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16. Abstract

A method to analyze the roughness of grade breaks at highway intersections is proposed. Although there are a variety of instruments to physically measure the road roughness, there are no known methodologies to analyze profile roughness during the design stage. The proposed analytical procedure is based on a series of simulation experiments performed for six types of intersections. Various transition-curve parameters directly affecting roughness are identified. International Roughness Index (IRI) is used as the performance measure of a profile. The results of the experiments show that in addition to curve parameters, profile roughness is also affected by the elevation difference between the main highway and the intersecting secondary roadway. In general, the roughness is proportional to the elevation difference between the intersecting roadways.

Based on the results of the experiments, a computer based decision support system called SIDRA is developed to analyze an existing profile or to generate profiles with low roughness. Statistical analysis shows a close correlation between SIDRA generated results and field measured data. SIDRA produced values of IRI are also correlated with serviceability index (SI), a commonly accepted roughness measure.

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ROUGHNESS ANALYSIS OF GRADE BREAKS AT INTERSECTIONS

FINAL REPORT

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ABSTRACT

A method to analyze the roughness of grade breaks at highway intersections is proposed. Although there are a variety of instruments to physically measure the road roughness, there are no known methodologies to analyze profile roughness during the design stage. The proposed analytical procedure is based on a series of simulation experiments performed for six types of intersections. Various transition-curve parameters directly affecting roughness are identified. International Roughness Index (IRI) is used as the performance measure of a profile. The results of the experiments show that in addition to curve parameters, profile roughness is also affected by the elevation difference between the main highway and the intersecting secondary roadway. In general, the roughness is proportional to the elevation difference between the intersecting roadways.

Based on the results of the experiments, a computer based decision support system called SIDRA is developed to analyze an existing profile or to generate profiles with low roughness. Statistical analysis shows a close correlation between SIDRA generated results and field measured data. SIDRA produced values of IRI are also correlated with serviceability index (SI), a commonly accepted roughness measure.

IMPLEMENTATION STATEMENT

SIDRA, the decision support system developed in this project, can be used as a design tool by highway engineers. The value of this computer program is in its capability for developing alternative grade break profiles with a minimum level of roughness. The program is quite fast and the validity of its output has been verified.

A grade break connecting a secondary roadway to a main highway usually consists of various segments which may be a parabola, a sag, or a tangent. The decision process regarding the combination of these curves and assigning appropriate curve length to each is not a trivial task; especially when the consequence of a decision affecting the induced roughness is not known. It is no wonder that many urban street crossings resemble a "camel hump".

SIDRA is an effective tool for determining roughness at a grade break. It uses International Roughness Index (IRI) as its performance measure to evaluate the roughness of a profile. It can be used to evaluate an existing roadway crossing or to evaluate the merits of a proposed design. The program is written in QuickBASIC, it is user friendly, and can easily be modified and upgraded.

The implementation of SIDRA in the design sections of LDOTD will greatly enhance the quality of the design of grade breaks with regard to profile roughness. The acceptance of SIDRA at LDOTD will encourage the private design professionals to take advantage of its usefulness in their design process.

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1 INTRODUCTION

The design and management of highway networks have been going through technologically driven changes. Many new developments in design methodologies, construction techniques, and management processes are affecting the way we plan, implement, and maintain the nation's transportation network.

In the area of geometric design of highways, the basic objective is to produce a profile that allows for a smooth transition from one point to another. Grade breaks are designed to make the transition from a secondary roadway elevation to the elevation of an intersecting main highway. Factors affecting the geometric design of a grade break include horizontal alignment and 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.

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 the vehicle wear, ride comfort, and safety (3) (4). Road roughness is gaining increasing importance as an indicator of road condition, both in terms of road 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) (6). As a result, many state highway departments and transportation agencies use road roughness to estimate the SI.

This study was initiated to determine the applicability of the International Roughness Index (IRI) as the measure of roughness at a grade break. Once the idea was found to be feasible, the IRI values were correlated with the SI values as the performance measure of the intersection.

Given a set of elevations for the secondary roadway and the main highway, the highway engineer designs a profile according to the topography of the land. The highway designer experiments with a combination of curves to provide for a smooth transition. Most often, a combination of parabolic curves and tangent (T) is used to join a secondary roadway and the main highway. There are two types of parabolic curves: Sag curves (S) and Parabolas (P). The properties of these curves are controlled by three parameters: start gradient, end gradient, and the length of the curve (11) (12). Selection of values for these parameters will directly influence the level of induced roughness at the intersection. Currently there are no guidelines to aid the designer in selecting these curve parameters. There is no tool available to generate an intersection profile with a low level of roughness or to improve an existing design. Since it is costly to modify an intersection after the highway is constructed, there is a need for the development of a procedure to evaluate the roughness during the design phase.

A series of preliminary studies were undertaken to determine the usefulness of various intersection designs. The study revealed that a profile made of an S-T-P combination provides a smooth transition while going upgrade. When traveling downgrade, a P-T-S seems to be a reasonable design. Based on these results, six common types of at-grade intersections, as shown in Figure 1, were selected to be studied. The first type of intersection is a T-intersection, referred to as profile TINT. The T-intersection consists of a combination of S-T-P. The second and the third intersections are X-types and are symmetrical about the center line of the main highway; they are called profiles SUD and SDU. The fourth intersection is also an X-type, called XUU, and is asymmetrical. The last two intersections, SVV and SCC, have compound profiles. A compound profile is defined as the one consisting of more then two tangents on one side of the main highway.

S-T-P and P-T-S configurations are the bases for the six type intersections studied. A series of simulation experiments were performed to determine the best combination of curves that provides for a smooth transition. The simulation experiments resulted in a set of heuristic procedures to be used as guides in the design of various intersection types.

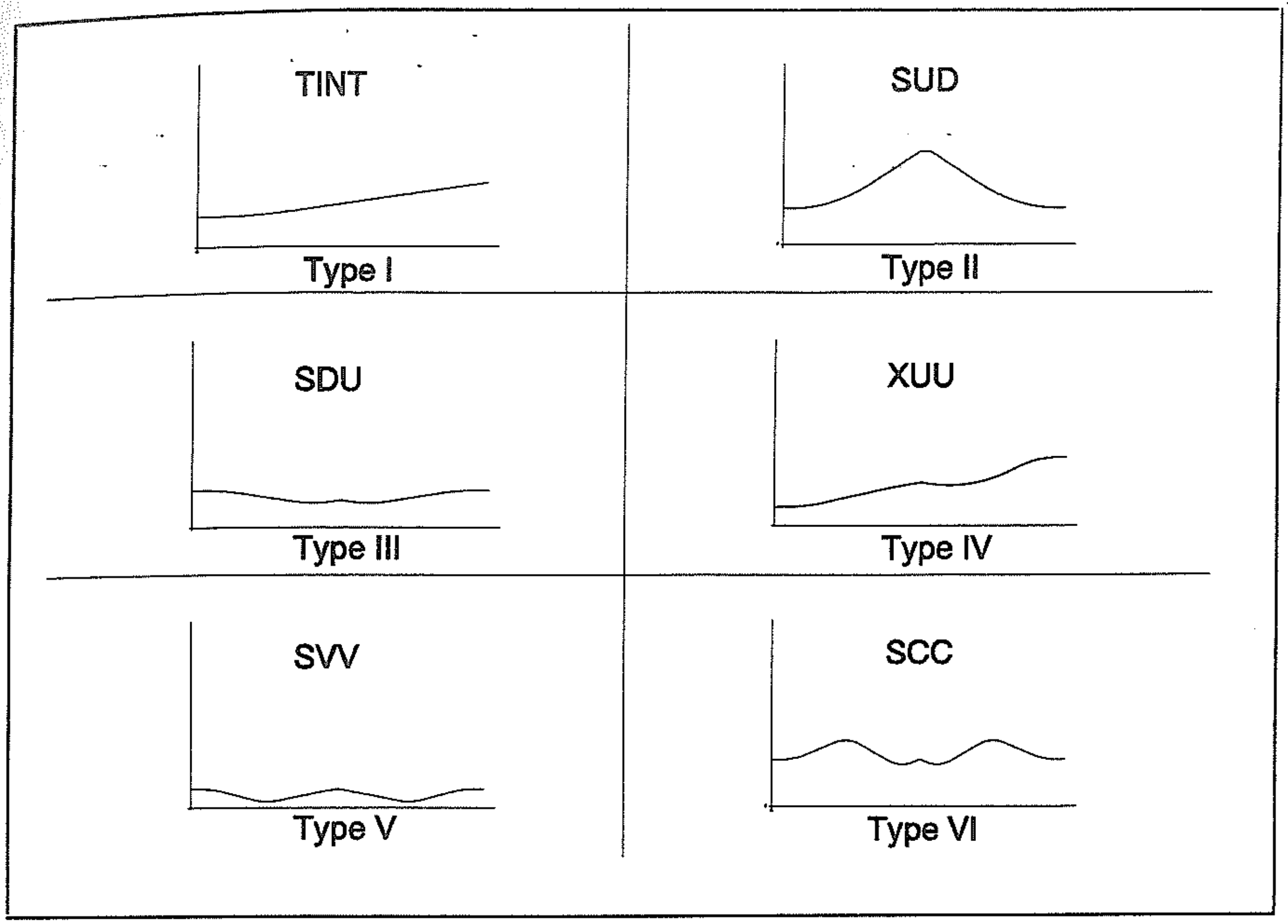

Figure 1 Profile for various types of intersections

The final product of this research is a decision support system called SIDRA. This computer program can be used as a design or an analysis tool.

2 OBJECTIVE

The main objective of this research is to develop a decision support system for the design of highway intersections that produces profiles with acceptable degrees of roughness. The decision support system is called SIDRA and is designed to analyze six common types of intersections and assist the highway designer in two ways:

1. Estimate the roughness measurement of an existing design through its IRI value, and suggest alternate designs with lower IRI.

2. Given the elevations of the secondary roadway, the main highway, and the topography of the land, generate a feasible design with an acceptable IRI value.

3 SCOPE

The scope of this project includes the following activities:

1. Simulation experiments - For each of the six intersections discussed above, a series of simulation experiments is performed to find the values of curve parameters that result in lower roughnesses.

2. Development of heuristic rules - Based on the results of the simulation experiments, a set of heuristic rules is developed to produce a grade break with minimum roughness.

3. Development of a decision support system called SIDRA.

4. Validation of IRI values produced by SIDRA.

5. Performance evaluation of the heuristics.

6. Correlation of IRI values to SI.

4 METHODOLOGY

In this study IRI has been used as the performance measure for the level of roughness at an intersection. A discussion of roughness measuring devices and development of IRI is presented in Appendix A. The calculation of IRI is accomplished by computing four variables as functions of the measured profile. These four variables simulate the dynamic response of a reference vehicle travelling over the measured profile. The equations for the four variables are solved for each measured elevation point, except for the first point. The average slope for the first 36 feet is used to initialize the variables by assigning some values (9). Then four recursive equations are solved for each elevation point from 2 to n, where n is equal to the number of elevation measurements. After these equations are solved for one point, the value of the initialized variable is reset for the next position. The IRI value is calculated as the average of the rectified slope variable over the length of the site.

This procedure is valid for any sample interval between 0.82 feet and 2 feet. For shorter sample intervals, the additional step of smoothing the profile with an average value is recommended. The computer program for calculating IRI is written in Basic language and is valid for any sample interval between .032 and 2 feet. The last IRI value computed for any profile is the cumulative IRI of that profile and this value is used to compare different profiles. The program is modified to directly read the elevation points from the file and compute the maximum IRI along the profile. Roughness analysis of a profile provides three results: Final-IRI, maximum IRI along the profile and the distance from the start of the profile at which this maximum IRI occurs.

The methodology employed in this project consisted of several parts. The following paragraphs present a general overview of various analysis that were performed. The following chapters present the details of the employed procedures.

After a set of preliminary studies, six profiles, as depicted in Figure 1, were selected to be analyzed. A series of simulation experiments were performed on each profile. The experiments were performed by varying the parameters of two curves for three values of elevation differences between the secondary roadway and the main highway. For each feasible profile generated, two corresponding IRI values were calculated; one for each direction. This procedure was repeated for all six intersections. Chapter 5 describes the detailed procedures for performing simulation experiments and summarizes the obtained results.

Based on the results from the simulation experiments, a set of heuristics was developed. For a given site topography, the heuristic rules determine the value of curve parameters which provides a feasible intersection design with an acceptable level of roughness. The development of six heuristic, one for each of six type profiles, is discussed in section 10.1.

The development of a decision support system based on the heuristic was accomplished in BASIC programming language. When provided with the value of curve parameters of an existing intersection, SIDRA generates an improved design by varying curve parameters within the allowable limits. A detailed description of SIDRA is given in section 10.2.

The verification process entailed comparison of SIDRA generated IRI values to 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. Comparison of the IRI values is presented in section 11.1.

To check the capabilities of SIDRA as a design tool, for a given set of elevation differences between the secondary roadway and the main highway, the profile generated by SIDRA was compared with a set of randomly generated feasible designs. A statistical t-test was performed to determine whether the profile generated by SIDRA had a lower roughness value as compared to the feasible profile randomly generated. The results of the t-tests are documented in section 11.2.

The Serviceability Index has been commonly used as a measure of riding quality on the roadways in many places. The relationship of SI to IRI on 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 based on the values of IRI and SI for ten intersections in Baton Rouge, Louisiana. A set of recommendations is presented in section 11.3.

5 SIMULATION EXPERIMENTS

This chapter presents a description and the results of simulation experiments performed on six types of intersections. These six intersection profiles can be classified into four categories: T-Intersections (Profile TINT), Symmetric X Intersections (Profile SUD & SDU), Asymmetric X Intersections (Profile XUU), and Compound Intersections (Profile SVV & SCC).

Each profile is characterized by a number of curves and a set of curve parameters. Based on the values of curve parameters, a computer program generates a set of elevations for the profile of the intersection. The elevations are generated at one foot intervals, and a cumulative IRI value is computed for the profile in both directions. For example, a 100 foot profile will have two cumulative IRI values, each consisting of 100 points. The performance measures used to compare designs are Final-IRI and the opposite Final-IRI values. 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 as the Final-IRI. The maximum IRI value is the largest cumulative IRI computed for one direction along the profile. The Opposite Final-IRI is determined when traversing the profile of the intersection in the opposite direction. The largest cumulative Opposite Final-IRI value is the Opposite Maximum IRI.

In the simulation experiments, profiles are generated systematically by changing one parameter at a time and adjusting the other parameters to meet a specified elevation difference. This procedure is repeated for several elevation differences. The Final-IRI and the opposite Final-IRI values of the generated profiles are plotted against the variation in curve lengths. The following chapters discuss the procedure used and the results obtained for the six profiles.

6 PROFILE TINT

The preliminary study on a T-intersection indicated that the curve parameters and the elevation difference between the main highway and the secondary roadway have an effect both on the maximum IRI and the Final-IRI of a profile. The profile considered for further experiments is depicted in Figure 2 and is referred to as TINT. The total horizontal length of the profile is 530 feet. It starts with a tangent on the secondary roadway of 36 feet in length and 0 percent gradient. The tangent is then joined by a combination sag curve of 150 feet in length, a tangent of 170 feet in length, and a parabola of 150 feet in length. This combination is called S-T-P. The parabola is then joined to the main highway with a width of 48 feet and cross slope of 2.5 percent.

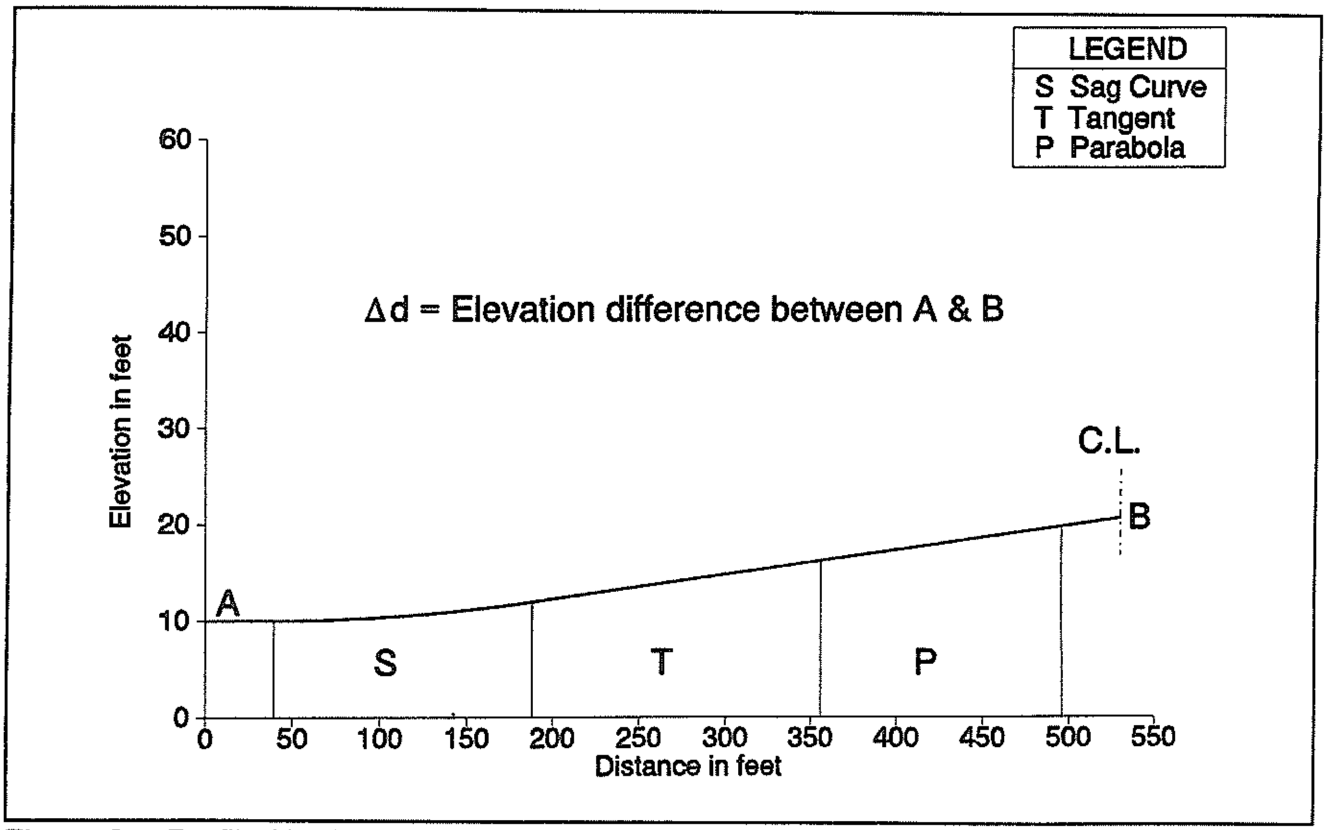

Figure 2 Profile No. TINT

A number of experiments are performed on profile TINT by systematically varying two factors: (1) the lengths of two of the three curves in S-T-P, and (2) 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 percent, 2 percent and 3 percent would result in the intersection. Table 1 summarizes the combination of factors used in the experiments.

