Geometrically Induced Roughness at Grade Breaks

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Grade breaks are used to make the transition from a secondary roadway elevation to the elevation of the main highway. At the design stage, wrong decisions regarding the geometrical composition of the transition profile may produce an undesirable level of roughness that may be unsafe. Although a variety of instruments can be used to physically measure the road roughness, there are no known standards for analyzing and estimating the level of profile roughness during the design stage. A methodology that uses the International Roughness Index (IRI) as the performance measure of profile roughness is presented. A series of simulation experiments was performed for six types of intersections to examine the relationship between roughness and the intersection design parameters. The results of the experiments show that profile roughness is affected by the transition curve parameters as well as the elevation difference between the main highway and the intersecting secondary roadway. A decision support system called SIDRA (System for Intersection Design with Roughness Analysis) was developed to estimate the roughness of an existing profile or to generate an alternate profile with a lower level of roughness. Statistical analysis showed a close correlation between SIDRA-generated results and data measured in the field. SIDRA-produced values of IRI were also correlated with the serviceability index, a commonly accepted roughness measure.

Design and management of highway networks have been going through technologically driven changes to provide the best possible service to highway users. The advent of computer visualization tools such as computer-aided design and drafting (CADD) and geographic information systems (GISs) allows designers to visually experience highway geometries before construction. These tools are used by the designers to achieve a basic design objective: to produce the best possible plan to meet the specified needs. In designing a transition profile, although one can easily view it at the design stage, at the present time, there are no available means of determining its inherent roughness owing to design assumptions.

Geometric design of a highway intersection usually incorporates one or more grade breaks to allow a transition from a secondary roadway elevation to the elevation of an intersecting main highway. The design of a grade break is affected by factors such as horizontal alignments, profile, plan of the intersection, clearances, and horizontal dimensions of the highway cross sections (*1*). An improperly designed grade break will produce a level of roughness that may not be acceptable to highway users or that may possibly be unsafe. Currently AASHTO does not have specific guidelines for the design of grade breaks. A search of the literature on established methodologies produced no results. It is conceivable that there may be design procedures at some departments of transportation or local municipalities for their internal use; however, the authors are unaware of such processes. To the best of the authors' knowledge, there is no tool that can be used to analytically generate a measure of roughness at the intersection, produce a profile with a low level of roughness, or improve an existing design.

Road roughness is defined as the variation in surface elevation that induces vibrations in traversing vehicles (*2*). By causing vehicle vibration, roughness has a direct influence on vehicle wear, ride comfort, and safety (*3,4*). Road roughness is gaining increasing importance as an indicator of road condition, both in terms of pavement performance and as a major determinant of road user costs. Of the various kinds of desired surface qualities, in the public view, road roughness has a strong influence on the measure of serviceability. In the AASHTO Road Test, road roughness was found to be the primary correlate of the present serviceability index (SI) (*5*). As a result many state highway departments and transportation agencies use road roughness to estimate the SI.

The main objective of the study was to develop a decision support system for the design of a highway intersection with an acceptable level of roughness. The performance measure of the design is based on the value of the International Roughness Index (IRI). IRI calculation is accomplished by incrementally computing four variables along the profile. These four variables—defined in a previous report (*6*) in which a detailed description of IRI is presented—simulate the dynamic response of a reference vehicle traveling over the profile.

The present study considered six different profiles ranging from a simple T-intersection to a compound design that included several vertical curves. The following section presents the particular makeup of each profile.

TRANSITION PROFILES

To define the variables associated with a particular profile, consider Figure 1. This type of profile, joining a secondary roadway and the main highway at different elevations, is referred to as profile SUD (symmetrical up-down); it is symmetrical about the centerline of the main highway (Point B) and consists of a combination of a parabola (P), a tangent (T), and a sag (S) curve. In this paper, for the sake of convenience, the term *parabola*—in contrast to the term *sag*—is used to designate the AASHTO type II crest vertical curve (*1*). For all the analyses, the starting profile consists of a 10.8-m (36-ft) tangent length of 0 percent gradient along the secondary roadway joined to a sag curve of 45 m (150 ft), which is joined by a second tangent of 51 m (170 ft) and finally a parabola of 45 m (150 ft) that joins the tangent to the cross slope of the main highway. The width of the main highway is assumed to be 14.4 m (48 ft), with a cross slope of 2.5 percent on both sides of the centerline. The difference in elevation be-

