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Applying Safety and Operational Effects of Highway Design Features to Two-Lane Rural Highways

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ABSTRACT

Applying Safety and Operational Effects of Highway Design Features to Two-Lane Rural Highways

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Abstract:

Background: Rural two-lane highways constitute a majority of the mileage of public roads in the United States. Rural two-lane highways have 40% of the total travel but experience 60% of the highway fatalities. The fatality rate for two-lane rural highways in the United States is 2.39 per hundred million vehicle miles vs. 1.43 per hundred million vehicle miles for the interstate system.

Objective of the Work: During the 1980's and 1990's, research was carried out in the United States to quantify the safety and operational effects of various key geometric design features including:

- Lane and Shoulder Widths
- Roadside Safety
- Horizontal and Vertical Alignment
- Sight Distance
- Rural Intersections

Study and analysis of the safety and operational benefits of these various key geometric design features has resulted in a series of reports and findings which include Transportation Research Board Special Report 214, State of the Art Report 6, NCHRP 247, 362, 374, 376, 383, 400, 430, 439, and 440, NCHRP Synthesis 299, FHWA Program Reports (1998 Flexibility in Highway Design, Prediction of the Expected Safety Performance of Rural Two-Lane Highways, 2001 Older Driver Highway Design Handbook, 2000 Roundabouts; an Informational Guide, 2002 Safety Effectiveness of Intersection Left- and Right-Turn Lanes) , 1999 ITE Traffic Safety Toolbox, AASHTO Roadside Design Guide, and the new AASHTO 2001 Policy on Geometric Design of Highways and Streets as identified in the bibliography for this paper.

Aggregating this research has resulted in a compendium of the safety benefits of certain geometric design features for two-lane rural highways which links design standards and safety. This aggregated research information provides a basis for software analysis of proposed highway designs to assess their expected safety performance as well as the traditional capacity performance. Application of these benefits and effects achieves a numerical methodology for safety in a similar manner as is commonly carried out for capacity.

This compendium of the safety and operational benefits of highway design features is being deployed in the United States to state highway departments in advance of the release of the software based analysis system.

TEXT

I. Introduction

Safety of two-lane rural highways in the United States is a significant component of overall traffic safety. Rural two-lane highways have a fatality Rate that is 2.5 times that for urban road. Rural two-lane highways have only 40 % of miles traveled but 60% of the total traffic fatalities.

Safety is one of three priority areas in the Federal Highway Administration's Vital Few as defined by Secretary Mary Peters.

II. Background

Toward addressing the two-lane highway safety problem in the United States, the Federal Highway Administration has carried out a significant body of safety research starting in 1986 as identified in the bibliography. In Special Report 214 "Designing Safer Roads: Practices for Resurfacing, Restoration, and Rehabilitation" by the Transportation Research Board in 1987, the relationship of lane width and shoulder width to crash frequency was established. Further research established the relationships of the "quality" of the roadside in terms of its hazard rating. The safety effects of horizontal curvature were established as well as the effects of intersection sight distance and the type of traffic control. FHWA recently added to this compendium of safety effects research in December of 2002 with the release of Report No. FHWA-RD-02-089 "Safety Effectiveness of Intersection Left-and Right-Turn Lanes.

III. Numerical Safety Analysis of Geometric Design Features

The relationships of the geometric features to crash frequency have been defined in terms of a series of mathematical models based upon research. A representative "model" for predicting crashes from lane width, should width, and other roadside information is the Zegeer Crash prediction model (FHWA, 1987) for 2-lane highways -- "Cross Section Related Crashes".

$$AO/Mi/Yr = 0.0019\ (ADT)^{0.8824}\ (0.8786)^{W}\ (0.9192)^{PA}\ (0.9316)^{UP}\ (1.2365)^{H}\ (0.8822)^{TER1}\ (1.3221)^{TER2}$$

