al. (*17*). By gathering empirical evidence regarding driver expectations of roadway features and relating violations of those expectancies to workload, a model was formed. The model is based on the presumption that the roadway itself provides most of the information that the driver uses to control his or her vehicle; hence the roadway imposes a workload on the driver. This workload is higher during encounters with complex geometric features and can be dramatically higher when drivers are surprised by encounters with unexpected or unusual combinations and sequences of geometric features.

The Messer driver workload procedure quantifies design consistency by computing a value for driver workload. The technique relies on a set of assigned ratings for various roadway elements. The following roadway features receive ratings (listed in order of severity): bridges, divided highway transitions, lane drops, intersections, railroad grade crossings, shoulder-width changes, alignment, lane-width reductions, and the presence of crossroad overpasses. The ratings, based on the type and severity of design element, are then modified in accordance with their locations. Influencing factors include sight distance to the element, similarity to previous elements, workload of previous segments, and percentage of drivers estimated to be familiar users of the facility.

The workload along the roadway is estimated by using an equation that defines a subjective level of consistency (LOC) in terms related to driver workload. The methodology is applicable to two- or four-lane highways in flat or rolling terrain and may be used to examine existing or proposed highways. The equation used for calculating the driver workload is defined as:

$$WL_n = UESR_f + CWL_l \tag{1}$$

where

WL_n = workload,
U = driver familiarity factor,
E = feature expectancy factor,
S = sight distance factor,
R_f = basic workload potential rating,
C = carryover factor, and
WL_l = workload of the previous feature.

The range of each of these terms was defined by the collection of empirical evidence and the collective experience of a group of experts (*16,17*). The first addend represents the workload associated with the feature in question, whereas the second addend represents the residual effects of the workload of the previous feature encountered by the driver.

Sample Application of Various Consistency Measures

Several different consistency and workload measures have been presented in the literature. Although a comparison of procedures on any one given roadway does not completely address differences and similarities between the various procedures, such a comparison was of interest. Lamm et al. (*18*) presented a hypothetical alignment (Figure 1) for which three different speed consistency analyses have been performed. McLean (*13*) used the same hypothetical alignment to contrast an Australian methodology with the three speed consistency analyses presented by Lamm et al. (*18*). A fifth measure of consistency, based on workload (*16,17*), has been added through the application of the Messer procedure (*16,17*). The results are shown in Table 1. It is highly significant that all four checks of operating speed rejected the same two curves (AB and EF). This agreement shows a very

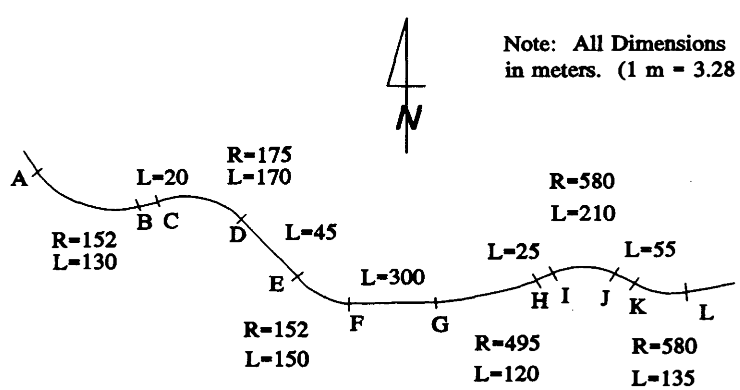

FIGURE 1 Hypothetical alignment.

TABLE 1 Operating Speed Predictions (*15,23*) (km/hr) (NAASRA is National Association of Australian State Road Authorities)

Method	Curve					
	AB	CD	EF	GH	IJ	KL
Leisch W-E	60•	63	60	71	76	85
Leisch E-W	60	63	60•	93	97	97
Swiss	69•	69	69•	100	100	100
German	70•	70	70•	86	86	86
NAASRA W-E	85⁺	77	76	91	100	100
NAASRA E-W	76	77	82•	99	100	100
†Messer W-E	F♦	F♦	F♦	B	B	B
†Messer E-W	E	F♦	F♦	E	D	B

• Unacceptable because of speed consistency criterion.
⁺ Unacceptable because of side friction factor criterion.
♦ Unacceptable because of high workload.
† Added by this author.

promising similarity of results, suggesting a convergence of research and methodology.