TABLE 1 TINT EXPERIMENT GROUPS

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

A total of nine sets of experiments is required to consider all possible combinations of two factors at three different levels. For each set, simulation experiments are performed by varying the tangent gradient; it is increased in an increment of 0.02 percent for each experiment. To accommodate this change, the lengths of two of the three curves are then adjusted to maintain a constant elevation difference (Δd). The width and the cross slope of the main highway are kept constant in all experiments. The experimentation is terminated when another feasible profile can not be obtained by further changing the lengths of two curves.

The nine sets of experiments are divided into three groups. Table 1 shows the curve parameters for each group. 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 using the same procedure for three different elevation differences (i.e., 5.3, 10.6 and 15.9 feet respectively). The following sections present the results obtained from these experiments.

6.1 EXPERIMENT GROUP TINT.ST

In the first group of experiments the length of sag curve and the length of tangent are systematically varied to determine their effects on the IRI. The tangent gradient is increased in increments of 0.02 percent. To keep the elevation difference between the secondary roadway and main highway (Δd) constant, the length of the sag curve is increased and the length of the tangent is decreased. The length of the parabola is kept constant in the process. A computer program generates all feasible designs. Once a feasible design is produced, the program calculates the IRI of the resulting profile in both directions. The program terminates when the length of tangent can not be further reduced. Three sets of experiments are performed corresponding to different elevation differences.

Experiment TINT.ST.01: In this experiment, the elevation difference Δd is set at 5.3 feet for a 1 percent grade on the intersection. The secondary roadway starts with a tangent of 0 percent gradient and a length of 36 feet, which is joined to a sag curve of 150 feet in length with start and end gradient of 0 percent and 0.9 percent respectively. The sag curve is joined with a tangent of 170 feet in length and a gradient of 0.9 percent. A parabola of 150 feet in length with a start and end gradient of 0.9 percent and 2.5 percent respectively joins the tangent and the cross slope of the main highway. Table 2 summarizes the curve parameters.

TABLE 2 INITIAL INPUT CURVE PARAMETERS FOR PROFILE TINT (Δd=5.3 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	0.9%	150
Tangent	0.9%	0.9%	170
Sag	0.9%	2.5%	150

Figure 3 shows the plot of calculated IRIs for the input parameters shown in Table 2. A lower IRI value is obtained when one travels from the secondary roadway to the main highway in comparison to travelling from the main highway to the secondary roadway. This is probably because of the sudden increase in the IRI when starting at the centerline of the main highway with a 2.5 percent cross slope.

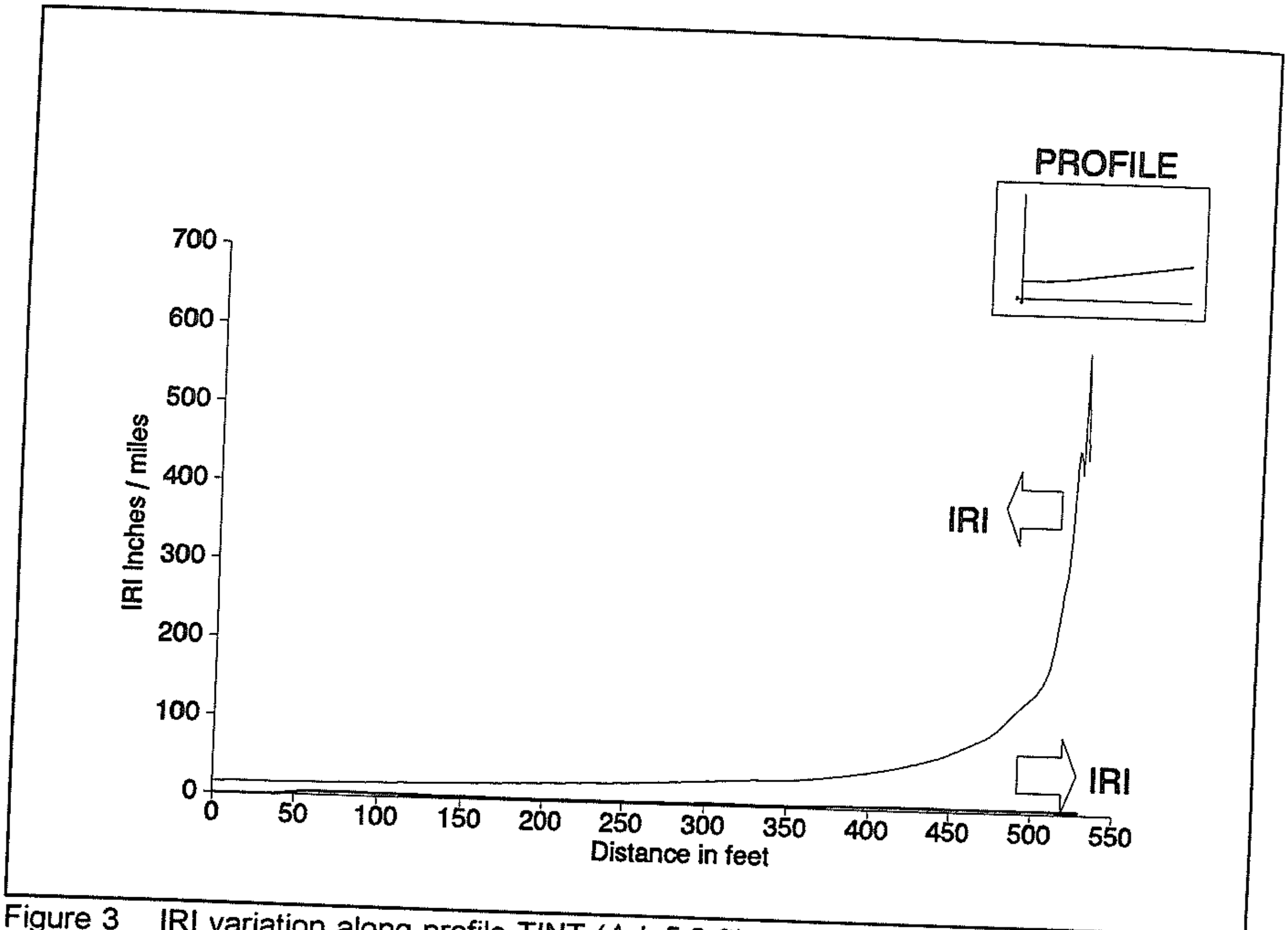

Figure 3 IRI variation along profile TINT (Δd=5.3 ft)

The Final-IRI is calculated for a total length of 530 feet from the tangent of the secondary highway to the center line of the main highway. The procedure for generating feasible profiles and IRI calculations is continued until all possible tangent lengths are exhausted.

A total of 18 profiles is generated for this setup. As the length of the tangent decreases, so does the value of Final-IRI. The minimum value of Final-IRI and the opposite Final-IRI occur for the tangent length of one foot. The minimum value of the Final-IRI and the opposite Final-IRI is 2.7 and 13.8 respectively. The plot of the Final-IRI values is depicted in Figure 4.

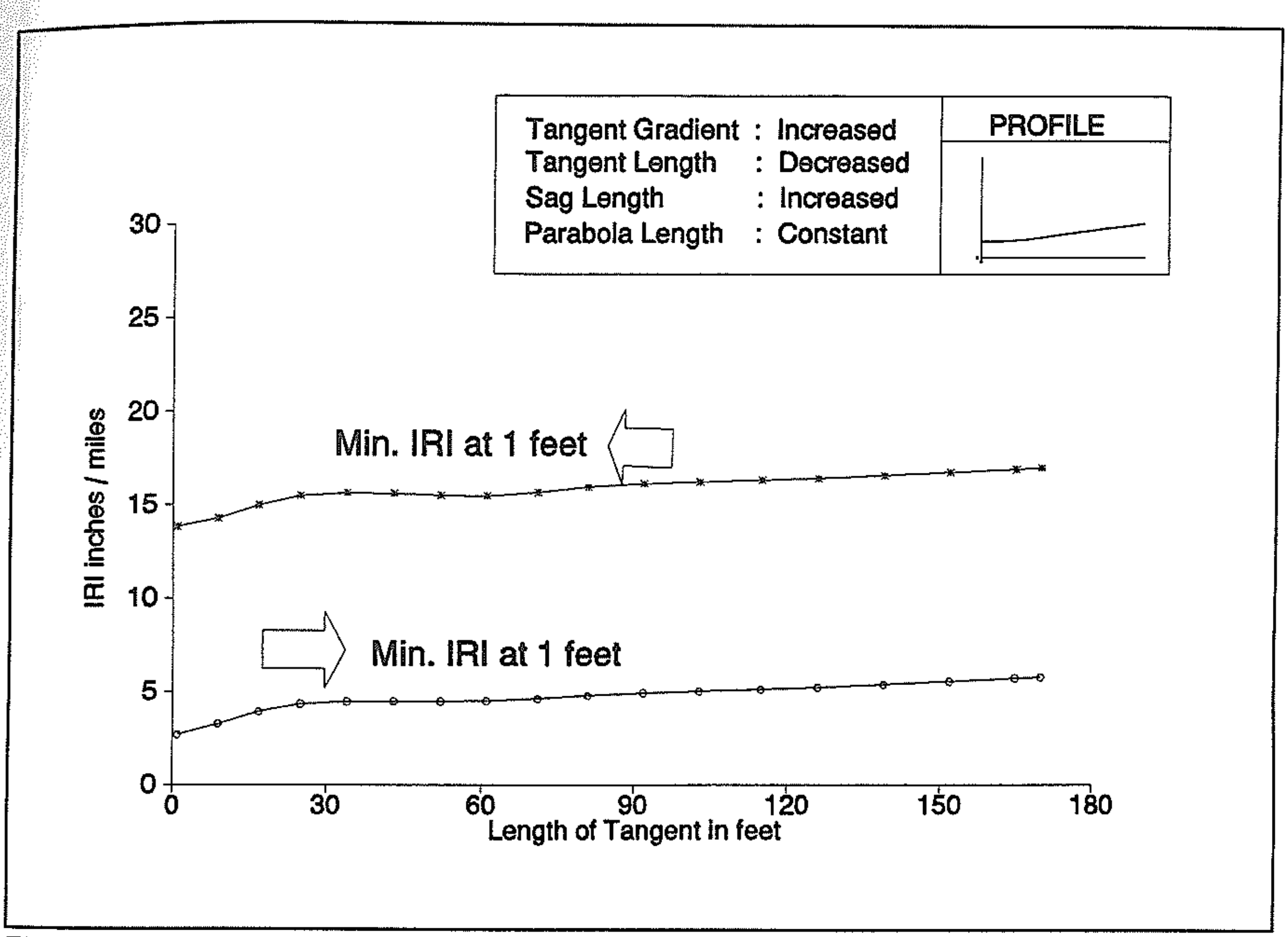

Figure 4 Final-IRI for experiment TINT.ST.01 (Δd=5.3 ft)

<u>Experiment TINT.ST.02:</u> In this experiment, the gradient of the tangent is increased from 0.9 percent to 2.55 percent to obtain an elevation difference of 2 percent (10.6 feet). The parameter setup for this experiment is depicted in Table 3. For this setup, the same procedure as for experiment TINT.ST.01 is repeated, which resulted in 48 profiles.

TABLE 3 INITIAL INPUT CURVE PARAMETERS FOR PROFILE TINT (Δd=10.6 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	2.55%	150
Tangent	2.55%	2.55%	170
Parabola	2.55%	2.5%	150

Figure 5 shows the calculated IRI along the profile with the initial setup.

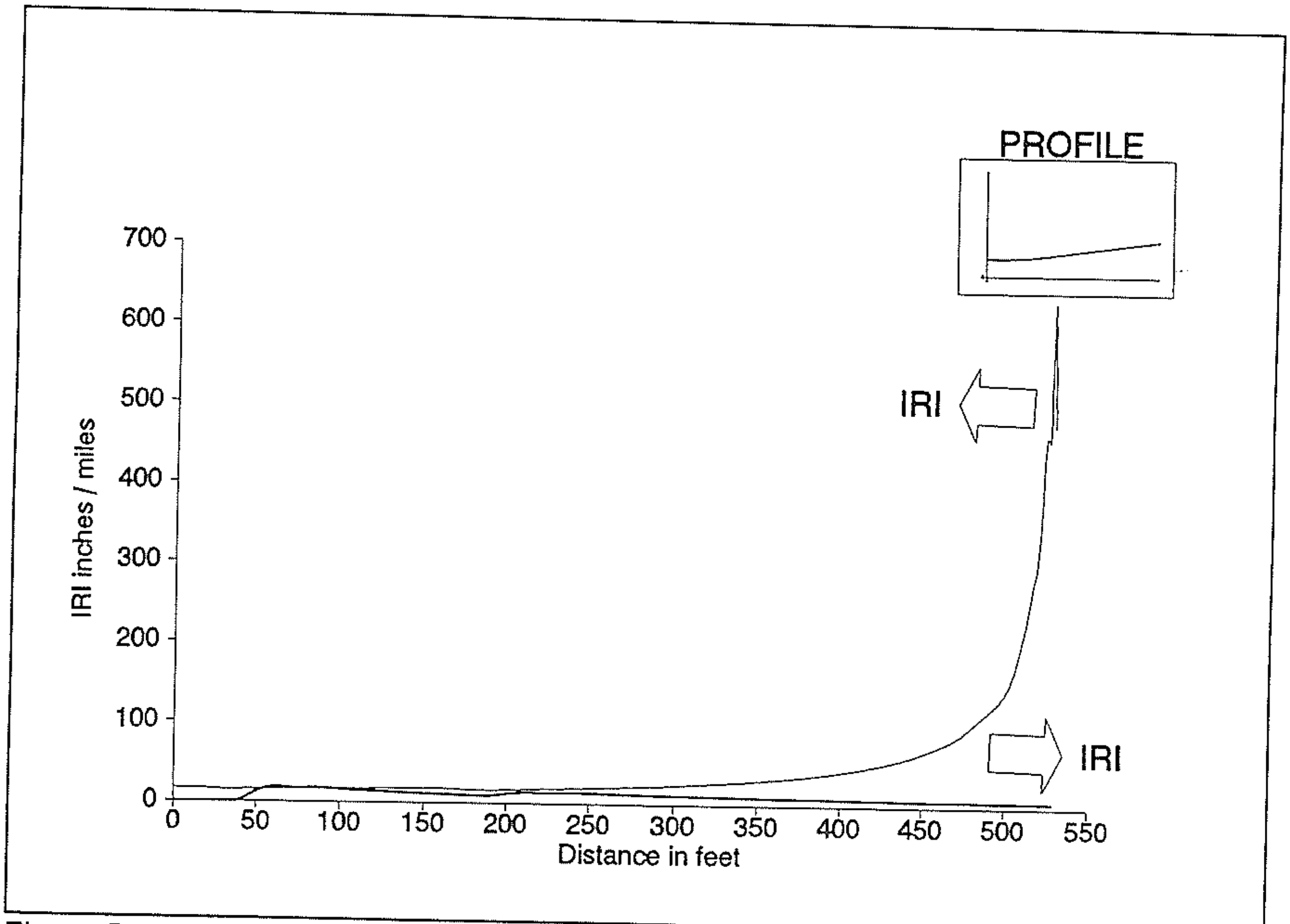

Figure 5 IRI variation along profile TINT (Δd=10.6 ft)

Figure 6 shows the Final-IRI values for 48 feasible designs. The minimum value for Final-IRI is 4.73 which is obtained for a tangent length of 30 feet. The minimum value for opposite Final-IRI is 13.69 and is obtained for a tangent length of 27 feet.