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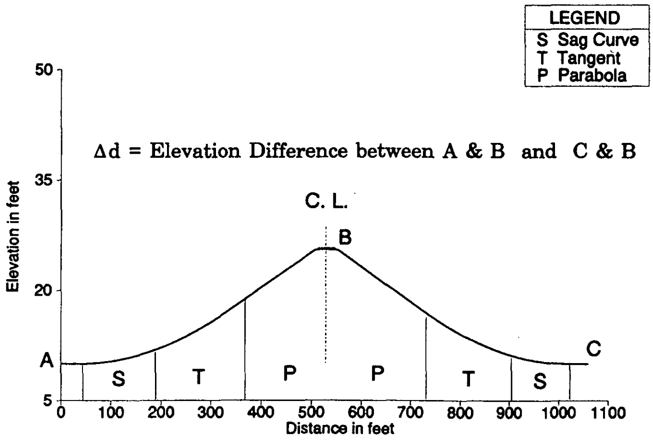

FIGURE 1 SUD profile.

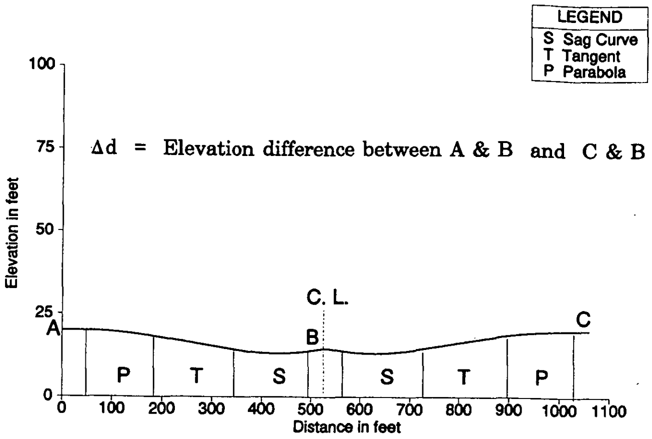

FIGURE 3 Profile SDU.

tween the starting point on the secondary roadway (Point A in Figure 1) and the elevation of the crown of the main highway (Point B) is defined as the elevation difference and is designated as Δ*d*.

The properties of the three curves (P, T, and S) are controlled by three parameters: start gradient, end gradient, and the length of the curve. For a given set of values and an elevation difference, the calculated value of IRI for the profile is the performance measure of that profile. The following sections present the descriptions of the remaining five profiles.

Profile TINT

Profile TINT is the simplest type of intersection considered in the study. This profile played an important role in the study because the S-T-P combination was used as a building block in more complex transitions. Figure 2 shows a TINT profile.

Profile SDU

When the right side of the main highway is a mirror image of the left side of the main highway, the profile is called a *symmetrical profile*. The SDU profile has a P-T-S combination on the left side of the main highway and an S-T-P combination on the right side. Figure 3 shows an SDU profile.

Profile XUU

For asymmetrical profile XUU, the elevation difference of the secondary roadway and the main highway is kept constant on both sides of the main highway. Both sides of the main highway have an S-T-P combination (Figure 4).

Profiles SVV and SCC

A compound profile consists of more than two tangents on one side of the main highway. There are two types of compound profiles: concave (C) and convex (V). A concave profile consists of a sag curve, a tangent, a parabola, a tangent, and a sag curve. In a concave profile, the roadway goes upward and then downward. The convex profile consists of a parabola, a tangent, a sag curve, a tangent, and a parabola. In a convex profile the roadway goes

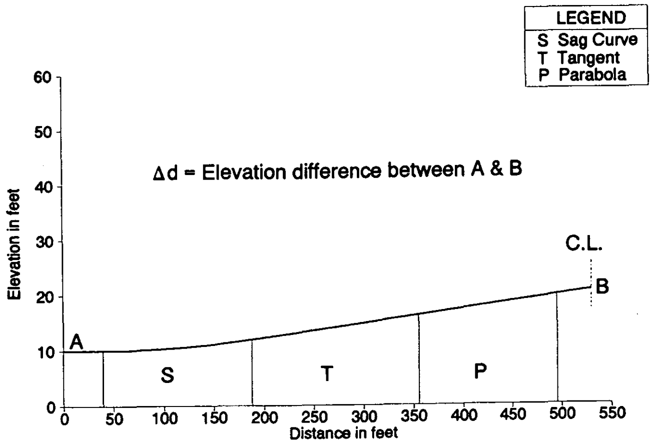

FIGURE 2 Profile TINT.