Although it does appear to be a promising technique for evaluating geometric roadway alignment, limitations of the speed profile methodology of examining design consistency are numerous. All the procedures examined ignore the influence of many design elements, such as intersections, narrow bridges, lane width changes, changes in the number of lanes, and so on (*19*). All of these features violate drivers' expectancies (*16,17*), yet their influences on the geometric design of the roadway are neglected if one examines only the speed profiles along the roadway.

A fifth measure of consistency, that provided by the application of the Messer driver workload procedure (*16,17*), is different in implication when applied to the hypothetical alignment of Lamm et al. (*18*) (added by the author). The results from the Messer procedure are reported in a range extending from A (no problem expected) to F (big problem possible). In addition to curves AB and EF in Figure 1, the Messer procedure predicts that problems may be predicted for curve CD for the west to east (W–E) direction of travel, and curves CD, GH, and IJ could present problems as well (although to a lesser extent). The application of the Messer procedure was completed by using an assumed 140-ft right-of-way (ROW) in the absence of further information; a further assumption was made, that is, that sight was restricted at the limits of that ROW; and a final assumption was made to use the speeds predicted by Leisch and Leisch (*10*) to represent the 85th percentile speeds on the alignment.

Clearly, significant differences are evident in the application of the various procedures outlined above. Although further information regarding the hypothetical alignment (e.g., providing a vertical alignment and showing structures) would provide a better comparison of the methodologies, this simple example does provide a basis for comparison. The Messer procedure (*16,17*) is highly sensitive to severe horizontal curvature; this sensitivity generally accounts for the differences in results. The speed profile procedures assume that once a driver has slowed for one curve, another similar curve is of little consequence; Messer, on the other hand, using workload, assumes that combining high-workload features in close proximity results in a higher workload for the second and following features. The different assumptions made by the respective researchers hence affect the results.

STUDY RELATING DRIVER WORKLOAD AND ACCIDENT EXPERIENCE

To validate a procedure that purports to enable the designer to improve safety, an examination of accident experience on actual roadways is necessary. This section reports the results of a study that examined one class of two-lane roadway in Texas (*20*). The hypothesis investigated in that research was that accident rates would be highest in areas associated with either very high workloads or extremely low workloads. A corollary to this hypothesis was that sudden increases or decreases in workload would also be associated with increased accident risk. As theorized in the Yerkes-Dodson Law (shown in Figure 2), performance level is low when arousal level is low. Performance gradually improves in quality as arousal increases until an inflection point is reached; after that point is passed and arousal continues to increase, performance declines (*21,22*). Since error rates generally increase as performance decreases, it was expected that accident rates would be highest in those areas where workloads were minimized or maximized. The general shape of the hypothesized relationship between workload and accident rate is illustrated in Figure 3.

Application of Messer Driver Workload Procedure

The Messer driver workload procedure (*16,17*) was applied to selected portions of 19 different farm-to-market roadways in Texas. Information regarding the functional and geometric characteristics of the study roadways was obtained from Texas Department of Transportation (TxDOT) personnel. Roadways selected for study were two-lane rural highways. The study roadways were functionally classified as rural collectors, were in rolling terrain, and had reasonably consistent traffic volumes. Speed limits on the roadways were 55 mph, with lower advisory speed limits on some sections.

Driver workloads were calculated for the study roadways by the Messer driver workload procedure. Geometric features such as vertical and horizontal curvatures, presence of intersections, and so on, were determined, and then various charts were consulted to determine feature ratings. Once the individual feature ratings were determined, various modifying factors such as sight distance and expectation (or familiarity) were calculated. Each feature along the roadway segment was then assigned a workload (*16,17*).

Accident History

The validation of the Messer procedure with regard to accident history required that accident records be obtained for each of the