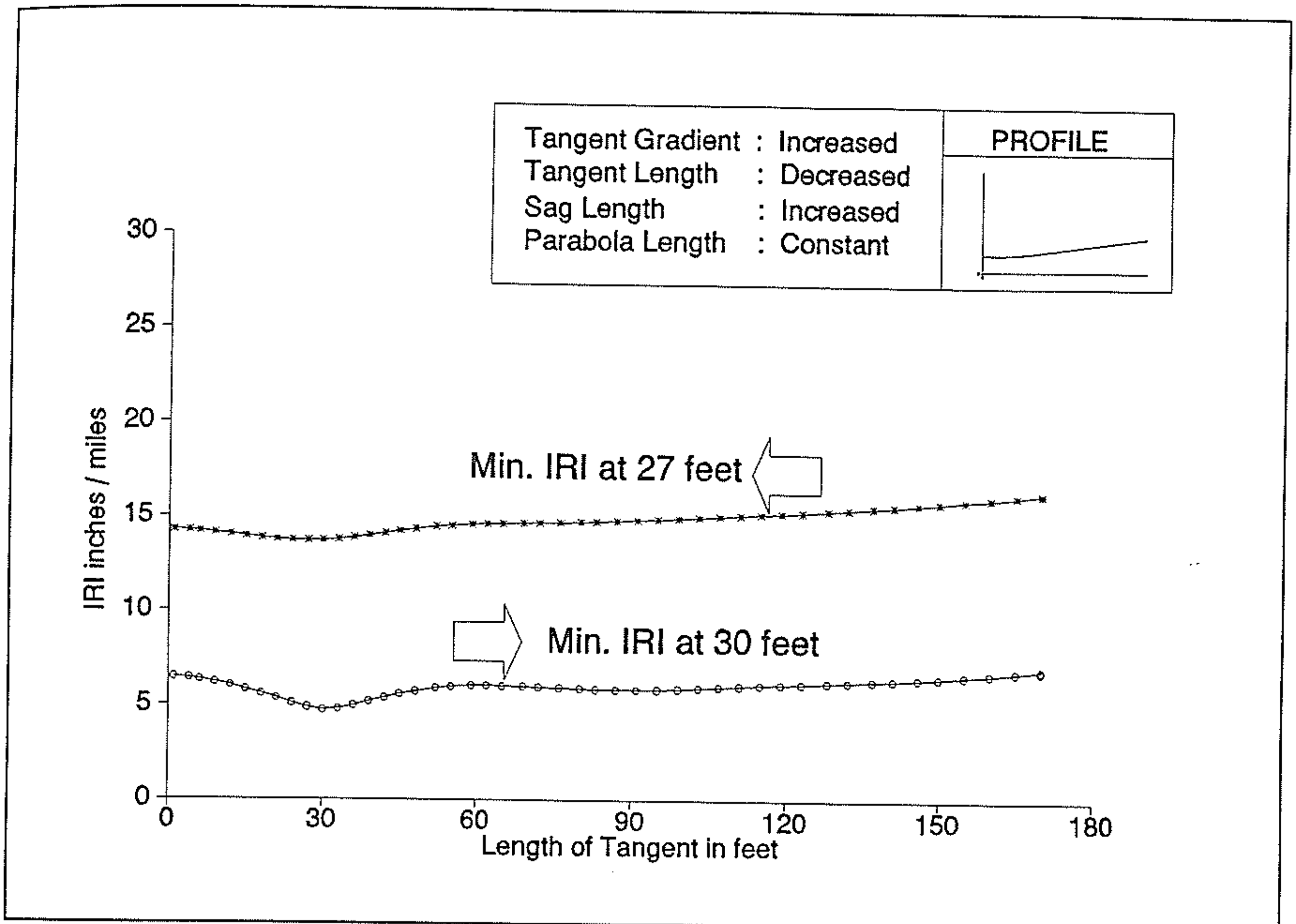

Figure 6 Final-IRI for experiment TINT.ST.02 (Δd=10.6 ft)

Experiment TINT.ST.03: The same procedure as before is repeated for an elevation difference of 15.9 feet. This configuration requires the tangent gradient to be increased to 4.2 percent. Figure 7 shows the calculated IRI along this profile, for the initial setup shown in Table 4.

TABLE 4 INITIAL INPUT CURVE PARAMETERS FOR PROFILE TINT (Δd=15.9 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	4.2%	150
Tangent	4.2%	4.2%	170
Parabola	4.2%	2.5%	150

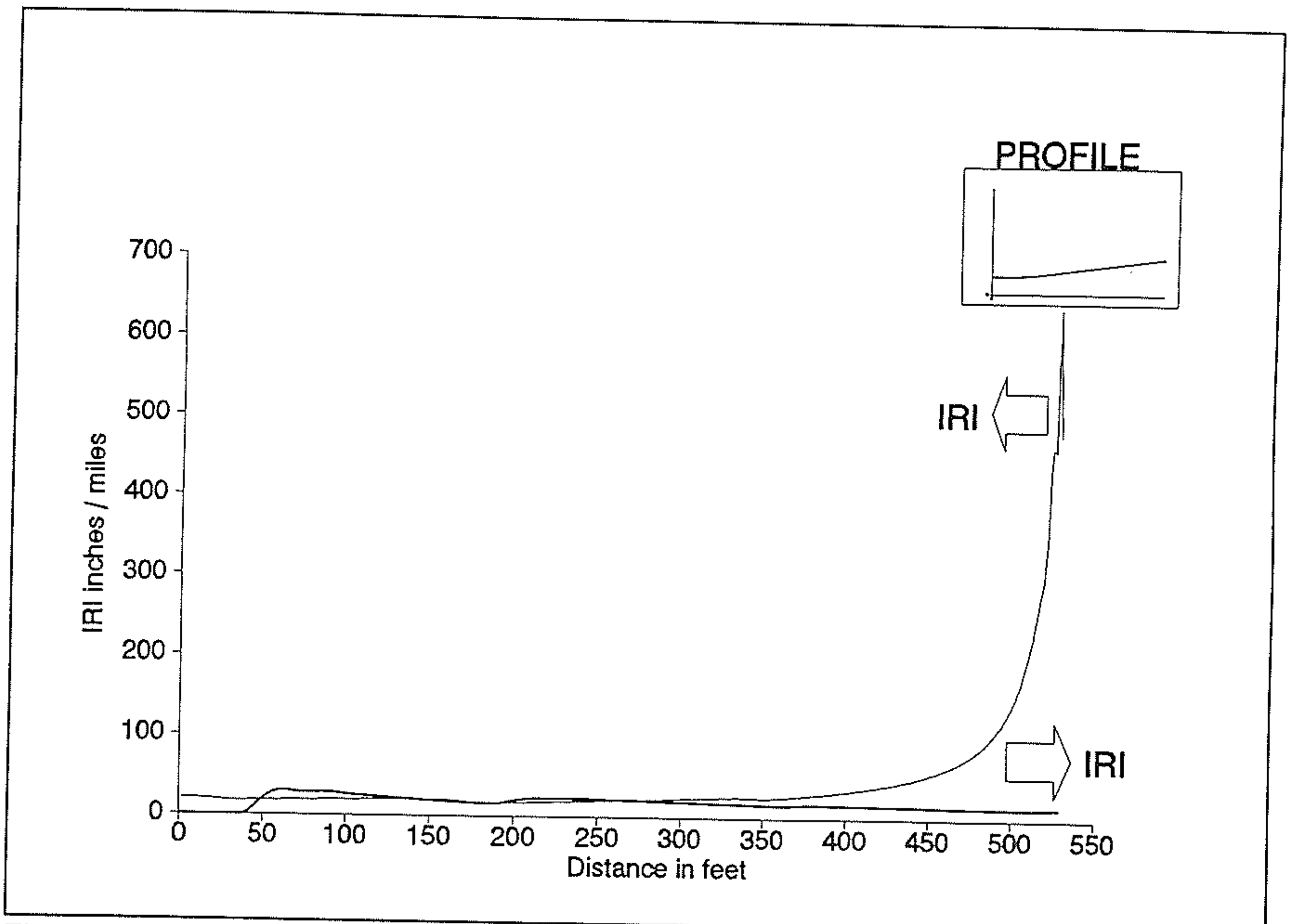

Figure 7 IRI variation along profile TINT (Δd=15.9 ft)

The number of profiles generated for this experiment is 78. Among the 78 profiles, the minimum value for Final-IRI and opposite Final-IRI both occurred for the tangent length of 31 feet. The minimum values for the Final-IRI and the opposite Final-IRI are 11.18 and 16.76 respectively. The plot of Final-IRI values is depicted in Figure 8.

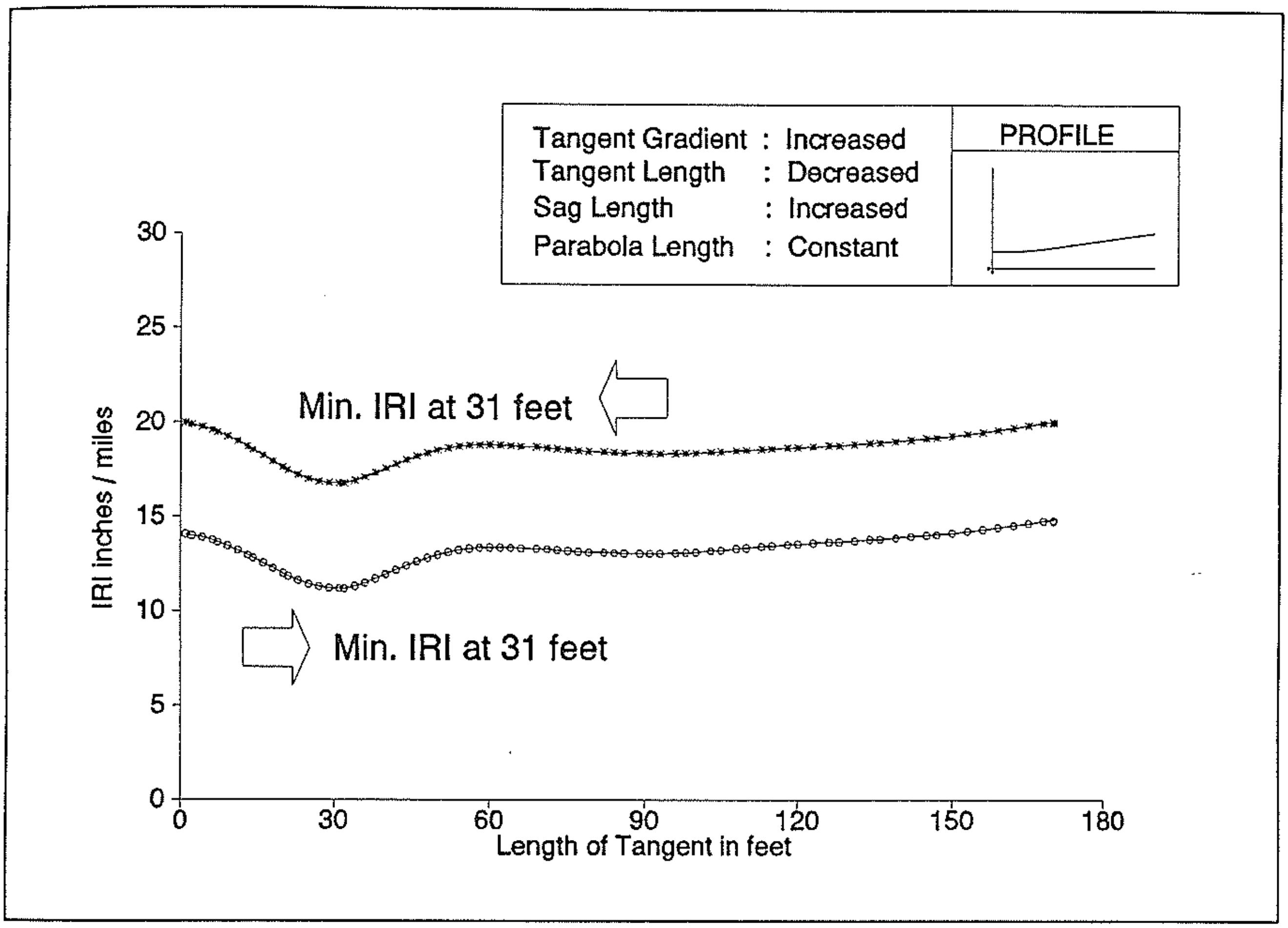

Figure 8 Final-IRI for experiment TINT.ST.03 (Δd=15.9 ft)

Table 5 summarizes the curve parameters of the profiles with lowest Final-IRI and the lowest opposite Final-IRI. For Δd of 5.3 feet and 15.9 feet, the same curve parameters gave the minimum Final-IRI and the minimum opposite Final-IRI. A tangent length of about 30 feet produces a lower value of Final-IRI. However, observation of Figures 4, 6, and 8 reveal that variation of the Final-IRI as a function of the length of the tangent curve is not significant. The shape of the Final-IRI and the opposite Final-IRI curves in Figures 6 and 8 are similar.

Neither Figures 6 nor 8 curves are similar to the curves in Figure 4.

TABLE 5 CURVE PARAMETERS FOR PROFILES TINT.ST WITH LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
5.3	1.24	1	319	2.7	
5.3	1.24	1	319		13.83
10.6	3.29	30	290	4.73	
10.6	3.31	27	293		13.69
15.9	5.4	31	289	11.18	
15.9	5.4	31	289		16.76

6.2 EXPERIMENT GROUP TINT.PT

This series of experiments are generated by adjusting the lengths of the parabola and the tangent to match the 0.02 percent increment in the tangent gradient. In the process, the length of the parabola is increased and the length of the tangent is decreased to keep Δd constant. A computer program is developed to calculate the Final-IRI of all feasible profiles in both directions.

Experiment TINT.PT.01: The first set of experiments is based on the initial parameter used in experiment TINT.ST.01. As the tangent gradient is increased by an increment of .02 percent, with the value of Δd kept at 5.3 feet, no additional combination of tangent and parabola lengths could be developed. The Final-IRI value is shown in Figure 9.

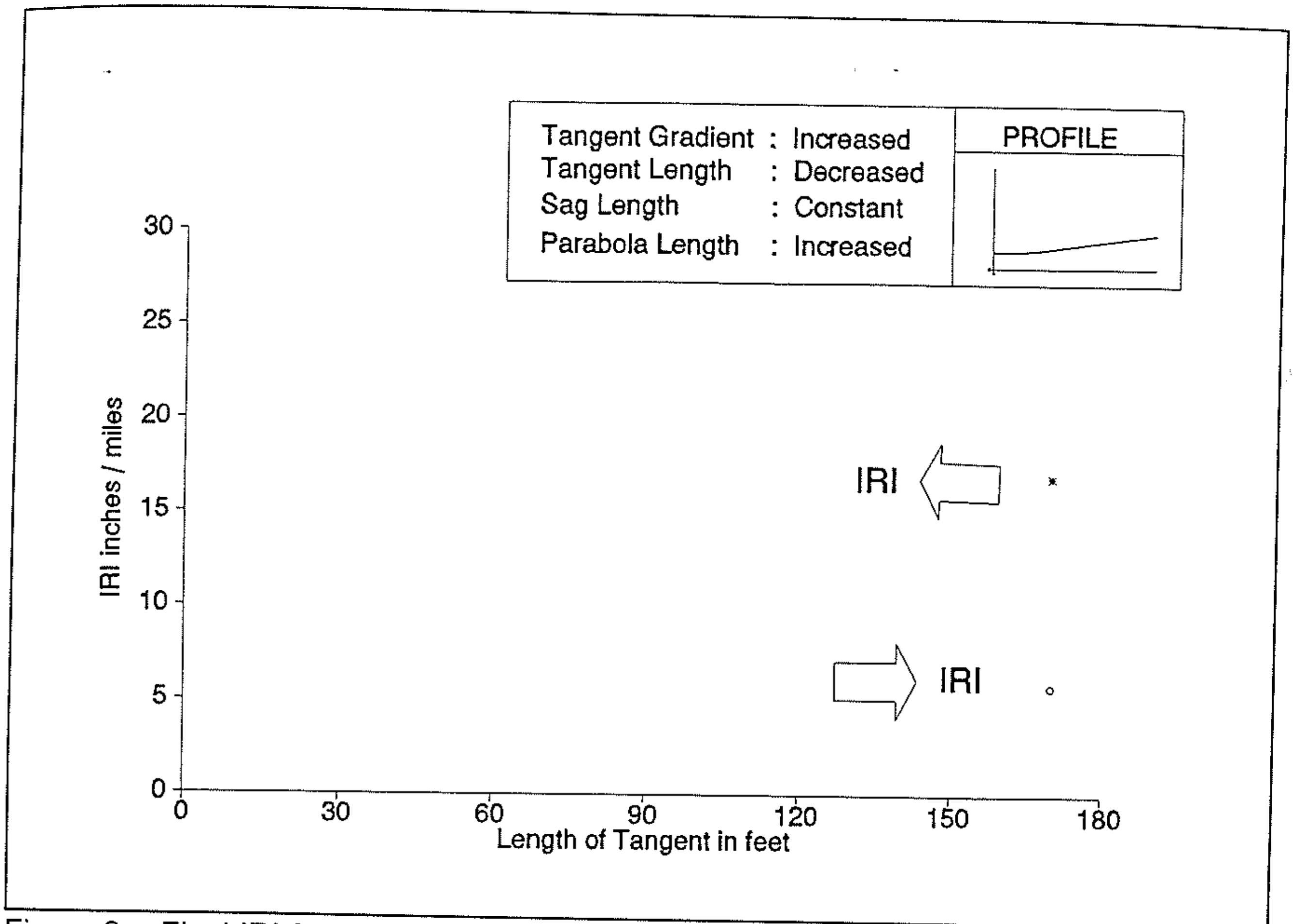

Figure 9 Final-IRI for experiment TINT.PT.01 (Δd=5.3 ft)

Experiment TINT.PT.02: The procedure used in experiment TINT.PT.01 was repeated for an elevation difference of 10.6 feet, which resulted in two different profiles. The minimum value of the Final-IRI (6.89) occurred for a tangent length of 31 feet. The minimum value of opposite Final-IRI is 16.31 and it occurred for the profile with a tangent length of 170 feet. As shown in Figure 10, the variation in the values of the Final-IRI as a function of the tangent length is not significant.