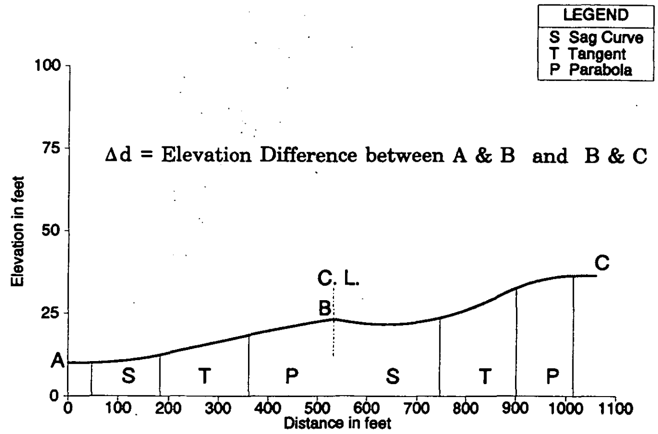

FIGURE 4 Profile XUU.

downward and then upward. Profile SVV is convex on both sides of the main highway (Figure 5), and profile SCC is concave on both sides of the main highway (Figure 6).

APPROACH

To examine the relationship between roughness and design parameters for intersections at grade, a series of simulation experiments was performed on each of the six profiles discussed in the previous sections. The experiments were performed by varying the parameters of two curves for three values of elevation difference between the secondary roadway and the main highway to generate profiles. For every profile generated two corresponding IRI values were calculated, one for each direction along the profile. This procedure was repeated for all six intersections.

On the basis of the results from the simulation experiments, a decision support system called *SIDRA* (System for Intersection Design with Roughness Analysis) was developed. When provided with the values of curve parameters for an existing intersection, a highway designer can use SIDRA to generate alternative or improved designs by varying the curve parameters within the feasible ranges.

The validation process of SIDRA consisted of comparing the generated IRI values with the measured IRI values on four existing intersections in Baton Rouge, Louisiana. The measured values were obtained by using two road roughness measuring devices: the K. J. Law model 8300 Roughness Surveyor and the Face Dipstick. The comparison of the IRI values is presented later in the paper.

The SI has commonly been used as a measure of riding quality on roadways in many places. The relationship of SI to IRI for roadways has been examined by many researchers. However there are no reported data on the relationship between SI and IRI at intersections. A correlation study was performed on the basis of the values of IRI and SI for 10 intersections in Baton Rouge, Louisiana.

SIMULATION PROCEDURE

This section presents the simulation procedure performed on six types of intersections. Each of the six profiles is characterized by the number of curves that make up the profile and a set of curve parameters. In the simulation profiles are generated systematically by changing one parameter at a time and adjusting the other parameters to meet the specified elevation difference. On the basis of the values of the curve parameters, a set of elevations is calculated for the profile. The elevations are generated at 1-ft intervals, and a cumulative IRI value is computed for the profiles in both directions; these profiles are called *Final-IRI* and the *opposite Final-IRI.* The last computed IRI value at the end of a profile is the cumulative IRI for the total length of the profile and is referred to as the *Final-IRI.* The opposite Final-IRI is determined by traversing the profile in the opposite direction. The general simulation procedure is summarized below.