Where: AO/Mi/Yr is single vehicle, head-on, opposite direction sideswipe, and same direction sideswipe crashes per mile per year,
ADT = Average Daily Traffic (vpd)
W = Lane Width (feet)
PA = Average Paved Shoulder Width (feet)
UP = Average Unpaved (dirt, gravel, turf, stabilized) Shoulder Width (feet)
H = Roadside Hazard Rating (1 to 7)
TER1 = 1 if flat; = 0 otherwise

TER2 = 1 if mountainous; = 0 otherwiseThe mathematical relationships or "models" linking the predicted crash frequency are detailed in Appendix A - Equations and Models of this paper; these mathematical relationships encompass:

- Cross Section Elements
- Total Crashes
- Single Vehicle Run-off-the-Road Crash Rates
- Fixed Object Roadside Crashes
- Horizontal Curves
- Speed of Vehicles on Approaches to Horizontal Curves
- Three-dimensional Design Characteristics
- Insufficient Sight Distance
- Stop Controlled Intersections
- Signal Controlled Intersections

These mathematical models from the research linking geometric and intersection control features to safety performance are the basis for the Interactive Highway Safety Design Modules. These models and their safety basis are the framework for numerical safety analysis of the safety of design alternatives including alternatives encountered in Context Sensitive Solutions. This body of safety research is the basis for the significant enhancement of the 2001 Policy on Geometric Design of Highways and Streets by AASHTO (2001 "Green Book") from a "nominal" safety point of view to as substantive safety basis. That is, when design engineers are asked about safety, they often speak about whether a roadway is "substandard" which is another way of saying one or more of its features doesn't meet current or applicable design criteria.

Nominal or "Standard" Safety is defined by the following:
–Roadway design must enable road users to behave legally
–Roadway design should not create situations with which a minority of road users has difficulties
–Owning agency requires protection against claims of moral, professional and legal liability

Substantive safety is the *performance of the road* as measured in terms of crashes, including their frequency, type and severity; substantive safety is a function of:
– resources are available (roadway design, maintenance, enforcement, emergency medical services)
–"context" of the location

The significant change of the 2001 "Green Book" is this change in philosophy from "nominal" safety to a "substantive" safety basis. In the Foreword of this policy is set forth this change in the following statements "Specific site investigations and crash history analysis often indicate that the existing design features are performing in a satisfactory manner. The cost of full reconstruction for these facilities, particularly where major realignment is not needed, will often not be justified."

With the adoption of the 2001 "Green Book" in March of 2002 by the Federal Highway Administration for all federal aid projects in the United States, the substantive safety approach is now recognized as a "best practice" for highway and street design.

IV. Current Status of Application

FHWA jointly with CH2Mhill developed a new training workshop on "Safety and Operational Effects of Geometric Design Features for Two-Lane Rural Highways" in 2001 to deploy the new numerical substantive safety analysis methodology to design engineers and transportation and planning professionals. To date, this workshop has trained engineers and planners in the states of Iowa, Minnesota, Wisconsin, Kansas, Indiana, Illinois, and New Mexico; training workshops are scheduled in Vermont, New York, and Colorado before the end of 2003.

V. Interactive Highway Safety Design Modules

Turner Fairbanks Highway Research Center has developed the Interactive Highway Safety Design Modules (IHSDM) to automate the numerical analysis process. IHSDM is a computer software program for CAD work stations. For a given roadway design, the numerical safety value is calculated for the user. Moreover, those segments of project with projected speed and operating inconsistencies are flagged for further investigation by the designer.

Five (8) pilot workshops are scheduled by FHWA for the summer of 2003 in the states of Iowa, Wisconsin, Mississippi, Maine, Montana, Washington, Wisconsin, and Colorado (Federal Lands) to roll out the IHSDM software analysis program. For 2004, FHWA will continue to deploy IHSDM to the state departments of transportation and their consulting engineers.