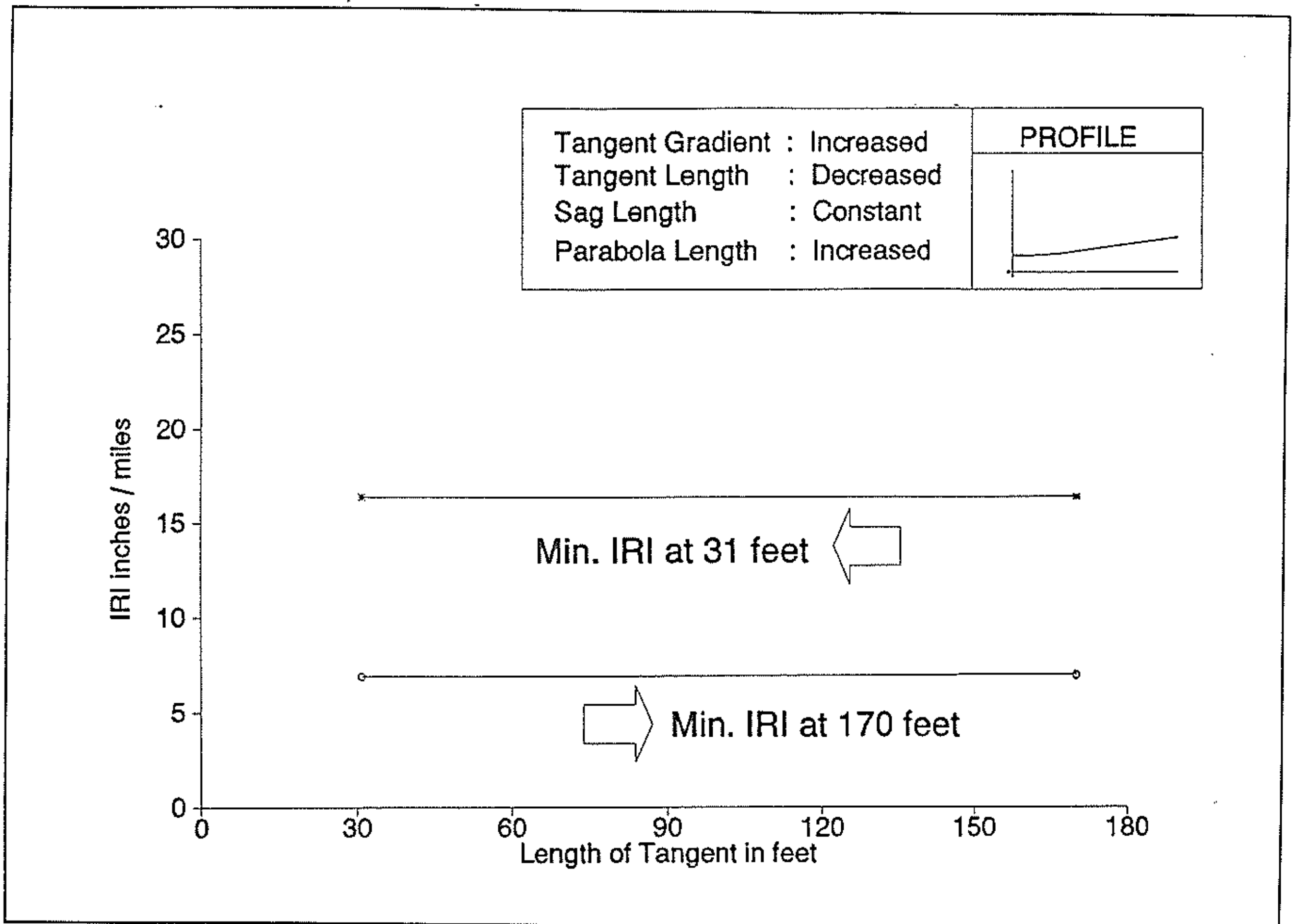

Figure 10 Final-IRI for experiment TINT.PT.02 (Δd=10.6 ft)

Experiment TINT.PT.03: The same profile generating procedure as for experiment TINT.PT.02 is repeated for the elevation difference of 15.9 feet. A total of 33 profiles are generated for this setup and their Final-IRI values are plotted in Figure 11. A tangent length around 32 feet gave the lowest value of the Final-IRI and the opposite Final-IRI.

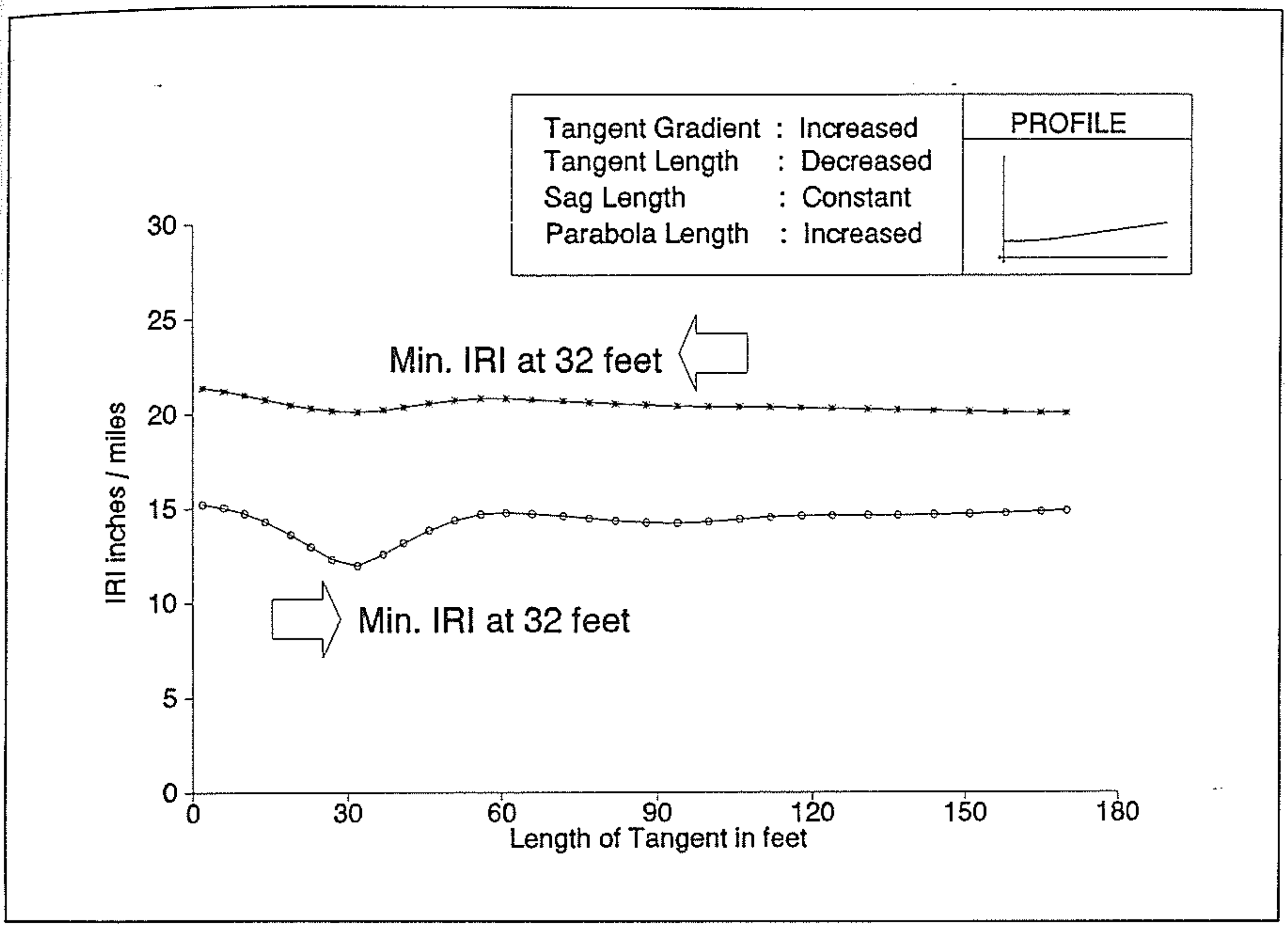

Figure 11 Final-IRI for experiment TINT.PT.03 (Δd=15.9 ft)

Table 6 summarizes the curve parameters of the profiles with the minimum IRI resulting from the three sets of experiments. Two profiles are selected for each elevation difference (Δd) : one for the profile with minimum Final-IRI and the other with minimum opposite Final-IRI. For Δd of 15.9 feet the tangent length of 32 feet generated the profile with the lowest IRI. Only one profile is generated for Δd value of 5.3 and three profiles for Δd of 10.6 feet.

TABLE 6 CURVE PARAMETERS FOR PROFILES TINT.PT OF LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
5.3	.9	170	150	5.8	
5.3	.9	170	150		17.01
10.6	2.59	31	289	6.89	
10.6	2.55	170	150		16.31
15.9	4.7	32	288	11.97	
15.9	4.7	32	288		20.1

6.3 EXPERIMENT GROUP TINT.SP

This series of experiments also involves generating profiles by first increasing the tangent gradient in an increment of 0.02 percent and then adjusting the length of two curves. To keep Δd constant, the length of parabola is decreased and the length of the sag curve is increased. The length of tangent is kept constant. Final-IRI values of all resulting profiles are computed and plotted for each of the three sets of experiments.

Experiment TINT.SP.01: The first set of experiments is performed for Δd of 5.3 feet. By decreasing the length of parabola, a total of 30 profiles is generated for this setup. The plot of Final-IRI values is depicted in Figure 12. It is noted that the Final-IRI values remained almost constant for parabolas of lengths of 100 to 150 feet. When the parabola length is further decreased, the Final-IRI value increases. There is a significant increase in the Final-IRI value with a parabola length below 60 feet. The lowest value of the Final-IRI and the opposite Final-IRI occurred at the parabola length of 150 feet.

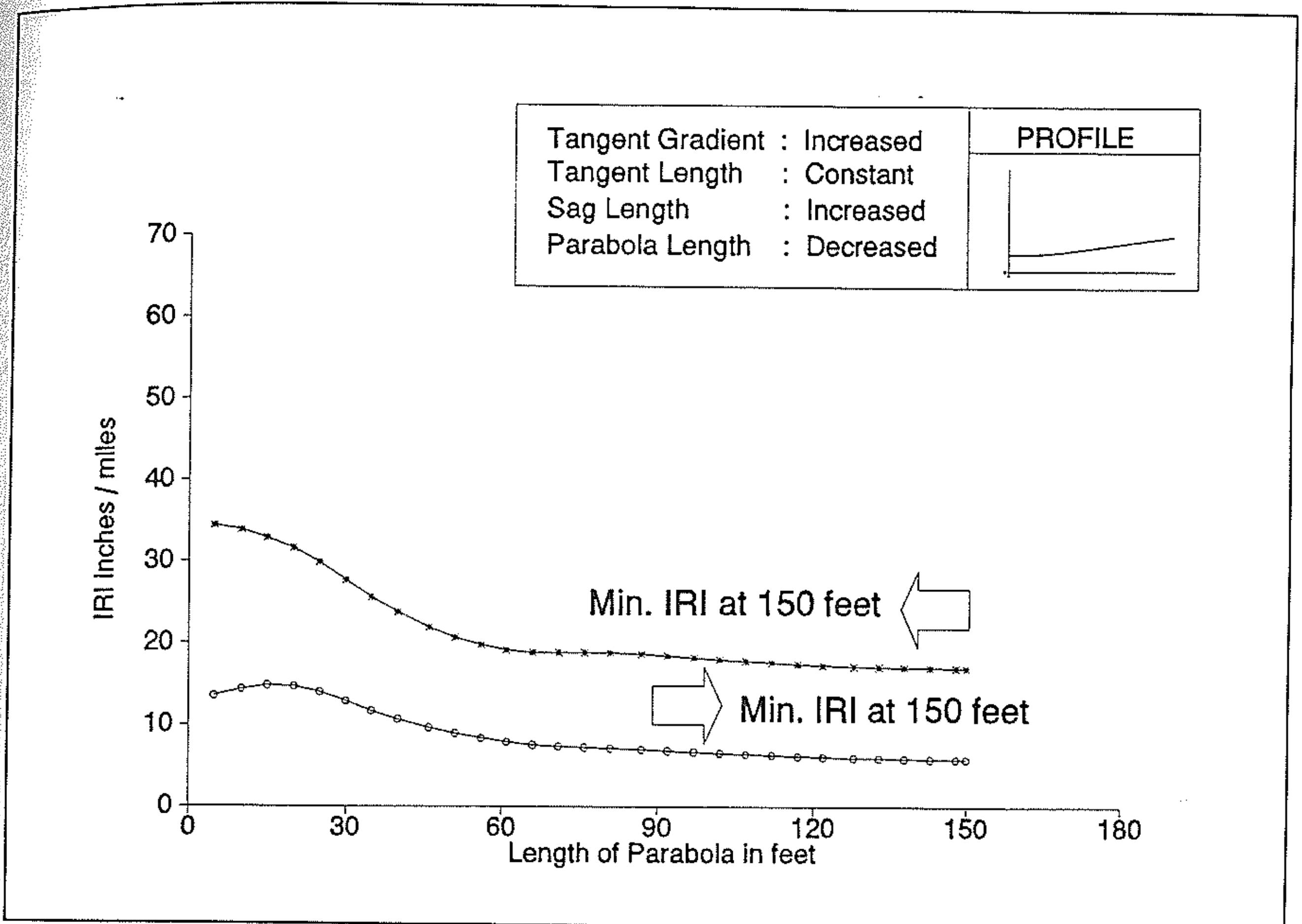

Figure 12 Final-IRI for experiment TINT.SP.01 (Δd=5.3 ft)

Experiment TINT.SP.02: The second set of experiments on Profile TINT.SP is performed for a Δd of 10.6 feet. The same profile generating procedure as in the last set of experiments results in 31 profiles. Figure 13 shows a plot of the Final-IRI values. The two curves reveal an interesting result: the profile with the minimum Final-IRI (6.36) corresponds to a parabola length of 104 feet while the profile with the minimum value of opposite Final-IRI (14.49) occurs at the parabola length of 47 feet. This result is in contrast to the result obtained from the previous experiment where the profiles of minimum IRI and minimum opposite IRI are the same.

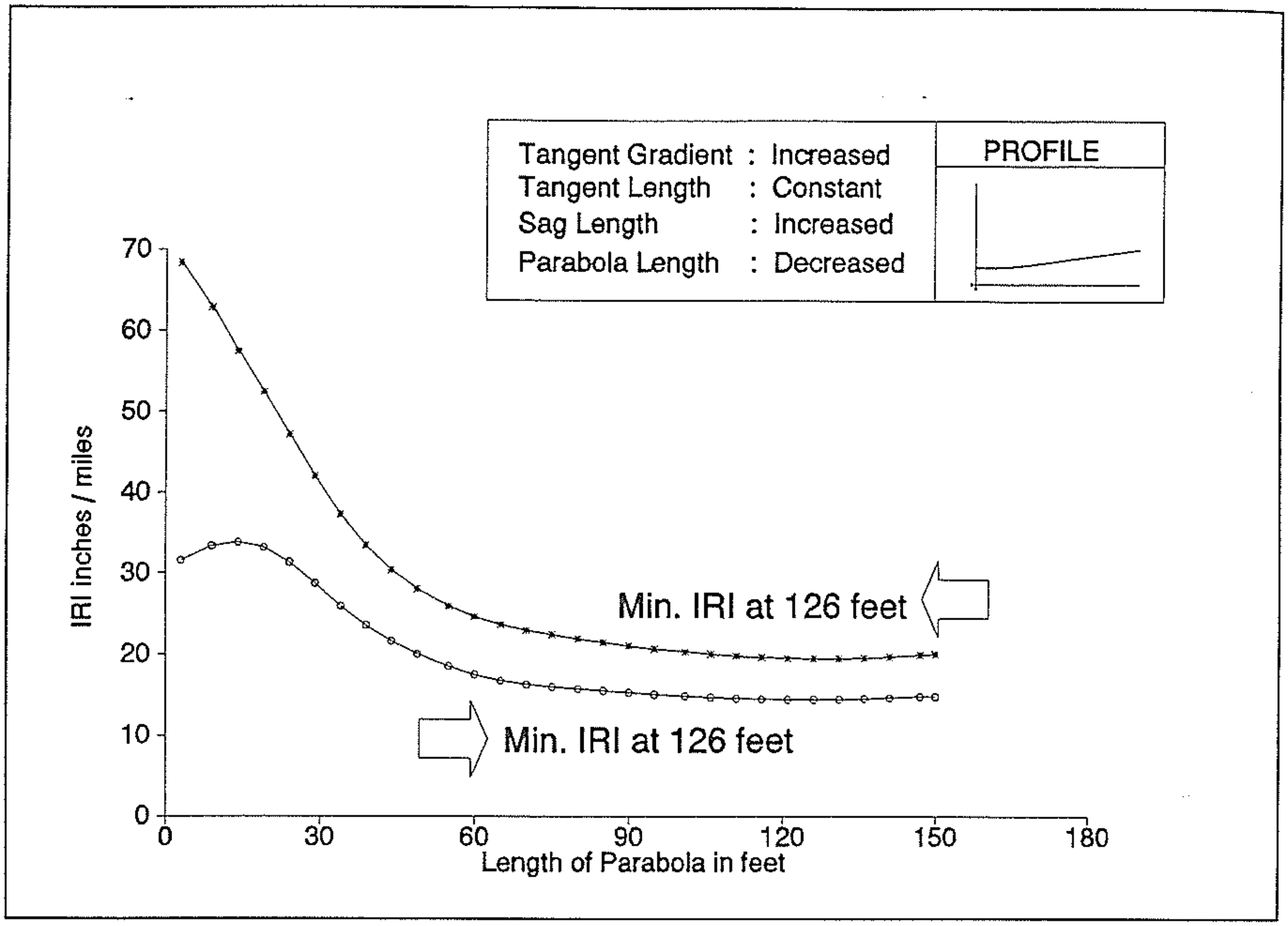

Figure 13 Final-IRI for experiment TINT.SP.02 (Δd=10.6 ft)

<u>Experiment TINT.SP.03:</u> The same procedure as experiment TINT.SP.02 is repeated for the Δd value of 15.9 feet. A total of 31 profiles is generated for this setup, the Final-IRI values of the generated profiles are presented in Figure 14. The shapes of the two curves are somewhat similar to the shapes of curves in experiment TINT.SP.02. But the profile with minimum Final-IRI and the profile with minimum opposite Final-IRI are the same with a parabola length of 126 feet.