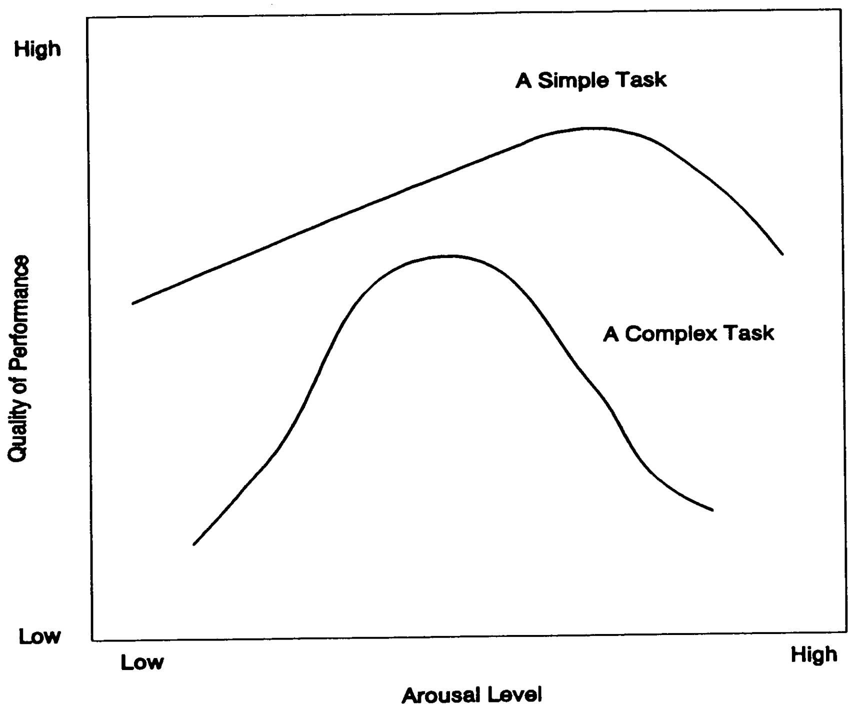

FIGURE 2 Yerkes-Dodson Law.

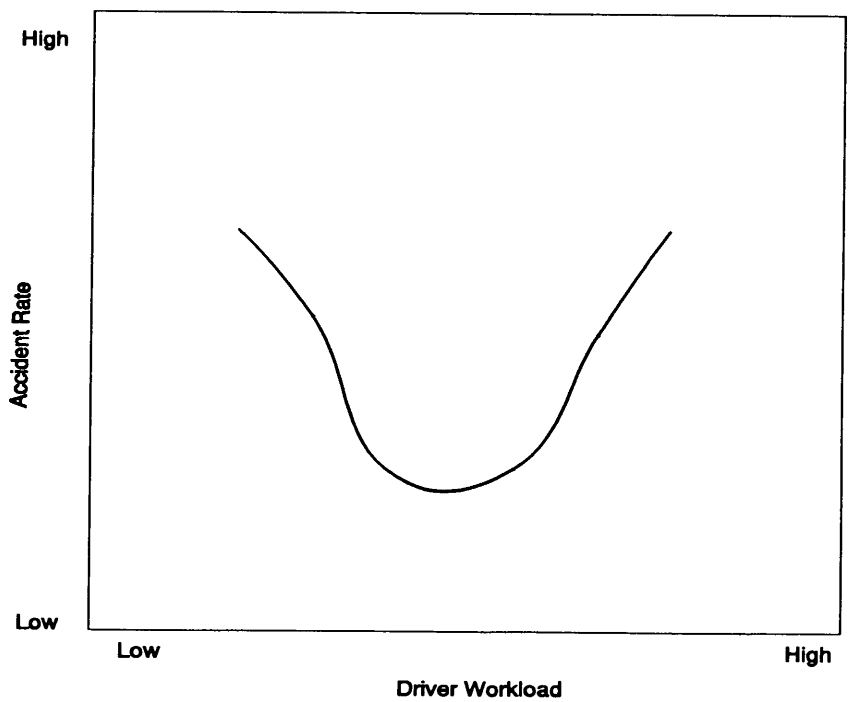

FIGURE 3 Hypothesized relationship between workload and accident rate.

roadway segments in the study. Since the Messer procedure is applied to travel directions of a highway independently, it was necessary to separate accidents by direction. Accident records for each roadway were obtained from TxDOT. The roadways that were included from Glascock's study (*20*) included accidents from January 1987 to June 1990 (3 years 6 months); the accidents listed for roadways added for the present study included accidents from January 1988 to May 1991 (3 years 5 months).

The length of the time period chosen, approximately 3.5 years, represented a compromise between instability in accident occurrence and instability in site characteristics. Accidents are random in nature, and accident occurrence fluctuates accordingly. Yearly numbers of accidents fluctuate, so it is desirable to use as many years of data as possible; however, site characteristics are changeable and dictate that short time periods be used to ensure that site conditions remain reasonably constant. The period of 3.5 years represented a compromise between these two conflicting requirements and was used in the study (*23*).