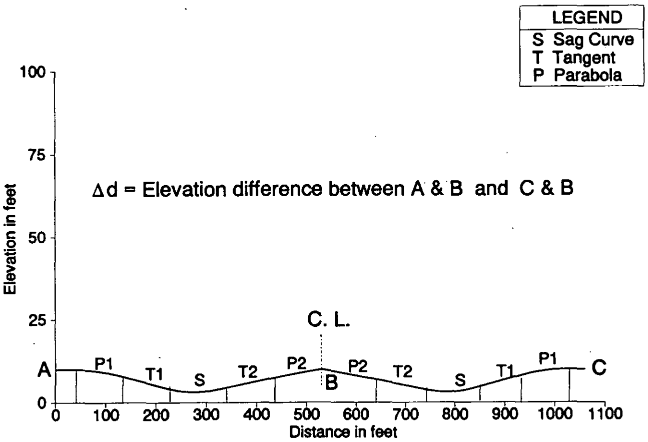

FIGURE 5 Profile SVV.

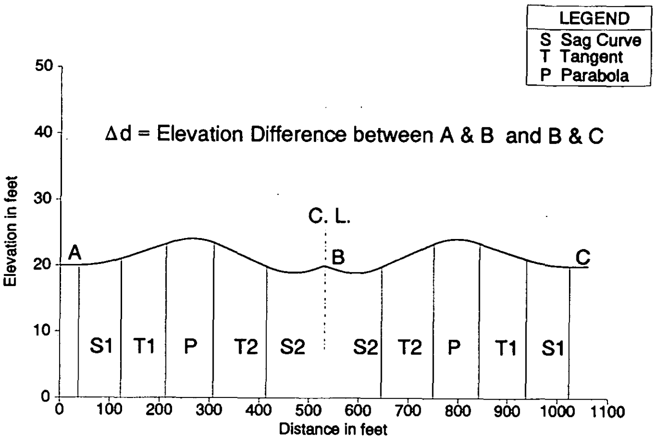

FIGURE 6 Profile SCC.

1. *Basic design of curve combination.* For a given type of intersection, preliminary studies are conducted to determine a curve combination that provides a smooth transition from a secondary roadway to the main highway. Normally at least one tangent is used to provide a smooth transition between curves. The number of curves including the tangent(s) in the transition profile is called N.
2. *Initial setting of design parameters.* An appropriate initial value for each of the following design parameters is selected: the total horizontal length of the intersection, the width and the cross slope of the main highway, the initial gradient of the secondary roadway, and the elevation difference between the secondary roadway and the main highway.
3. *Initial setting of curve parameters.* On the basis of an initial setting of design parameters in Step 2, the curve parameters of a feasible profile (as defined by AASHTO geometric design standards) are determined by setting the lengths of the three curves approximately equal. Next, a profile based on the curve parameters is generated and the Final-IRI and opposite Final-IRI are computed. Subsequently, the curve parameters and the other design parameters to be varied in the simulation experiments are identified.
4. *Experiments with varied curve lengths.* Given an N-curve combination, a number of feasible profiles for intersection design are generated in the following way.
   a. Increase the gradient of the first tangent in the N-curve combination by a small percentage, R. Vary the length of two other curves to accommodate this change. Generate a profile

on the basis of the new curve parameters and compute the Final-IRI and opposite Final-IRI.

b. Repeat Step *a* above by increasing the tangent *R* percent and adjusting the length of the two curves selected in Step *a* above to generate a feasible profile. This step is repeated until a feasible profile cannot be generated either by increasing the tangent gradient or by exhausting all possible tangent lengths.

c. For all the feasible profiles generated in Steps *a* and *b*, select the profiles with the lowest Final-IRI and the lowest opposite Final-IRI. Output the curve parameters of the two profiles.

d. Repeat Steps *a*, *b*, and *c* by varying the lengths of the two other curves. For an *N*-curve combination, this step is repeated $C(N,2)$ times, as defined below.

$$C(N,2) = \frac{N!}{(N-2)!2!}$$

5. *Experiments with varied elevation differences.* The elevation difference between the secondary roadway and the main highway is increased by a small percentage, *E*. Steps 3 and 4 are repeated with the new elevation difference.

In most of the experiments completed in the present study, the elevation difference is tested at three different levels. Therefore $3 \times C(N,2)$ sets of experiments are performed for each of the six types of intersections. The number of profiles to be generated per experimental set is dependent on the initial settings of the design parameters and the step size *R*. An illustrative example is presented below to demonstrate the simulation procedure as applied to profile TINT.