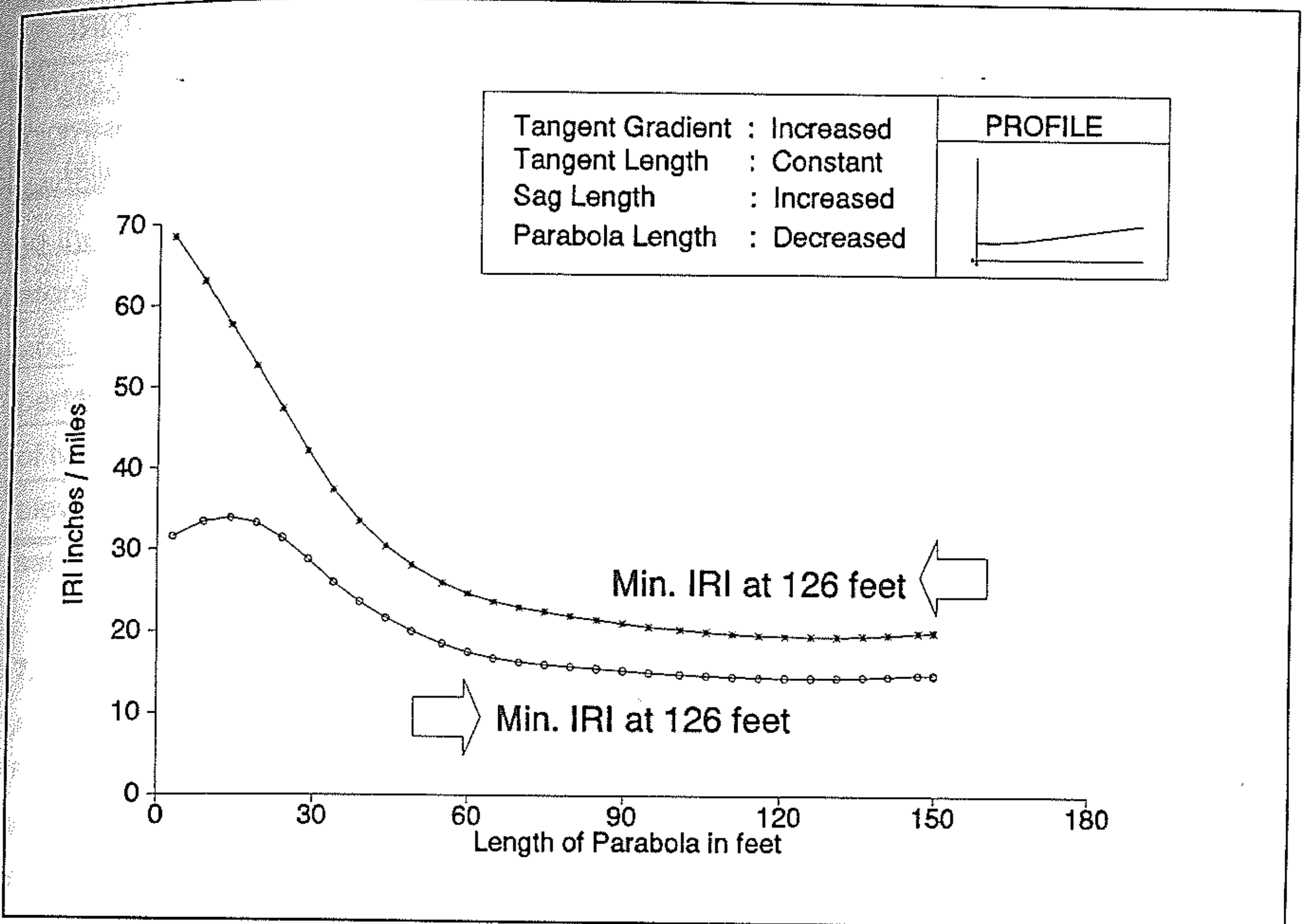

Figure 14 Final-IRI for experiment TINT.SP.03 (Δd=15.9 ft)

Table 7 summarizes the curve parameters of profiles with minimum Final-IRI and minimum opposite Final-IRI for the experiment group TINT.SP. For Δd of 5.3 and 15.9 feet the best profiles from two directions of travel have the same parabola length. However, the direction of travel affects the value of minimum Final-IRI when Δd is 10.6 feet. In general, the Final-IRI value is more sensitive to change in the parabola length with a constant tangent length than to change in parabola length with a constant sag length. It is also discovered that a profile with lower parabola length tends to have higher value of Final-IRI.

TABLE 7 CURVE PARAMETERS FOR PROFILES TINT.SP WITH LOWEST IRI

Δd	Tangent Gradient	Parabola Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
5.3	.9	150	150	5.8	
5.3	.9	150	150		17.01
10.6	2.75	104	196	6.36	
10.6	2.97	47	253		14.49
15.9	4.32	126	174	14.47	
15.9	4.32	126	174		19.52

6.4 SUMMARY RESULTS FOR PROFILE NO. TINT

Based on the results from experiment groups TINT.ST and TINT.PT, a profile with a tangent length around 30 feet (56/1000 of the total profile length) produces a good design. For TINT.SP, a profile with a parabola length of more then 100 feet (about 1/5 of the total profile length) gives lower value of Final-IRI. The Final-IRI and the opposite Final-IRI value are more sensitive to the variation in parabola length than to variation in tangent length.

7. ANALYSIS OF SYMMETRIC X INTERSECTIONS

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. This section describes experiments performed on two symmetrical profiles SUD and SDU shown in Figures 15 and 22. The input to the program is a profile in the form of curve parameters. Then the program generates more profiles and calculates their IRI values. Experiments are classified into groups according to the method used to generate more profiles. Three sets of experiments are performed for each profile, by increasing the tangent gradient and then adjusting the length of two of the three curve parameters. This profile generating procedure is repeated for three elevation differences. In the following sections we will discuss the procedure used for each set and the results obtained for these profiles.

7.1 PROFILE SUD

A set of simulation experiments is performed on a symmetric profile as depicted in Figure 15. The design of the transition on the right side of the main highway is a mirror image of the profile on the left side. This symmetrical property is not altered as various curve parameters are changed. The secondary roadway always started with the tangent length of 36 feet and 0 percent gradient. The tangent is joined to the sag curve length of 150 feet, which is joined to another tangent of 170 feet in length. Then a parabola of 150 feet in length joined the tangent and the cross slope of the main highway. The main highway is 48 feet wide with a gradient of 2.5 percent on both sides of the centerline. The width and the cross slope of the main highway is kept constant for all the experiments.

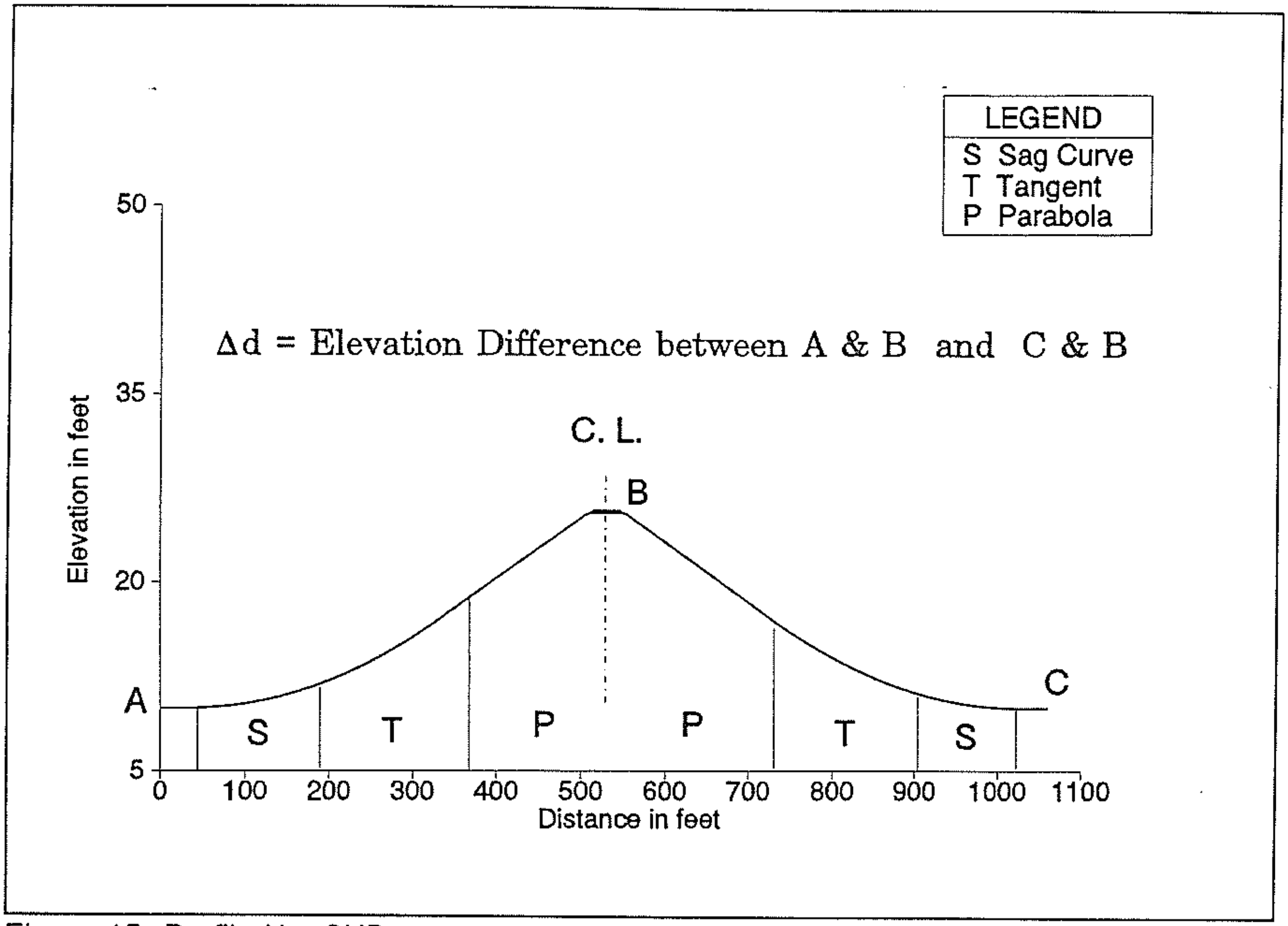

Figure 15 Profile No. SUD

The experiments in this set are divided into three groups. For each group, we perform a number of simulation runs by changing the parameters for two of the curves while keeping the length of the third curve constant. In each group of experiments, the gradient of the tangent is increased in an increment of 0.02 percent. To accommodate for this change, the lengths of two of the curves are adjusted to maintain a constant elevation difference (Δd). Table 8 shows the experimental setup for the three groups. The following sections present the descriptions and the results obtained from these experiments.

TABLE 8 SUD EXPERIMENTAL GROUPS

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

7.1.1 Experiment Group SUD.ST

In the first group of experiments the tangent gradient is increased by an increment of 0.2 percent. To keep Δd constant, the length of the sag curve is increased and the length of the tangent is decreased. The length of the parabola is kept constant in the process. Once a feasible design is produced, the program calculates the IRI of the resulting profile. Three sets of experiments are performed corresponding to different elevation differences.

Experiment SUD.ST.01: In this experiment, the elevation difference, Δd, is set at 5.3 feet. The secondary roadway starts with a tangent of 0 percent gradient and a length of 36 feet. Then there is a sag curve of 150 feet with a start and an end tangents of 0 percent and 0.9 percent respectively. The sag curve is joined with a tangent of 170 feet in length and a gradient of 0.9 percent. A parabola of 150 feet in length with start and end gradients of 0.9 percent and 2.5 percent respectively joins the tangent and the cross slope of the main highway. Table 9 summarizes the curve parameters.

TABLE 9 INPUT CURVE PARAMETERS FOR PROFILE SUD (Δd=5.3 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	0.9%	150
Tangent	0.9%	0.9%	170
Sag	0.9%	2.5%	150

The study of T-Intersections revealed that a combination of sag, parabola, and tangent will produce the smoothest transition going upgrade. In this type of transition, the gradient of the start tangent of a parabola must be more than the gradient of the end tangent. But for this experiment, for the given length of the curve and the cross slope of the main highway, the gradients of the start and end tangent of the parabola are 0.9 percent and 2.5 percent respectively. Therefore the parabola is replaced by a sag curve joining the tangent and the cross slope of the main highway. Figure 16 shows the calculated IRI values for the profile SUD. The IRI value remains low until the main highway is reached; at that point there is a sudden rise. The rise in IRI at the centerline of the main highway is a result of the cross slope of the main highway.

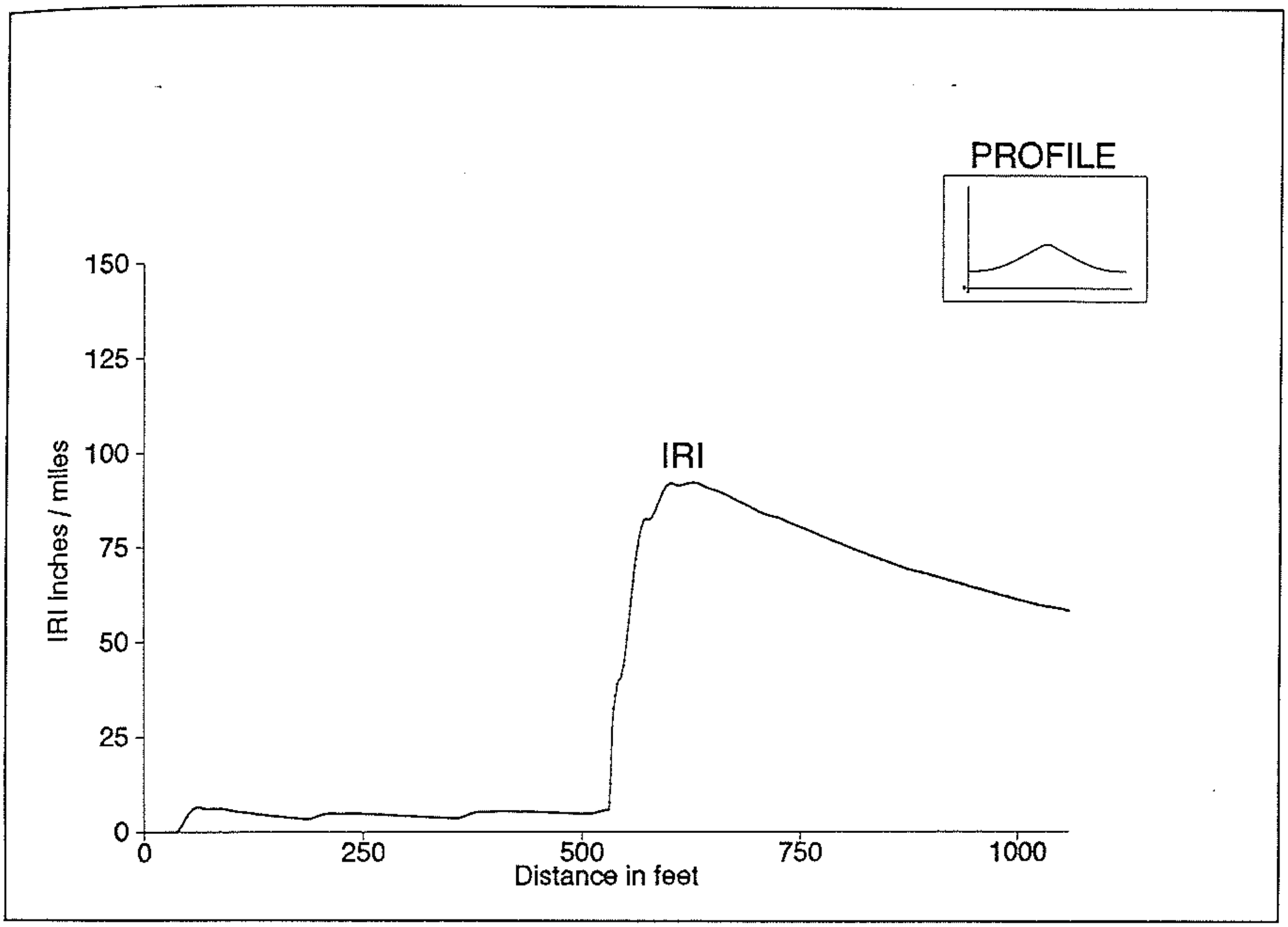

Figure 16 IRI variation along profile SUD (Δd = 5.3 feet)

The Final-IRI is calculated for a total length of 1060 feet, 530 feet each side of the center line of the main highway. The procedure for generating feasible profiles is continued until all possible tangent lengths are exhausted. A total of 18 profiles is generated for this setup. As the length of the sag curve increases, the values of Final-IRI decreases. The minimum value of Final-IRI (55.20) is obtained for a tangent length of one foot. The plot of the Final-IRI values is depicted in Figure 19.

Experiment SUD.ST.02: The criteria for experiment SUD.ST.01 is repeated for an elevation difference of 10.6 feet. Figure 17 shows the calculated IRI along the profile. The gradient of the tangent is increased from 0.9 percent to 2.55 percent. The initial setup for this experiment is depicted in Table 10. A total of 48 profiles is generated for this experiment. The minimum value of the Final-IRI (56.22) is obtained for the tangent length of 30 feet. The plot of the Final-IRI values is also depicted in Figure 19.