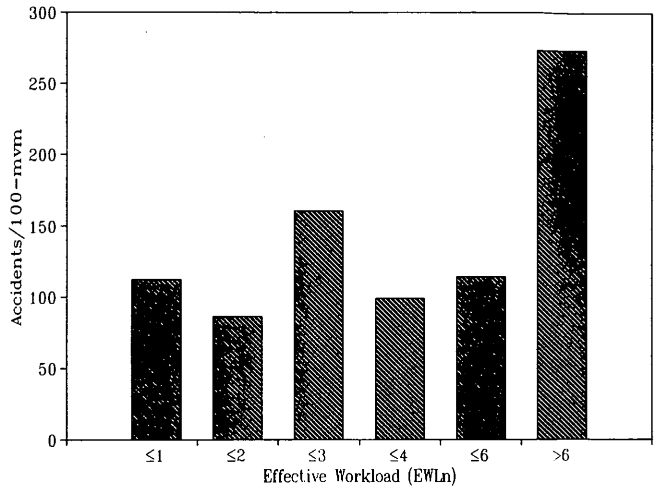

FIGURE 4 Evaluation of effective workload.

Data Analysis

An evaluation associating driver workload with accident rates was performed. The evaluation related driver workloads associated with individual portions of roadway with the accident rates on those portions of roadway. The microscopic evaluation was accomplished by using two individual variables. In an attempt to determine the influence of a priori expectancy, a grouping was made of those segments with workloads within the six levels of consistency presented by Messer. Ad hoc expectancy was examined through the determination of the yaw of the workload on individual features. *Yaw* was defined as the difference between the moving average workload and a specific feature's workload. In this way the yaw provided a measure of the change in workload on a microscopic level.

The analysis examined accident rates for roadway features after first sorting them for workload rating and workload yaw. Yaw was calculated according to the following equation:

$$\text{Yaw} = (\text{workload rating of feature}) - (\text{moving average workload}) \quad (2)$$

The extent of roadway length considered in the determination of the moving average was 1,000 ft. This length was determined after consideration of research by Lamm et al. (*9*) as well as Matthews and Barnes (*24*). The use by Lamm et al. (*9*) of an independent or nonindependent tangent length when the tangent length between successive curves influenced the level of consistency of the following curves led to an examination of the lengths used in their proposed methodology. The lengths at which the 85th percentile speed (V_{85}) in the tangent could be expected to be 58 mph (or maximum) ranged from 1,100 to 475 ft, depending on the V_{85} in the curve. In Matthews and Barnes' research (*24*), accident risks were determined to be four to seven times as high for curves located immediately after 300-m (984-ft) or longer tangents when compared with the accident risks on standard curves. Extending their research to the workload concept, it was decided to examine each feature's associated workload in relation to the workload in the previous 1,000 ft. Both the workload ratings and the yaws were grouped into ranges, and the numbers and cumulative lengths of features with those characteristics were determined. The number of accidents in those grouped features was then determined.

The roadway features were grouped in two different schemes. The first scheme grouped features according to Messer's proposed LOC, which ranged from A to F. The number of accidents per 10^8 vehicle mi was then calculated for the cell groupings. The results are given in Figure 4. As may be seen from the graph in Figure 3, accident rates dramatically increased for those features with effective workloads of greater than 6 (LOC F). This finding is consistent with Messer's projected "big problems possible" for this LOC (*16,17*). In a second grouping scheme, roadway segments belonging to various categories of yaw were grouped. As shown in Figure 5 the accident rate was much higher for the segments with yaws of greater than or equal to 4.

Those roadway segments that had high effective workloads and those that had effective workloads much higher than the moving average had much higher accident rates than those segments that had lower effective workloads and those segments that had low yaw values. This finding was expected; an elevated accident rate

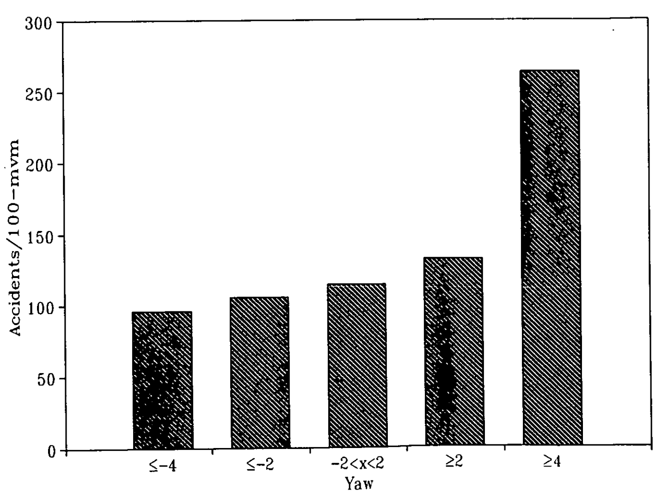

FIGURE 5 Evaluation of yaw.

for areas with extremely low workloads and yaws was not found, however. A possible cause for this might have been that the driver workloads on the study roadways might not have been low enough in absolute terms, since roadways were chosen by criteria that included the requirement that all of the roadways pass through rolling terrain. In general, the study roadways had a larger amount of topographical relief and roadway curvature than most roadways, which produced higher driver workloads than are found on most roadways.