VI. Conclusion

Application of numerical substantive safety analysis methods are now available to quantitatively evaluate alternative designs and their geometries in addition to the traditional process based upon nominal safety. This numerical substantive safety-based methodology is particularly advantageous for rehabilitation and improvement of lower trafficked two-lane rural highways rather than application of the nominal standards of the "green" book for geometric design and to assess the safety impacts of alternative designs encountered in Context Sensitive Solutions

Many public highway agencies have a backlog of improvement projects with high overall costs which have languished for years waiting funding. Application of numerical substantive safety analysis methods can provide a means to consider them for improvement. Alternative designs developed of spot locations and spot segments with high crash frequency and severity result in reduced overall project costs and with an end result of improvements being carried out.

Some “after” crash data is now becoming available from those states which implemented the numerical substantive safety analysis approach in 2001; this data indicates reduced crash frequency and crash totals for these projects in comparison to the crash experience before improvement.

State departments of transportation have adopted this methodology and are applying it to difficult projects involving older rural two-lane highways in improving their operational and safety performance, in Iowa, Minnesota, Wisconsin, Georgia, Illinois, New Mexico, Vermont, and Indiana.

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Appendix A - Equations and Models

Cross Section Elements, Lane Widths and Shoulder Widths

Model for predicting crashes related to Cross Section elements

$$AO/Mi/Yr = 0.0019\,(ADT)^{0.8824}\,(0.8786)^{W}\,(0.9192)^{PA}\,(0.9316)^{UP}\,(1.2365)^{H}\,(0.8822)^{TER1}\,(1.3221)^{TER2}$$

Where:

AO/Mi/Yr is single vehicle, head-on, opposite direction sideswipe, and same direction sideswipe crashes per mile per year.
ADT = Average Daily Traffic (vpd)
W = Lane Width (feet)
PA = Average Paved Shoulder Width (feet)
UP = Average Unpaved (dirt, gravel, turf, stabilized)
Shoulder Width (feet)
H = Roadside Hazard Rating (1 to 7)
TER1 = 1 if flat; = 0 otherwise
TER2 = 1 if mountainous; = 0 otherwise

Note : Model for use on homogeneous sections of highway. Model does not include additional crashes associated with intersections. Data limits of input to model: ADT less than 10,000 vpd, two-lane, two-way paved rural highways on state primary and secondary systems, lane widths of 8 to 12 feet and shoulder widths less than or equal to 10 feet.

Model for predicting crashes related to Total Crashes

$$AO/Mi/Yr = 0.0015\,(ADT)^{0.9711}\,(0.8897)^{W}\,(0.9403)^{PA}\,(0.9602)^{UP}\,(1.2)^{H}$$

Where:

AO/Mi/Yr is total crashes per mile per year
ADT = Average Daily Traffic (vpd)
W = Lane Width (feet)
PA = Average Paved Shoulder Width (feet)
UP = Average Unpaved (dirt, gravel, turf, stabilized)
Shoulder Width (feet)
H = Roadside Hazard Rating (1 to 7)
TER1 = 1 if flat; = 0 otherwise
TER2 = 1 if mountainous; = 0 otherwise

Note : Model for use on homogeneous sections of highway. Model does not include additional crashes associated with intersections. Data limits of input to model: ADT less than 10,000 vpd, two-lane, two-way paved rural highways on state primary and secondary systems, lane widths of 8 to 12 feet and shoulder widths less than or equal to 10 feet.

Cross Section Elements, Roadside

Model for predicting single vehicle run-off-road crash rates

$$CRs = 7.31\ (0.839)^{W}\ (0.99995)^{ADT}\ (0.975)^{RECC}\ (0.909)^{SW}\ (1.373)^{SS2}\ (1.349)^{SS2}\ (1.238)^{SS4}\ (1.164)^{SS5}\ (1.091)^{SS6}$$

Where:
CRs = single vehicle run-off-road crash rate (per 100 million vehicle miles)
W = lane width (feet)
ADT = Average Daily Traffic
RECC = Recovery area distance (feet) measured from outside edge of shoulder to nearest obstruction
SW = Total shoulder width, paved and unpaved (feet)
SSj, etc = 1 if sideslope = j:1 or steeper, or = 0 otherwise

Note : Model for use on homogeneous sections of highway. Model does not include additional crashes associated with intersections. Data limits of input to model: ADT less than 10,000 vpd, two-lane, two-way paved rural highways on state primary and secondary systems, lane widths of 8 to 12 feet and shoulder widths less than or equal to 10 feet.