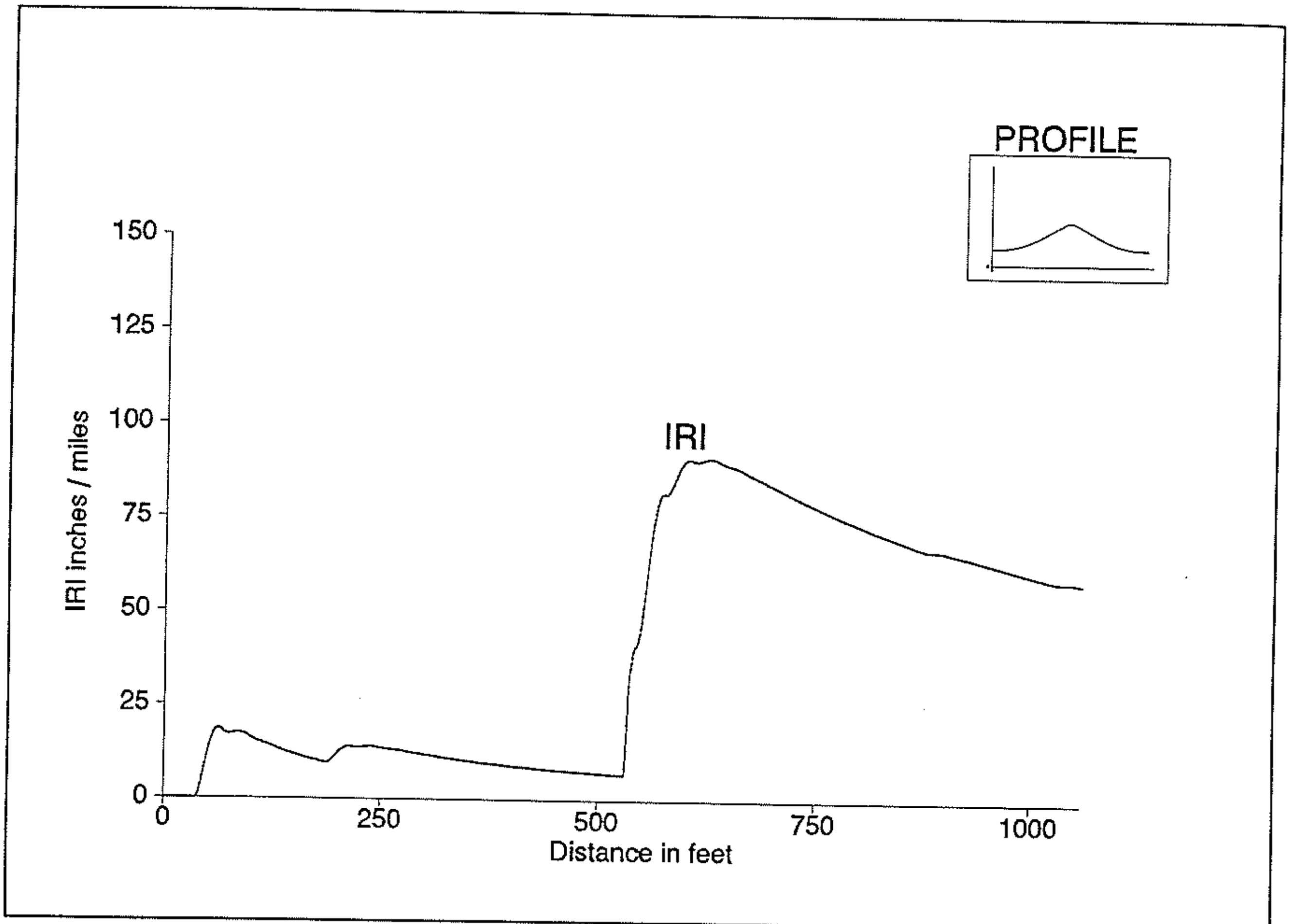

Figure 17 IRI variation along profile SUD (Δd=10.6 ft)

TABLE 10 INPUT CURVE PARAMETERS FOR PROFILE SUD (Δd=10.6 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	2.55%	150
Tangent	2.55%	2.55%	170
Parabola	2.55%	2.5%	150

Experiment SUD.ST.03: The same profile generating procedure used in experiment SUD.ST.02 is repeated for an elevation difference of 15.9 feet. Figure 18 shows the calculated IRI along the profile, for the initial setup shown in Table 11. The number of profiles generated for this setup is 78. The minimum value of Final-IRI is 60 and it is obtained for a tangent length of 31 feet. The plot of Final-IRI values is depicted in Figure 19.

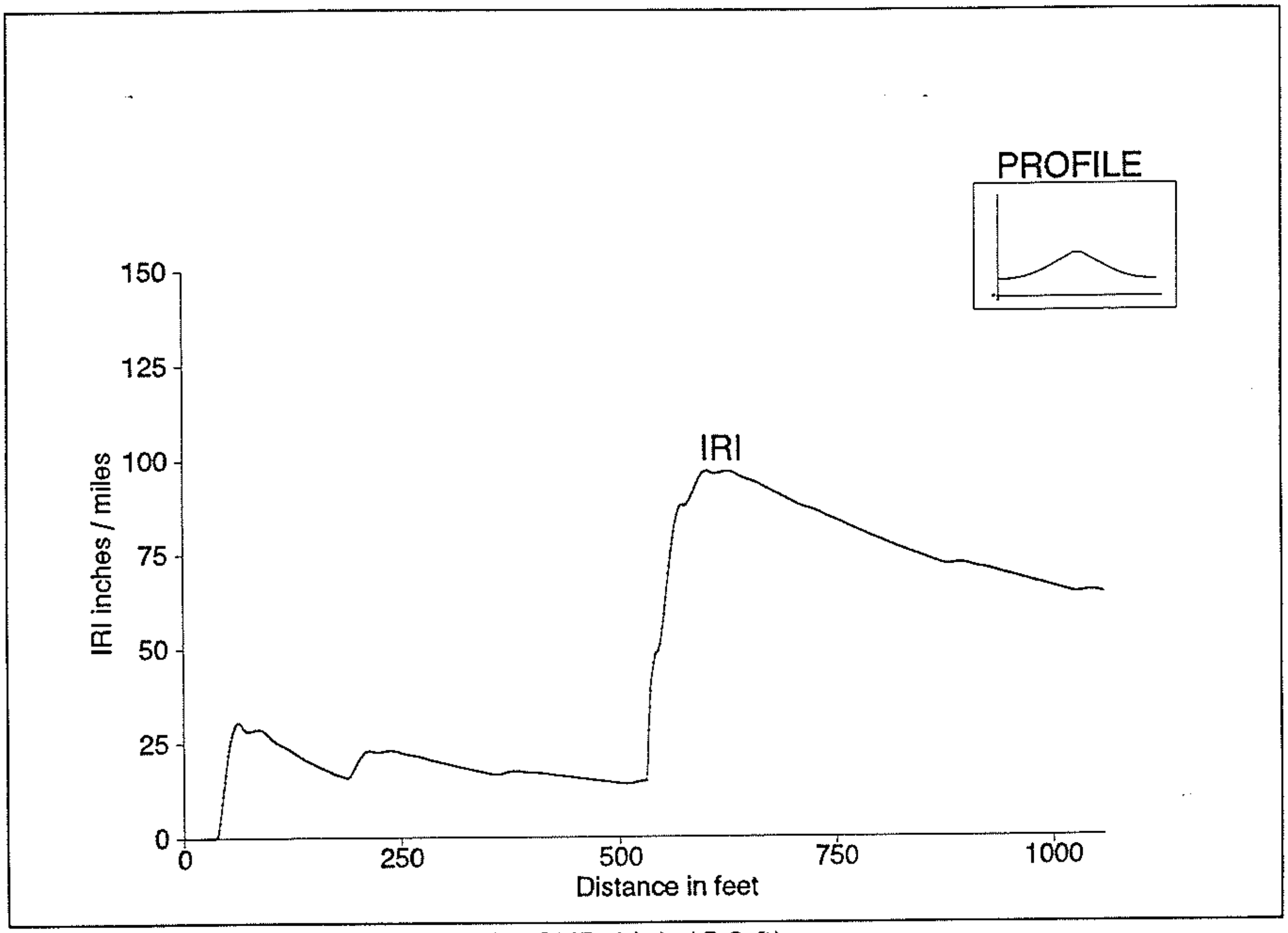

Figure 18 IRI variation along profile SUD (Δd=15.9 ft)

TABLE 11 INPUT CURVE PARAMETERS FOR PROFILE SUD (Δd=15.9 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	4.2%	150
Tangent	4.2%	4.2%	170
Parabola	4.2%	2.5%	150

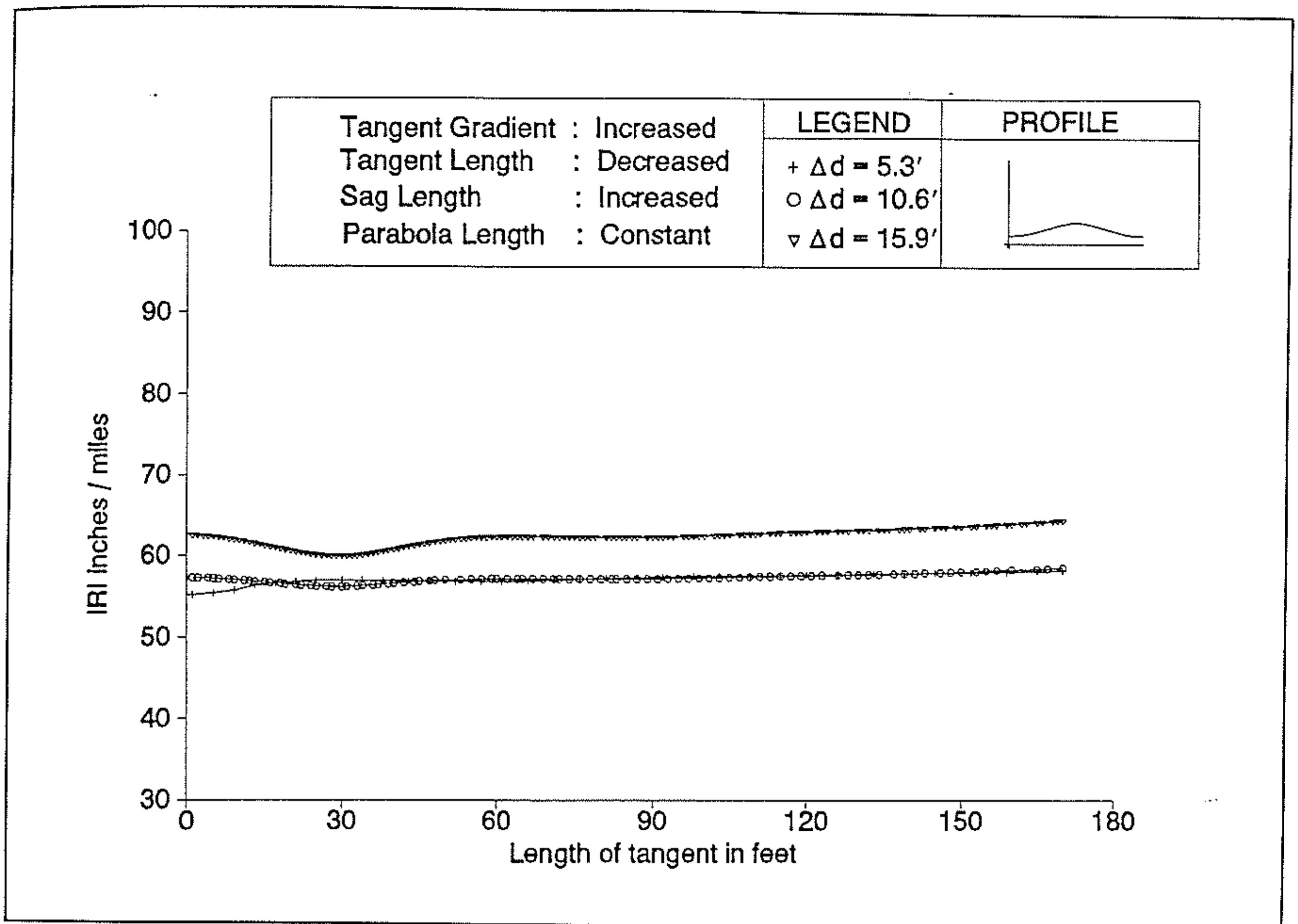

Figure 19 Final-IRI for experiment SUD.ST

Table 12 shows the curve parameters corresponding to the minimum values of Final-IRI for all three elevation differences. Observation of Figure 19 reveals that the Final-IRI values are not significantly effected by the length of the tangent curve. The Final-IRI value for Δd of 15.9 feet is always larger then corresponding values obtained for Δd values of 5.3 and 10.6 feet. The Final-IRI values for Δd of 5.3 and 10.6 feet are almost the same for different curve parameters.

TABLE 12 CURVE PARAMETERS FOR SUD.ST PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)
5.3	1.24	1	319	55.20
10.6	3.29	30	290	56.22
15.9	5.4	31	289	60.00

7.1.2 Experiment Group SUD.PT

The initial setup for this group of experiments is also shown in Table 8. The experiments are performed by increasing the tangent gradient by increments of 0.2 percent. In the process, to keep Δd constant, the length of parabola is increased and the length of the tangent is decreased while keeping the sag length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile.

Experiment SUD.PT.01: For a specified Δd value of 5.3 feet, the first set of experiments results in only one profile. As the tangent gradient is increased from 0.9 percent to 1.01 percent, for all possible tangent lengths less then 170 feet the value of Δd could not be kept at 5.3 feet and thus violated the established criteria. The Final-IRI value for the experiment is shown in Figure 20.

Experiment SUD.PT.02: The same procedure as in experiment SUD.PT.01 is repeated for the elevation difference of 10.6 feet. A total of three profiles is generated; two of the three profiles have common tangent lengths. The minimum value of the Final-IRI is 58.61 and it occurs for a tangent length of 170 feet. This value coincides with the Final-IRI value for Δd of 5.3 feet and tangent length of 170 feet. The variation in the values of the Final-IRI as a function of tangent length is not significant in this case. The plot of Final-IRI values is depicted in Figure 20.

Experiment SUD.PT.03: The above profile generating criteria is repeated for the elevation difference of 15.9 feet which results in 33 profiles. The Final-IRI value remains almost constant for tangent lengths between 65 and 170 feet. When the tangent length decreases below 65 feet, the Final-IRI value also decreases, and it increases as the length decreases below 32 feet. The minimum value of the Final-IRI (63.22) occurs at 32 feet tangent length. The plot of Final-IRI values is depicted in Figure 20.

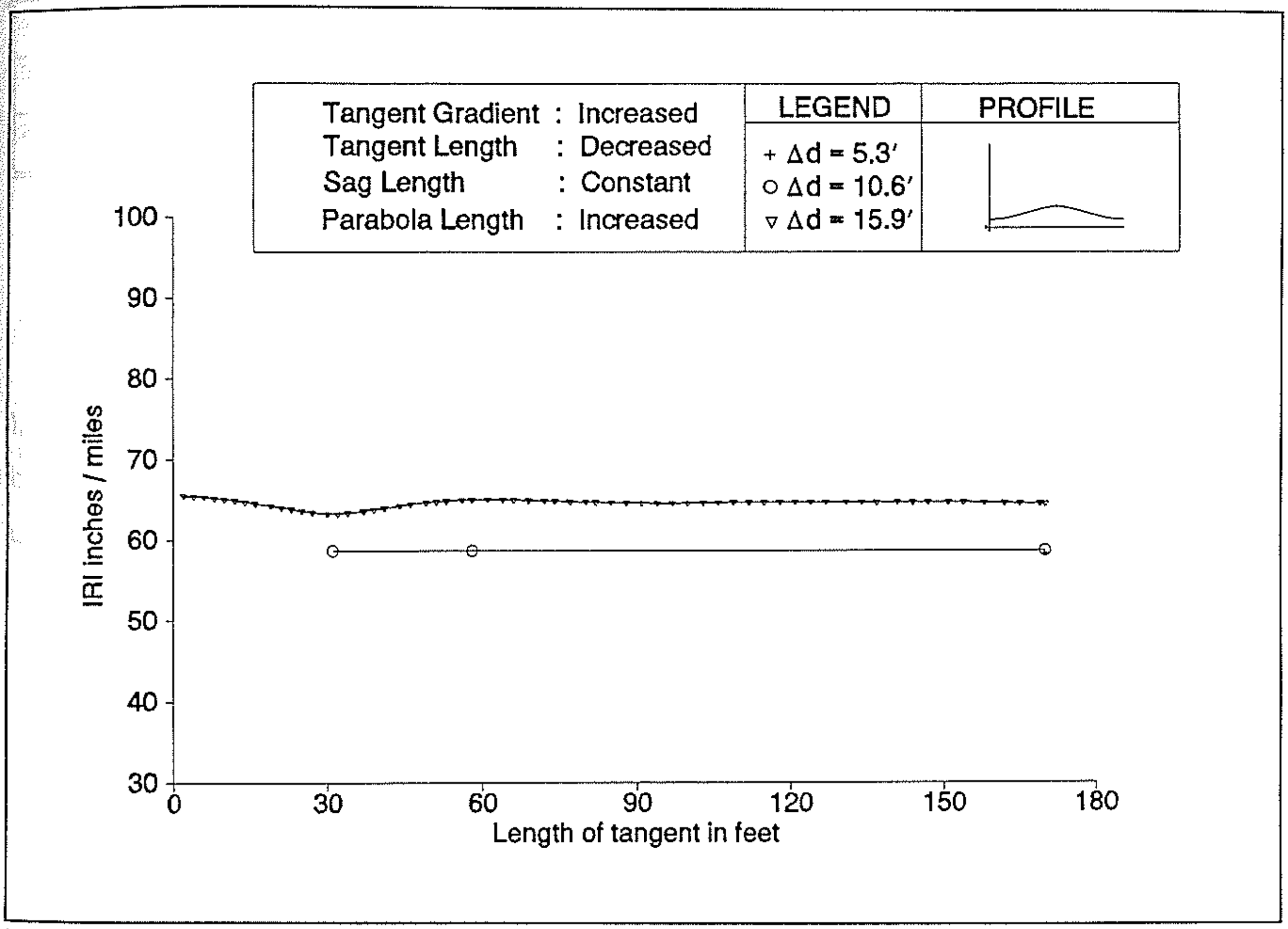

Figure 20 Final-IRI for experiment SUD.PT

Table 13 summarizes curve parameters corresponding to the minimum values of Final-IRI. Only one profile is generated for Δd value of 5.3 and three profiles for Δd of 10.6 feet. The Final-IRI value for Δd of 15.9 feet is always greater than Final-IRI for Δd of 5.3 and 10.6 feet.

The minimum Final-IRI for Δd of 5.3 and 10.6 feet occurs at the tangent length of 170 feet. The variations in Final-IRI values as a function of an increase in the lengths of tangent and the parabola are not significant.