SIMULATION EXAMPLE: PROFILE TINT

Preliminary studies on T-intersections indicated that both the curve parameters and the elevation difference between the main highway and the secondary roadway affect the maximum IRI and the Final-IRI. Figure 2 depicts a TINT profile that has a total horizontal length of 159 m (530 ft). The profile starts with a 0 percent tangent that is 10.8 m (36 ft) long on the secondary roadway. The tangent is then joined by a combination of a 45-m (150-ft) sag curve, a 51-m (170-ft) tangent, and a 45-m (150-ft) parabola that connects to the main highway with a width of 14.4 m (48 ft) and a cross slope of 2.5 percent.

Experiments are performed on profile TINT by systematically varying two factors: (a) the lengths of two of the three curves in the S-T-P combination and (b) the elevation difference between the main highway and the secondary roadway. Possible pairs of curves from the S-T-P combination (S-T, P-T, and S-P) are tested at three levels of elevation differences. The levels are selected in a manner that grade changes of approximately 1, 2, and 3 percent would result in the intersection.

The experiments can be divided into three groups, as shown in Table 1. For example Group TINT.ST experiments are performed by reducing the tangent length and increasing the sag length to meet the induced 0.02 percent change in the tangent gradient. In each group experiments are repeated by using the same procedure for three different elevation differences, that is, 1.59 m (5.3 ft), 3.18 m (10.6 ft), and 4.77 m (15.9 ft). Two profiles with the lowest Final-IRI and opposite Final-IRI are selected from each experiment for a total of 18 profiles. The curve parameters of the 18 profiles and their Final-IRI or opposite Final-IRI are summarized in Table 2. Figure 7 shows the IRI variation along the TINT profile for one experiment. The variation of IRI as a function of the length of parabola is plotted in Figure 8. In Figures 7 and 8, the IRI values are computed for both directions of travel. The arrows in the figures show the direction of travel.

TABLE 1 TINT Experiment Groups

Experiment Group	Sag Length	Tangent Length	Parabola Length
TINT.ST	Increase	Decrease	Constant
TINT.PT	Constant	Decrease	Increase
TINT.SP	Increase	Constant	Decrease

SIMULATION RESULTS

A large number of simulation experiments were performed in the study for six types of intersections on the basis of the simulation procedure described in the previous section. The purpose of the simulation is to study the relationship between design parameters and the roughness. In general, the Final-IRI value is directly proportional to the elevation difference between the secondary roadway and the main highway. IRI variation is also sensitive to the variation in the parabola length. The suggested parameter settings from the simulation experiments are summarized in Table 3 by profile type.

SOFTWARE IMPLEMENTATION

A decision support system called SIDRA was developed on the basis of the experimental results. It is written in QuickBASIC

TABLE 2 Results of TINT Experiments

Experiment Type	Sag Length (ft.)[a]	Tangent Gradient %	Tangent Length (ft.)	Parabola Length (ft.)	Final-IRI (in/mile)[b]	Opposite Final-IRI (in/mile)
			Δd = 5.3 ft.			
ST	319	1.24	1	150	2.7	-
ST	319	1.24	1	150	-	13.83
PT	150	.9	170	150	5.8	-
PT	150	.9	170	150	-	17.01
SP	150	.9	170	150	5.8	-
SP	150	.9	170	150	-	17.01
			Δd = 10.6 ft.			
ST	290	3.29	30	150	4.73	-
ST	293	3.31	27	150	-	13.69
PT	150	2.59	31	289	6.89	-
PT	150	2.55	170	150	-	16.31
SP	196	2.75	170	104	6.36	-
SP	253	2.97	170	47	-	14.49
			Δd = 15.9 ft.			
ST	289	5.4	31	150	11.18	-
ST	289	5.4	31	150	-	16.76
PT	150	4.7	32	288	11.97	-
PT	150	4.7	32	288	-	20.1
SP	174	4.32	170	126	14.47	-
SP	174	4.32	170	126	-	19.52