Model for predicting the frequency of fixed object roadside crashes

$$CO = (0.00002)\ (ADT)\ (0.88)^{W}\ (1.10)^{C}\ (0.86)^{D}\ (1.2)^{T}$$

Where:
CO = Fixed object crashes per mile per year
ADT = Average Daily Traffic
W = Lane Width
C = Percent coverage of roadside
D = Average distance of objects from edge of pavement
T = 1 if mountainous or rolling terrain, 0 otherwise

Horizontal Alignment

Model for predicting the speeds of vehicles on the approaches to horizontal curves

$$V_{85} = 102.44 - 1.57D + 0.012L - 0.01DL$$

Where:

V_{85} = 85th percentile speed on curve (km/h)
D = degree of curve
L = Length of curve (km)

Model for predicting the speeds of vehicles on the approaches to horizontal curves

$$V_{85} = 41.62 - 1.29D + 0.0049L - 0.12DL + 0.95\,V_t$$

Where:

V_{85} = 85th percentile speed on the curve
D = degree of curve
L = length of curve (mi)
V_t = 85th percentile approach speed (mi/h)*
*this should be measured in the field

Note: This model predicts 85th percentile curve speeds as a function of approach speed and other variables. For best use of the model, actual spot speed data on the curve approaches is desirable.

Model for predicting the accident frequency for a curve on a two-lane rural highway

$$A = [(1.552)(L)(V) + (0.014)(D)(V) - (0.012)(S)(V)]\,(0.978)^{W-30}$$

Where:

A = Number of total crashes on the curve in 5 years
L = Length of curve (mi.)
V = Volume of vehicles in million vehicles passing through curve in 5-year period
D = Degree of Curve
S = 0 if no spiral exists; = 1 if spiral exists
W = total width of lanes and shoulders on the curve (feet)

Note: This model predicts the total number of crashes expected at a curve over a five-year period.

Model for predicting the probability or likelihood that a curve will be a high accident location

D = 0.0713 (DC) + 2.9609 (LC) + 0.1074 (RR) - 0.03512 (PR) - 0.1450 (SW) - 1.5454

$$D = 0.0713 (DC) + 2.9609 (LC) + 0.1074 (RR) - 0.03512 (PR) - 0.1450 (SW) - 1.5454$$

Where:
D = Discriminant Score
DC = Degree of Curve
LC = Length of Curve (mi)
RR = Roadside Rating (scale of 1 to 50)
PR = Pavement Rating (SN)
SW = Shoulder Width (ft)

Note: This model describes the probability that a curve will be a high accident location. The independent variable output of the model is a non-dimensional discriminant value, which must be translated to a probability for interpretation. This model can be used to assist in identification or screening of potential curve sites for review and treatment.

Model for predicting the accident frequency for a curve on a two-lane rural highway

$$A = AR_s (L) (V) + 0.0336 (D) (V) \quad \text{for } L>L_c$$

Where:
A = Annual number of accidents at a segment
AR_s = Accident rate of straight (tangent) segment (per MVM)
L = Length of segment (miles)
L_c = length of curve (miles)
V = Annual Traffic volume through segment (millions of vehicles)

Note: This is the base model used in FHWA's Interactive Highway Safety Design Model (IHSDM) for two-lane rural highways. It is shown for reference. Users are encouraged to access the IHSDM directly for use of the model.