TABLE 13 CURVE PARAMETERS FOR SUD.PT PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
5.3	0.9	150	170	58.31
10.6	2.55	150	170	58.61
15.9	4.7	32	288	63.22

7.1.3 Experiment Group SUD.SP

The next series of experiments involves increasing the tangent gradient in an increment of 0.2 percent. In this process to keep Δd constant, the length of parabola is decreased and the length of the sag is increased while keeping the tangent length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile.

Experiment SUD.SP.01: The first set of experiments is performed for Δd of 5.3 feet. A total of 30 profiles is generated for this setup. The Final-IRI values remain almost constant from the parabola length of 100 to 150 feet. When the parabola length is further decreased, the Final-IRI value increases and then decreases until the length of parabola reaches 51. There is a sudden increase in the Final-IRI value with further reduction in the parabola length. The plot of Final-IRI values is depicted in Figure 21.

Experiment SUD.SP.02: The above profile generating criteria is repeated for Δd value of 10.6 feet. The number of profiles generated for this setup is 31. The shape of the Final-IRI curve is opposite to the shape obtained in experiment SUD.SP.01. The minimum value of Final-IRI is 51.89 and it occurs for a parabola length of 6 feet. The plot of Final-IRI values is depicted in Figure 21.

Experiment SUD.SP.03: The same procedure as experiment SUD.SP.02 is repeated for the Δd value of 15.9 feet which again resulted in 31 profiles. The shape of the Final-IRI curve is similar to experiment SUD.SP.02. However, the Final-IRI values are larger for all possible parabola lengths. The minimum Final-IRI value (53.08) occurs for the parabola length of 9 feet. The Final-IRI curve for all three elevation differences is shown in Figure 21.

Table 14 summarizes curve parameters corresponding to the minimum values of Final-IRI. The parabola lengths of 6 and 9 feet produce the lowest values of Final-IRI for Δd of 10.6 and 15.9 feet respectively.

TABLE 14 CURVE PARAMETERS FOR SUD.SP PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Parabola Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)
5.3	1.3	51	249	57.39
10.6	3.13	6	294	51.89
15.9	4.78	9	291	53.08

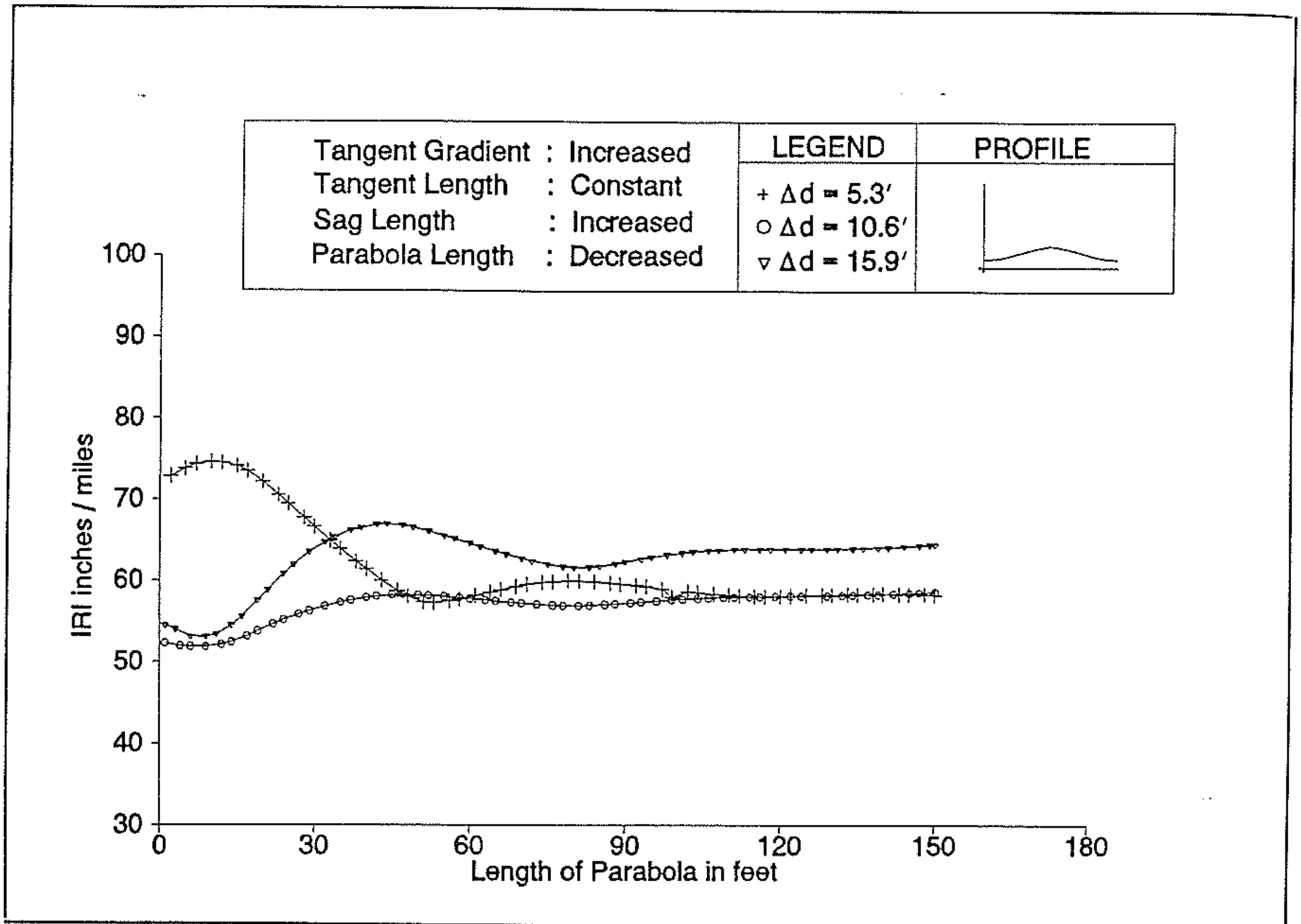

Figure 21 Final-IRI for experiment SUD.SP

7.1.4 Summary Results for Profile SUD

Overall, Final-IRI values for Δd of 15.9 feet are always greater then those for Δd values of 5.3 and 10.6 feet. But the Final-IRI values for Δd of 5.3 and 10.6 feet are almost the same for different curve parameters. This is because we have not used the combination of sag, tangent, and parabola for Δd of 5.3 feet. This difference is also evident from Figure 21, in which the shape of the Final-IRI curve for Δd of 5.3 feet is opposite to the Final-IRI curve for Δd of 10.6 and 15.9 feet. A SUD profile tangent length of 30 feet and parabola length of 9 feet gives lower values of Final-IRI.

7.2 PROFILE SDU

The next set of simulation experiments is performed on a symmetric profile as depicted in Figure 22. The design of the transition on the right side of the main highway is a mirror image of the profile on the left side. This symmetrical property is not altered as various design parameters are considered.

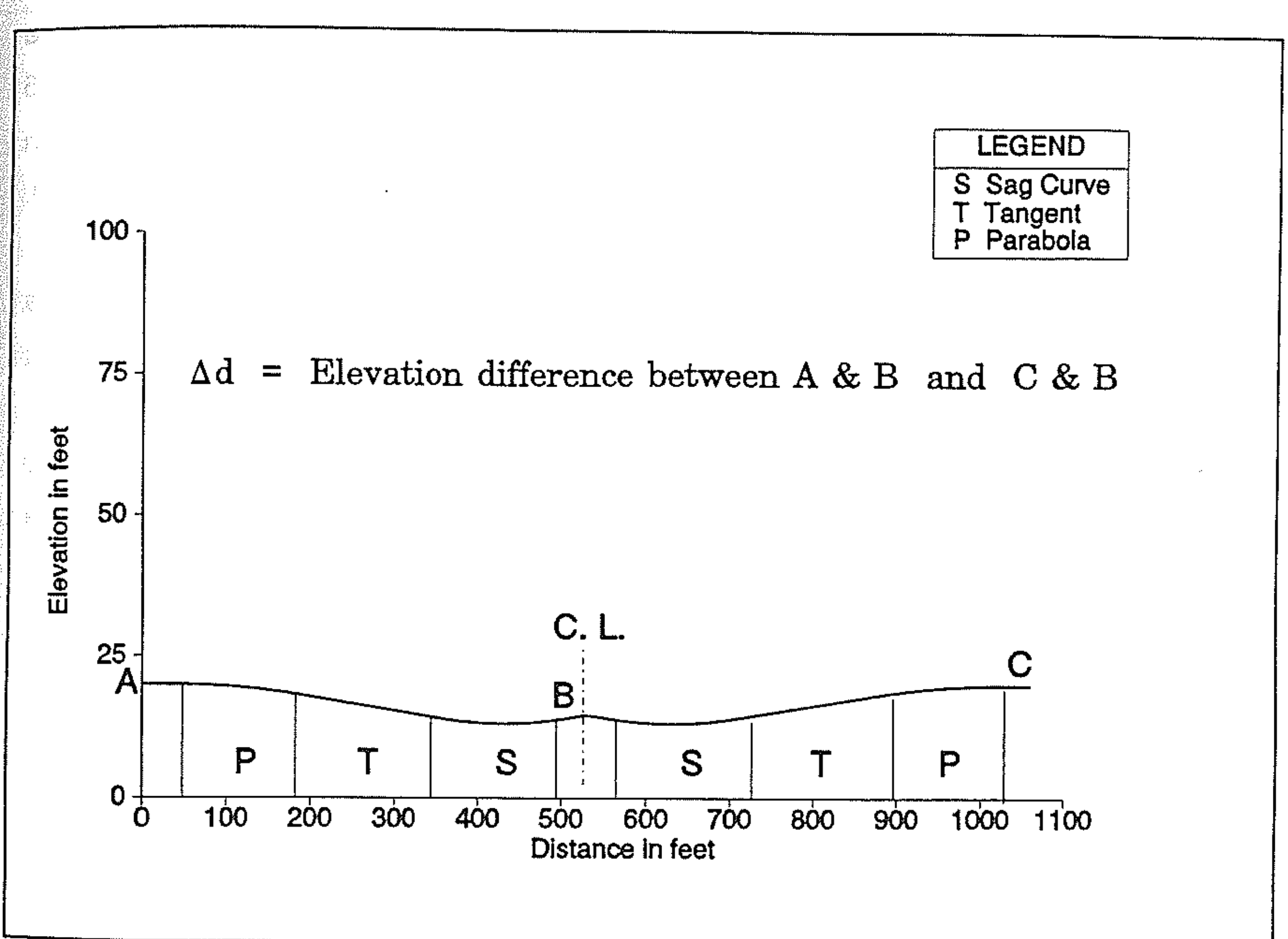

Figure 22 Profile No. SDU

Study of different profiles joining a secondary roadway and a main highway reveals that a combination of parabola, tangent, and sag will produce the smoothest transition going downgrade. The secondary roadway always starts with a tangent of length 36 feet and 0 percent gradient. The tangent is joined to the parabola of 150 feet in length, which is joined and the cross slope of the main highway. The main highway is 48 feet wide and has a gradient of 2.5 percent on both sides of the center line. The width and the cross slope of the main highway are kept constant for all experiments.

A number of experiments are performed on profile SDU by systematically varying two factors: (1) the lengths of two of the three curves, S-T-P, that produce a feasible design, and (2) the elevation difference between the main highway and the secondary roadway. Three curve combinations are possible: S-T, P-T and S-P. The values for elevation difference are selected in such a manner that grade changes of approximately 1 percent, 2 percent and 2.5 percent occur at the intersection. These three levels of grade change result in elevation differences of 5.3 feet for 1 percent, 10.6 feet for 2 percent, and 13.25 feet for 2.5 percent.

Nine sets of experiments are required to consider all possible combinations of two factors at three different levels. For each set, experiments are performed by controlling the gradient of tangent: it is increased in increments of 0.02 percent after a feasible profile is generated. To accommodate for this change, the lengths of two of the three curves are then adjusted to maintain a constant elevation difference (Δd). The simulation is stopped when a feasible profile can not be obtained by changing the length of two curves.

Based on the feasibility of adjusting the lengths of the curves, three groups of experiments are formed from the set of nine. Table 15 shows the curve parameter setup by group. For example, Group SDU.PS is performed by reducing the sag curve length and increasing the parabola length to meet the 0.02 percent change in the tangent gradient. In each group, experiments are repeated using the same procedure for three different elevation differences (i.e., 5.3, 10.6 and 13.25 feet respectively). The following sections present the descriptions and the results obtained from these experiments.

TABLE 15 SDU EXPERIMENT GROUPS

Experiment Group	Tangent Gradient	Tangent Length	Sag Length	Parabola Length
SDU.ST	Increase	Decrease	Increase	Constant
SDU.PT	Increase	Decrease	Constant	Increase
SDU.PS	Increase	Constant	Increase	Decrease

7.2.1 Experiment Group SDU.ST

Experiments in this group are performed to study the effect of variation in sag and tangent length on IRI. The tangent gradient is increased by 0.2 percent once a feasible profile is generated. To keep Δd constant, the length of the sag curve is increased and the length of the tangent is decreased, while the parabola length is kept constant. Once a feasible design is produced, the program calculates the IRI of the resulting profile. Three sets of experiments are performed corresponding to different elevation differences.

<u>Experiment SDU.ST.01:</u> For this set of experiments, the elevation difference Δd, is set at 5.3 feet. The input profile starts with a tangent of length 36 feet and 0 percent gradient on the secondary roadway. A parabola length of 150 feet with start and end tangents of 0 percent and -2.43 percent respectively is joined to the tangent. A tangent length of 170 feet and a gradient of -2.43 percent joined the parabola to a sag curve of 150 feet in length with start and end gradients of -2.43 percent and 2.5 percent respectively. Curve parameters for the input profile are summarized in Table 16.

TABLE 16 INPUT CURVE PARAMETERS FOR PROFILE SDU (Δd=5.3 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Parabola	0%	-2.43%	150
Tangent	-2.43%	-2.43%	170
Sag	-2.43%	2.5%	150

Figure 23 shows the calculated IRI values along the profile SDU for the parameters shown in Table 16. The IRI value remains low till the main highway is reached, then there is a sudden rise in the IRI value. This rise in IRI value at the center line of the main highway is due to the cross slope of the main highway.

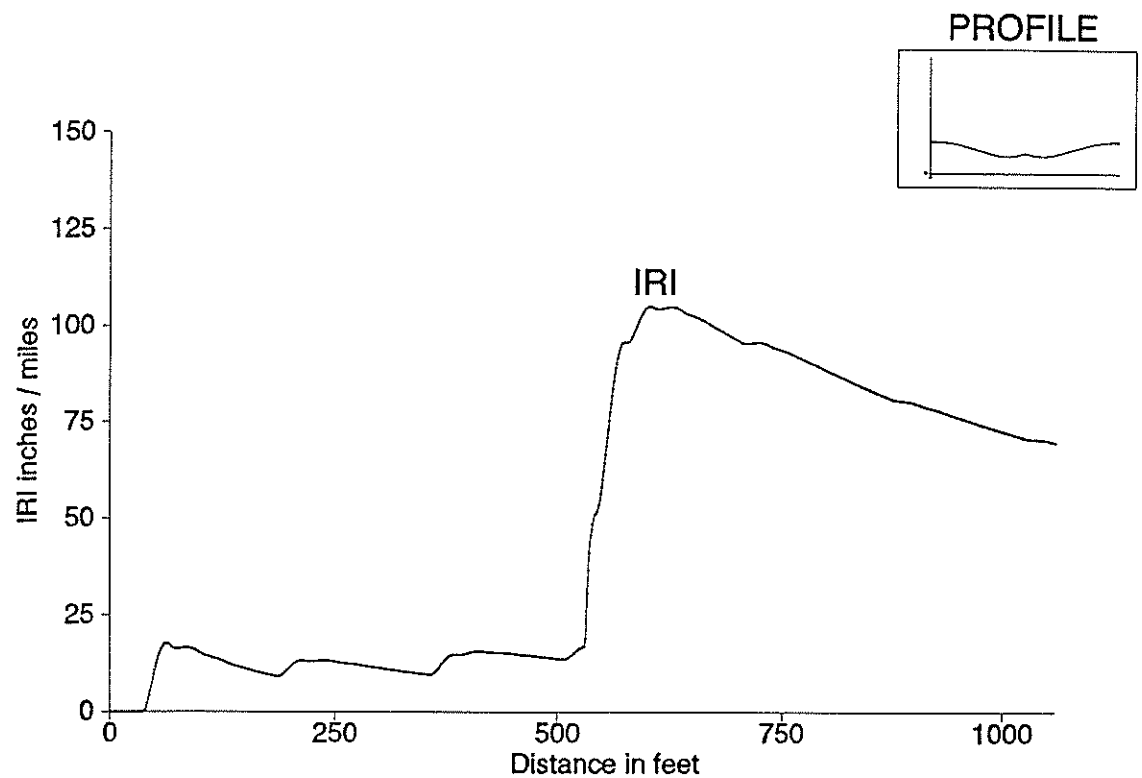

Figure 23 IRI variation along profile SDU (Δd=5.3 ft)

This procedure of generating the profiles is continued until all tangent lengths are exhausted. A total of 44 profiles is generated for this setup. The minimum value of Final-IRI is 66.27 and is obtained for a tangent length of 30 feet. A plot of the Final-IRI values is shown in Figure 26.

Experiment SDU.ST.02: The profile generating criteria used in experiment SDU.ST.01 is repeated here for an elevation difference of 10.6 feet. The gradient of the tangent is increased from -2.43 percent to -4.08 percent to obtain a Δd value of 10.6 feet. The initial setup for this experiment is depicted in Table 17. Figure 24 shows the calculated IRI along the profile for this setup. A total of 74 profiles is generated for this experiment. The minimum value of the Final-IRI is 72.65 and is obtained for a tangent length of 31 feet. The plot of the Final-IRI values is also depicted in Figure 26.