[a] 1 ft. = 0.3 m; [b] 1 in/mile = 15.875 mm/km

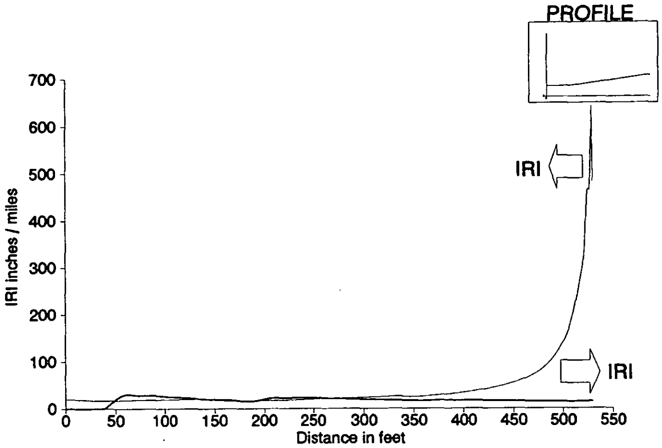

FIGURE 7 IRI variation for TINT profile.

TABLE 3 Summary of Simulation Results

Profile	Basic Design	Parameter Settings for Low IRI Values (approximate values)		
		Curve Type	Curve Length as % of Profile Length	IRI is Sensitive to the Length of
TINT	S-T-P	T P	6 9	P
SUD	S-T-P (left) P-T-S (right)	T P	12 4	
SDU	P-T-S (left) S-T-P (right)	T P	12 50	S and P
XUU	S-T-P (for both sides)	T P	12 50	P
SVV	P1-T1-S-T2-P2 (for both sides)	T1 P1 T2 P2	12 22 16 4	P2
SCC	S1-T1-P-T2-S2 (for both sides)	T1 S1 T2	12 24 34	

language (*7*) on an IBM compatible PC. The user has the option of calculating the roughness of a profile when the elevation points are provided in an ASCII file. When provided with the elevation difference and the length between the secondary roadway and the main highway, the program generates feasible profiles and selects the ones with lower IRI values. There is a separate module for each type of intersection.

VALIDATION OF SIDRA

To validate the accuracy of SIDRA surface elevation data were collected from two street intersections in Baton Rouge, Louisiana. On the basis of those data IRI values were generated by SIDRA and were compared with the values obtained from two road roughness measuring devices: the K. J. Law model 8300 Roughness Surveyor and the Face Dipstick. The K. J. Law surveyor uses an ultrasonic road sensor and an accelerometer to measure the longitudinal profile of the road. The measured profile is used to compute the Mays Index, which is identical to the IRI (*8*). The Face Dipstick measures the profile by automatically recording the change in elevation at every foot. An on-board computer system was used to compute the IRI values of the profiles.

Two sets of data were obtained for each intersection: one for each traffic lane. The road test was conducted by the technical staff of the Louisiana Transportation Research Center (LTRC). Table 4 depicts the IRI values. Close correlations between the values were observed.

RELATIONSHIP OF IRI TO SI

The concept of SI was first introduced at the AASHTO Road Test in the late 1950s. The basic concept is that a panel of users rates the pavement as to its roughness and ability to serve the motoring public. The SI scale is from 0 to 5, with a pavement rated as 0 being impassable and a pavement rated as 5 being perfectly smooth. On the other hand, an IRI value is the measure of roadway roughness; in contrast to SI, it does not clearly express the level of rider's comfort. Since the AASHTO Road Test, the SIs of the roads have been routinely correlated with the outputs of various roughness measuring devices. In one such study, the relationship of SI to IRI (as measured with the K. J. Law model 8300 Roughness Surveyor) has been documented by Cumbaa (*8*). The study concluded, "The International Roughness Index appears to be a useful tool for identification of the relative roughness levels between pavements and for predicting the rideability rating which a panel might provide irrespective of pavement type."