CONCLUSIONS AND RECOMMENDATIONS

The 19 highway segments that were studied all shared some basic characteristics: they all functioned as rural collector highways, and they were all defined as passing through rolling terrain. In addition they were generally designed and constructed in the late 1940s to the late 1950s. Although some were reconstructed at later dates, generally most of the alignments remained unchanged from the original time of construction. The roadways are presumed to have met the standards in place at the time of construction, although when examined according to today's standards and guidelines the roadways appeared to be in need of improvement. Vertical and horizontal curvatures were severe, sight distance was limited, shoulders were generally lacking, and bridges sometimes lacked approach guardrail or adequate bridge rail. Despite these and other problems, the roadways remain in active use and will presumably remain in active use for some time. An evaluation of accident experience on the roadways was undertaken in an attempt to determine if the various measures of workload might be related to that experience.

Conclusions

1. The microscopic evaluation of the study roadways showed that large changes in workload over a short distance were strongly associated with high accident rates. When feature workloads were compared with the average workload in the previous 1,000 ft, it was found that roadway segments exhibiting a large positive change in workload experienced a greatly increased accident rate when compared with those on other segments of the study roadways. This finding would seem to indicate that when ad hoc driver expectancies are not met, accident risk increases.
2. The microscopic evaluation of the study roadways showed that segments associated with high workloads (LOC F) were also associated with high accident rates. The accident rates for those segments were much higher than those for the other roadway segments. Although conclusive statistical evidence has not been provided, the available information seems to support Messer's contention that features with high workloads can be expected to have "big problems." This finding would seem to indicate that when a priori expectancies are not met, accident risk increases.
3. The Messer driver workload procedure (*16,17*) was found to be a practical means of assessing design consistency and driver workload. The application of the procedure and the relationship between procedure results and accident history indicate that the procedure is a demonstrated, viable means of analyzing geometric design consistency and driver workload in terms of accident risk.

Recommendations for Future Research

1. A logical next step in the analysis of the Messer procedure would be to couple a study of driver workload with a study of speed variations along a series of roadways. In this way levels of workload could be more precisely calculated (since the V_{85} is one input to the Messer procedure), and the findings could be compared with those recommendations made by various speed consistency procedures (*9,10,13,16,17*).
2. Another area in need of research is the further refinement and extension of the Messer procedure through reexamination of the levels of workload obtained for various roadway features. One way that this objective could be accomplished would be through the use of the occluded vision device currently being tested at the Texas Transportation Institute. The device lets drivers control explicitly the amount of information that they receive through regulation of their sight. Drivers determine the amount of vision time that they need to operate a vehicle as they drive; presumably drivers increase the amount of time they have clear vision during those times when high-workload areas are being traversed. By monitoring error rates, it is possible to screen out those drivers who are overly brave or optimistic about being able to drive a feature. This screening ability could be one mechanism that could further validate the Messer procedure as well as extend the guidelines provided by Messer.
3. Another area that appears to be in need of further research is the concept implicit in the yaw variable used in the examination of driver workload. Further study and analysis of the effects of large abrupt increases in workload seem justified given the relationship between yaw and accident risk revealed in the present study.
4. One last area of research that could prove to be helpful would be to validate the Messer procedure through the study of higher-class roadways, including four-lane divided highways. Although not substantiated by the present research, elevated accident risk is expected on segments of roadway associated with extremely low workloads. It seems reasonable to assume that traffic volume provides a significant part of the workload that a driver experiences; high-standard roadways with low traffic volumes might well experience high accident risks. Texas (and other states) is in the process of forming a trunk system consisting of four-lane divided highways with high standards; many of those roadways will have very low traffic volumes. Through the study of roadways with these characteristics, it would be possible to predict whether these roadways will experience increased accident rates when compared with those on other, similar facilities.

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