<u>Model for predicting the accident experience of a two-lane rural highway based on its three-dimensional design characteristics</u>

$$Nc = ADT\ (365)\ L\ (10^{-6})\ e^{(CSF)}\ \{sum\ WHi\ e^{(0.0450\ DEGi)}\}\ \{sum\ WVi\ e^{(0.4652Vi)}\}\ \{sum\ WGi\ e^{(0.1048\ GRi)}\}$$

$$\text{with } CSF = (0.6409 + 0.1388\ STATE - 0.0846\ LW - 0.0591\ SW + 0.0668\ RHR + 0.0084\ DD)$$

Where:

Nc = total crashes per year on roadway segment
ADT = Average Daily Traffic
L = Length of segment (miles)
CSF = cross section factor
STATE = 0 or 1*
LW = Lane width (feet)
SW = Shoulder width (feet)
RHR = Roadside hazard Rating (1 to 7)
DD = Driveway density (driveways per mile)
*STATE = 0 for Minnesota; calibration required

And where:

WHi, WVj and WGk represent weighting factors for curvature, grade and crest vertical curvature, with DEGi the degree of the ith vertical curve, WVj the jth crest vertical curve rate and WGk the kth straight grade rate.

<u>Model for predicting the accident experience of a two-lane rural highway based on its three-dimensional design characteristics.</u>

$$N_c = (ADT)\ (L)\ (365)\ (10^{-6})\ e^{(-0.4865)}$$

Lane Width = 12 feet
Shoulder Width = 6 feet
Roadside Hazard Rating = 3
Driveway Density = 5 driveways per mile
Flat tangent alignment

This model is based on the default values inserted into the IHSDM base model (above).

Model for developing accident modification factors for horizontal curves.

$AMF = \{1.55 L_c + (80.2/R) - 0.012S\} / 1.55L_c$

Where:
L_c = Length of Curve (mi)
R = Radius of Curve (ft)
S = 1 if spiral transition is present, 0 if not present

Note: This model can be used to compute accident modification factors for any combination of curve geometry.

Section 7 – Stopping Sight Distance

Model for estimating the risk of a location with insufficient stopping sight distance

$$N = AR_h (L) (V) + AR_h (L_r) (F_{ar})$$

Where:

N = Number of crashes on a segment of highway containing a crest vertical curve
AR_h = Average crash rate for the highway type (e.g., 2-lane rural, freeway, etc.)
L = Length of highway segment (miles)
V = Annual traffic volume (millions of vehicles)
L_r = Length of highway with restricted SSD
F_{ar} = Crash rate factor (see Tables in Section 7)

Note: this model is uncalibrated and should be used only for the purposes of estimating or demonstrating the relative sensitivity of a potential safety problem associated with a sight restriction. Application of the model requires a default or actual accident rate for the two-lane highway being studied.

Section 8 – Intersections

Model for estimating frequency of accidents at rural stop-controlled intersections

$$C_A = (ADT1)^{0.850} \times (ADT2)^{0.329} \times e^{(-9.463)} \times e^{(0.110 \times PK\%LEFT1 - 0.484 \times LTLN1S)}$$

Where:

C_A = Annual number of crashes within 250 feet of intersection
ADT1 = Average two-way major road traffic (vpd)
ADT2 = Average two-way minor road traffic (vpd)
PK%LEFT1 = percent major road traffic during peak hours turning left
LTN1S = 0 if major road has no left-turn lanes; 1 if major road has at least one left turn lane

Model for estimating frequency of accidents at rural signalized intersections

$$C_A = (ADT1)^{0.62} \times (ADT2)^{0.395} \times e^{(-6.954)} \times e^{(-0.0142 \times PK\%LEFT2 + 0.0315 \times PK\%TRUCK)} \times e^{(-0.675 \times PROT\ LT + 0.130 \times VEICOM)}$$

Where:

C_A = Total number of annual crashes within 250 feet of intersection
ADT1 = Average two-way major road traffic (vpd)
ADT2 = Average two-way minor road traffic (vpd)
PK%LEFT2 = percent minor road traffic during peak hours turning left
PK%TRUCK = percent of traffic entering intersection during peak hours that consists of trucks
PROT LT = 0 if major road has at no protected left turn; 1 if the major road has at least one protected left turn
VEICOM = 0.5 [(VEI1 + VEI2)] where
VEI1 = sum of absolute percent grade change per 100 feet for each vertical curve along major road; any portion of which is with 800 feet of intersection; divided by number of vertical curves; VEI2 is for minor road profile