To the best of the authors' knowledge, the SI concept has never been applied to the geometric design of intersections. Furthermore the propriety of extending the established relationships to inter-

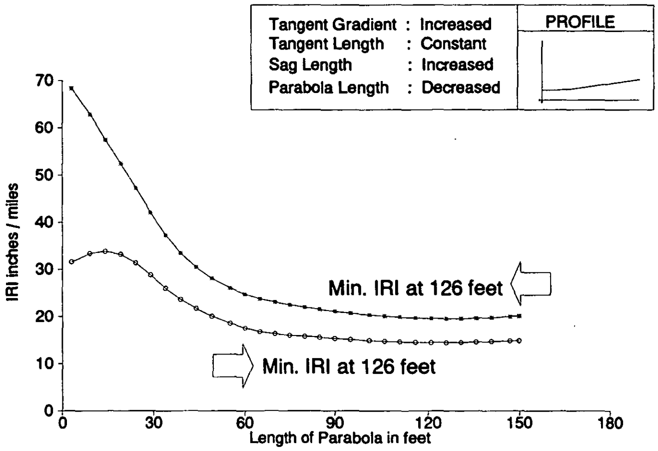

FIGURE 8 IRI variation with respect to length of parabola.

TABLE 4 IRI Comparison with Instrument Readings

Hwy Name/ Lane	K.J.Law IRI (in/mile)*	Dipstick IRI (in/mile)*	SIDRA IRI (in/mile)*	K.J.Law / SIDRA	Dipstick / SIDRA
LA-1/N	147	141.43	140.9	1.040	1.003
LA-1/S	210	208.73	208.8	1.005	0.999
PICOU/E	278	261.18	262.7	1.050	0.994
PICOU/W	278	267.08	266.5	1.040	1.002

*1 in/mile = 15.875 mm/km

sections for which a panel of motorists may rate intersection roughness differently than normal highway roughness has not been verified. A section of highway and an intersection may have the same measured roughness over a given length, but a panel may subjectively rate them as having differing SIs.

Ten intersections in Baton Rouge, Louisiana, were rated by an experienced team of LTRC staff while taking measurements of IRI with the K. J. Law model 8300 Roughness Surveyor. Table 5 summarizes the data for the 10 intersections. A linear regression was performed on the measured IRI and the rated SI values (Table 5), with IRI as the independent variable. The following relationship resulted:

$$SI = 4.46 - 0.00592 * IRI$$

The coefficient of determination (R^2) of the regression was 0.8, which indicates that there is a good linear relationship between SI and IRI for intersections. This regression equation was used to estimate the SI values for the measured IRI values at the 10 intersections. The estimated SI (produced by the regression equation) and the percent difference between the rated and the estimated SIs are presented in Table 5.

To study the relationship between the SIs of roadways and intersections further, the rated SIs of the 10 intersections were plotted against the measured IRI. Figure 9 shows the relationships. A review of Figure 9 indicates that, although there is a strong relationship between IRI and SI, it is possible for a rating panel to subjectively rate the intersection roughness somewhat differently than it rates the highway segments.

The actual IRI of any roadway segment consists of two parts: the IRI due to the design and the IRI due to construction. In the intersection design, one should always strive for a lower value of design IRI, knowing that additional roughness will be added during construction. The LTRC technical staff has recommended that the values given in Table 6 be used as guides for the IRI values of an intersection owing to design.

The IRI of newly constructed highways in Louisiana generally ranges between 1270 mm/km (80 in./mi) and 3175 mm/km (200 in./mi), with a propensity of the value estimated to be approximately 1746 mm/km (110 in./mi). If this latter value is used as the construction IRI and is added to the IRI value owing to the geometric design of the intersection, the sum of the two values can be a good approximation for the total IRI at an intersection.

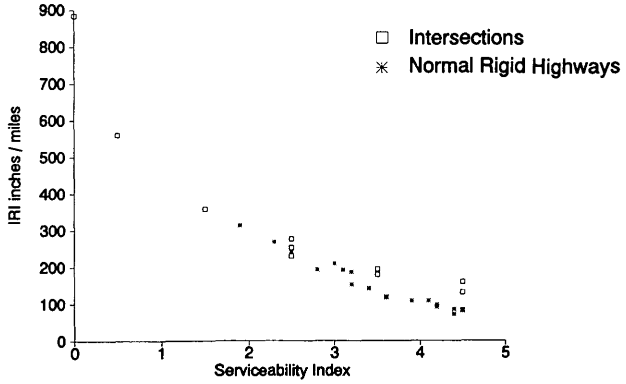

FIGURE 9 Relationship of IRI to SI.

TABLE 5 Comparison of IRI and SI at Intersections

Intersection	IRI (in/mile)^a	Rating	Rated SI	Estimated SI	% Difference
Lee Dr. (W.B.) X Highland Road	562	Very Poor	0.5	1.13	126
O'Neal Lane (N.B.) X Florida Blvd.	884	Impassable	0	0	-
Burbank (S.B.) X Ben Hur	230	Fair	2.5	3.09	23.6
Bluebonnet (N.B.) X Highland Road	359	Poor	1.5	2.33	55.3
O'Neal Lane (S.B.) X Old Hammond	276	Fair	2.5	2.82	12.8
Park Blvd. (S.B.) X Tulip	253	Fair	2.5	2.96	18.4
Perkins Rd. (N.B.) X Terrace	180	Good	3.5	3.39	3.1
Hyacinth (W.B.) X Cloverdale	195	Good	3.5	3.30	5.7
Hyacinth (E.B.) X Stuart	160	Very Good	4.5	3.51	22
Burbank (S.B.) X Lee Drive	131	Very Good	4.5	3.68	18.2

^{a}1 in/mile = 15.875 mm/km

CONCLUSIONS

The objective of the research described here was to develop a decision support system that aids the highway designer in designing an intersection. The project started with a series of simulation experiments to provide an understanding of how various profiles are affected by the properties of the curves that make up the profile. The results showed that the roughness of an intersection is affected both by the curve parameters and the elevation difference between the main highway and the secondary roadway. The values of the curve parameters have a significant effect on the roughness of the road. For most of the intersections, the roughness is directly proportional to the elevation difference between the secondary roadway and the main highway.

From the results of the six sets of simulation experiments, a computer program called SIDRA was developed. SIDRA can generate feasible profiles with low levels of roughness on the basis of the input data, including elevations of the secondary roadway and the main highway, the length between the secondary roadway and the main highway, and the cross slope and the width of the main highway. The results produced by SIDRA are verified in several different ways. The IRI computation is verified by comparing SIDRA output with the IRI measured by two road roughness measuring devices. There was a close match between the generated and measured data.

Finally, a regression model was developed to examine the relationship between IRI and SI. The coefficient of determination indicated a strong relationship between SI and IRI. Overall,

TABLE 6 Recommended Upper Limits for Design

Posted Speed (mph)^a	SI(overall)	IRI(Design) in/mile^b
10 to 25	≥ 2.0	190
30 to 40	≥ 2.5	130
45 or greater	≥ 3.0	90

^{a}1 mph = 1.6 km/hr; ^{b}1 in/mile = 15.875 mm/km

SIDRA is an excellent decision support tool that can easily be used at the design stage.

ACKNOWLEDGMENTS

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REFERENCES

1. *A Policy on Geometric Design of Highways and Streets.* AASHTO, Washington, D.C., 1990.
2. Sayers, M. W., T. D. Queiroz Gillespie, and A. V. Cesar. *The International Road Roughness Experiment: Establishing Correlation and a Calibrating Standard for Measurements.* World Bank Technical Paper 45. 1986.
3. Brickman, A. D., W. H. Park, and J. C. Wambold. *Road Roughness Effects on Vehicle Performance.* Report TTSC-2707. Pennsylvania Transportation and Traffic Safety Center, 1972.
4. Garrett, J. W., and K. J. Thrap. *NCHRP Report 79: Development of Improved Methods for Reduction of Traffic Accidents.* HRB, National Research Council, Washington, D.C., 1969.
5. Janoff, M. S. *NCHRP Report 308: Pavement Roughness and Rideability, Field Evaluation.* TRB, National Research Council, Washington, D.C., 1988.
6. Sayers, M. W., T. D. Gillespie, and L. Segel. *NCHRP Report 228: Calibration of Response-Type Road Roughness Measuring Systems.* TRB, National Research Council, Washington, D.C., 1980.
7. *QuickBASIC Bible*, Programming in Basic Version 4.5. Microsoft Corporation, 1988.
8. Cumbaa, S. L. Correlation of Profile Based Roughness Devices and Response Type Devices for Louisiana's HPMS Program. Presented at 69th Annual Meeting of the Transportation Research Board, Washington, D.C., 1990.

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