TABLE 17 INPUT CURVE PARAMETERS FOR PROFILE SDU (Δd=10.6 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	-4.08%	150
Tangent	-4.08%	-4.08%	170
Parabola	-4.08%	2.5%	150

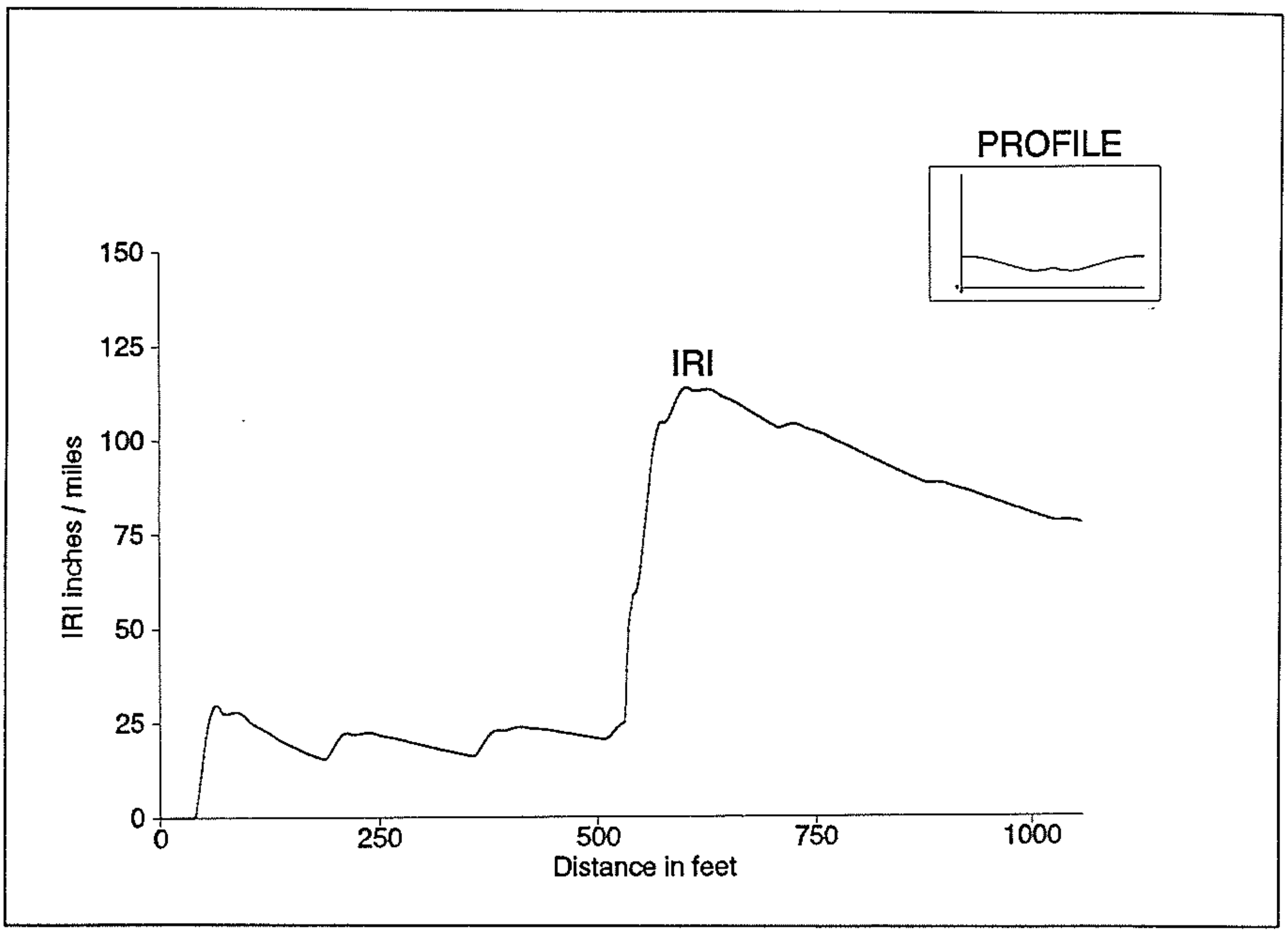

Figure 24 IRI variation along profile SDU (Δd=10.6 ft)

Experiment SDU.ST.03: The same procedure used in experiment SDU.ST.02 is repeated for an elevation difference of 15.9-feet. Figure 25 shows the calculated IRI along the profile for the initial setup shown in Table 18. The number of profiles generated for this setup is 89. The minimum value of Final-IRI is 75.82 which is obtained for a tangent length of 31 feet. The plot of Final-IRI values is depicted in Figure 26.

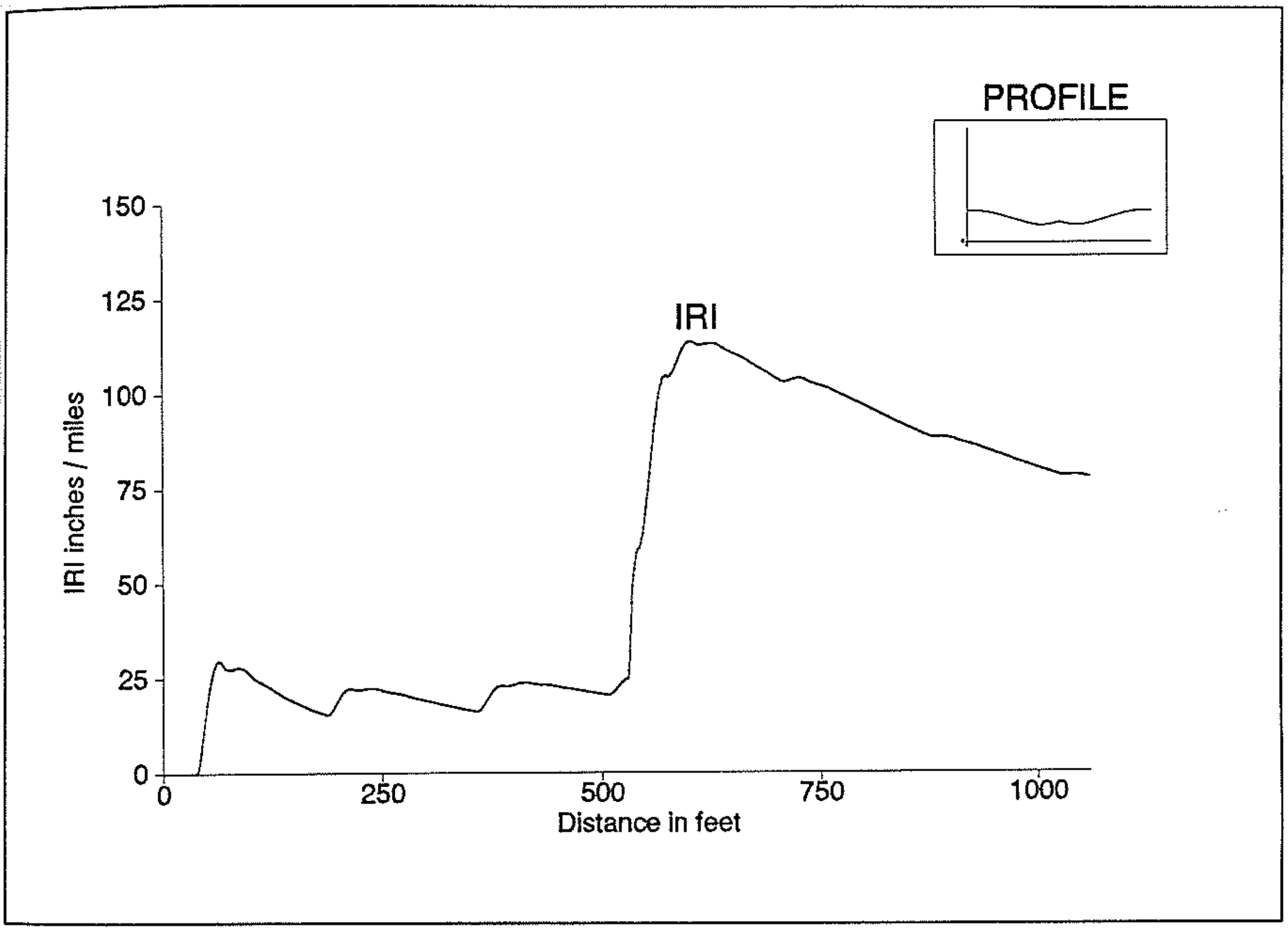

Figure 25 IRI variation along profile SDU (Δd=13.25 ft)

TABLE 18 INPUT CURVE PARAMETERS FOR PROFILE SDU (Δd=13.25 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	0%	4.2%	150
Tangent	4.2%	4.2%	170
Parabola	4.2%	2.5%	150

Figure 26 reveals that the shape of the Final-IRI curve is similar for all the three elevation differences. The tangent length of approximately 30 feet produces lower Final-IRI values.

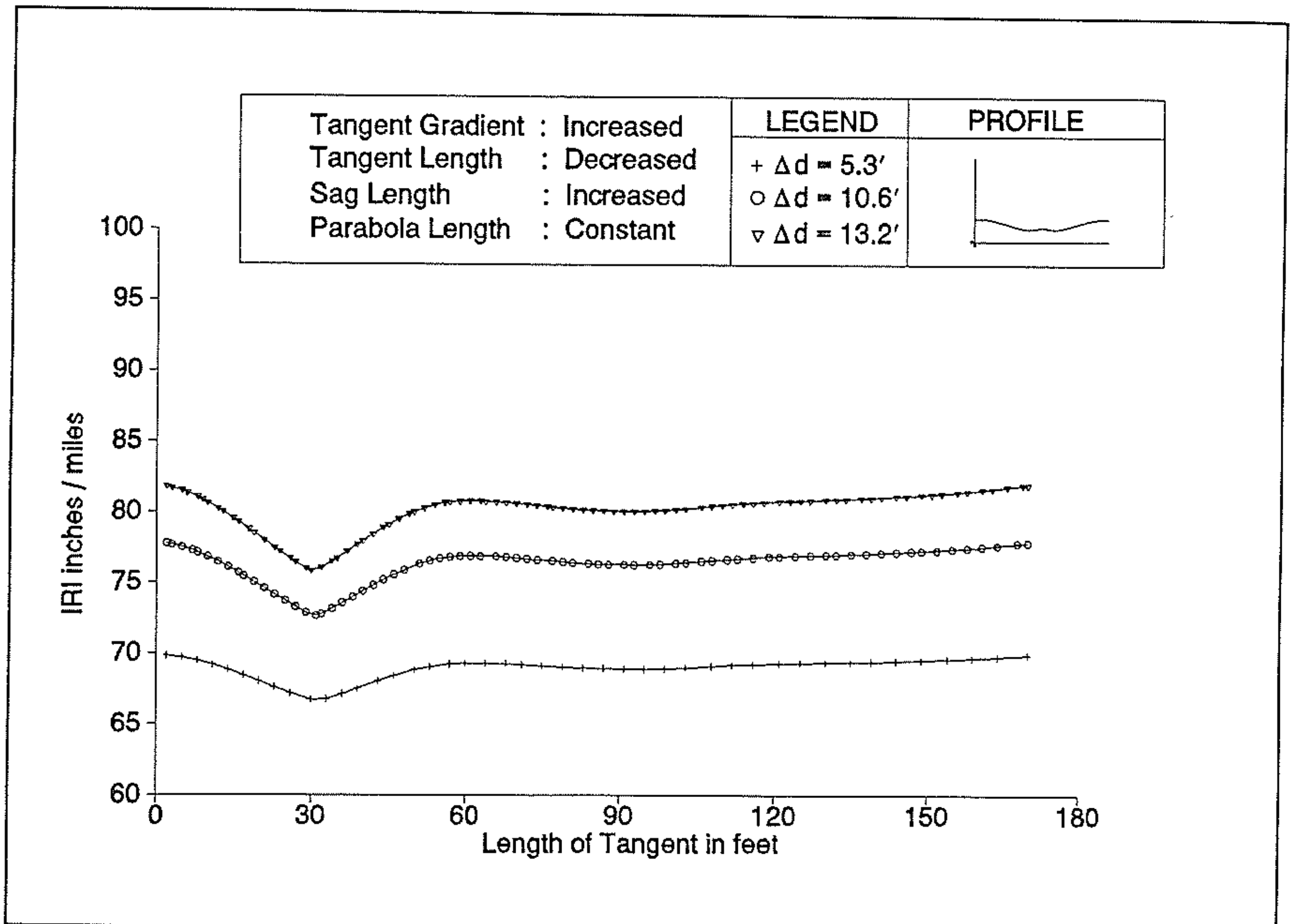

Figure 26 Final-IRI for experiment SDU.ST

Table 19 summarizes curve parameters corresponding to the minimum values of Final-IRI for all three elevation differences.

TABLE 19 SUMMARY CURVE PARAMETERS FOR GROUP SDU.ST PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)
5.3	-3.11	30	290	66.72
10.6	-5.22	31	289	72.65
15.9	-6.3	30	290	75.82

7.2.2 Experiment Group SDU.PT

Initial setup for the next group of experiments is also shown in Table 15. In this series of experiments we increase the tangent gradient in increments of 0.2 percent. In the process, to keep Δd constant, the length of parabola is increased and the length of the tangent is decreased while keeping the sag length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile in both directions.

Experiment SDU.PT.01: The first set of experiments is performed for a total of 89 profiles. The minimum value of Final-IRI is 66.25 and is obtained for the tangent length of 30 feet. The plot of Final-IRI values is shown in Figure 27.

Experiment SDU.PT.02: The same profile generating procedure for the previous group is repeated for the elevation difference of 10.6 feet, which resulted in 119 profiles. The minimum value of the Final-IRI is 72.56 and occurs at a tangent length of 31 feet. The variation in the values of the Final-IRI as a function of tangent length is not significant in this case. The plot of Final-IRI values is also depicted in Figure 27.

Experiment SDU.PT.03: The above criterion is repeated for the elevation difference of 13.25

feet, which resulted in 33 profiles. Again the minimum Final-IRI value occurs at the tangent length of 31 feet. The plot of Final-IRI values is depicted in Figure 27.

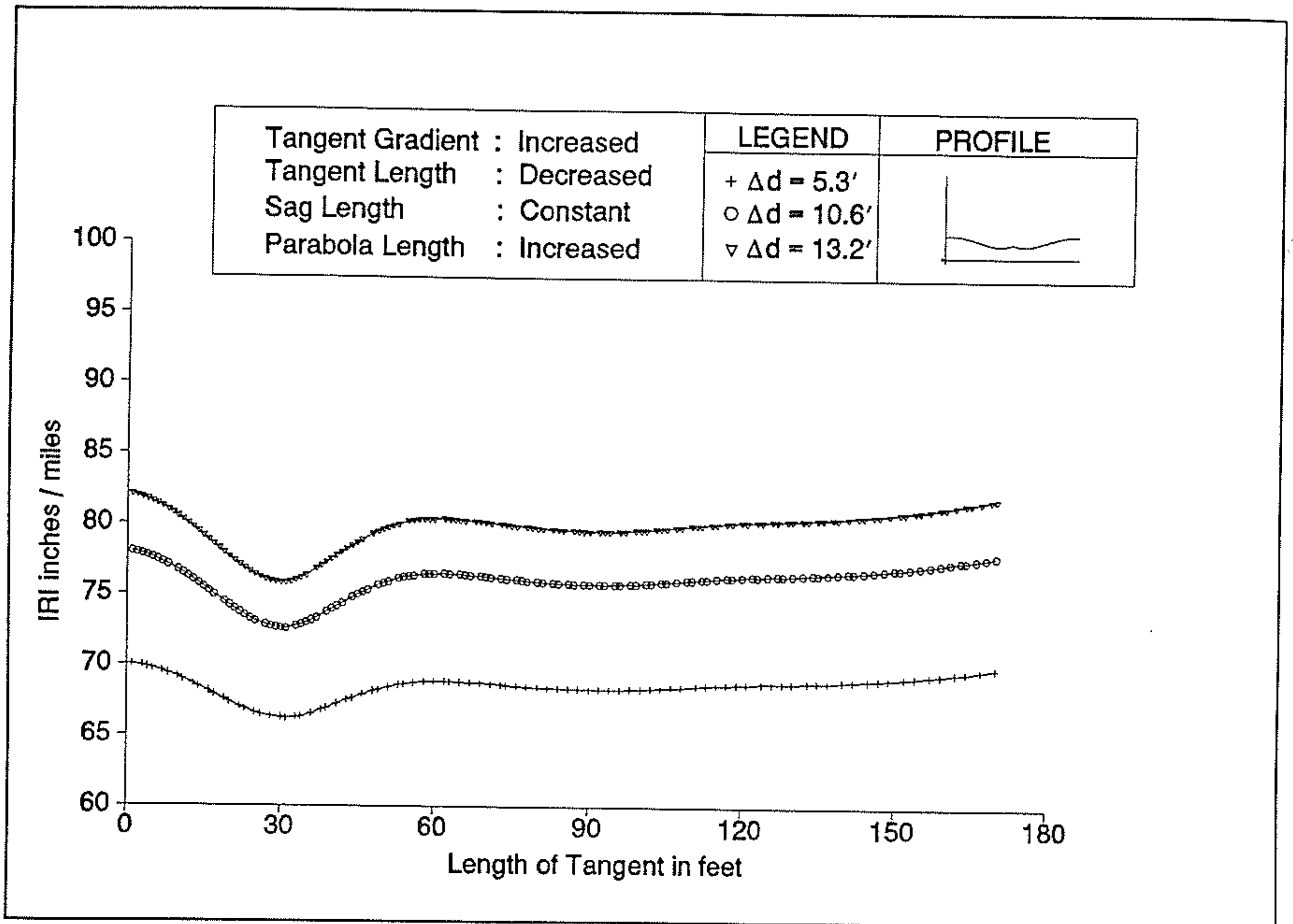

Figure 27 Final-IRI for experiment SDU.PT

Table 20 summarizes the curve parameters for the minimum value of Final-IRI for all three elevation differences. Figure 27 reveals that the shape of the Final-IRI curve is similar for all the three elevation differences. In this group, the tangent length of approximately 31 feet gives lower value of Final-IRI. From Figure 27, it is also evident that the value of Final-IRI is directly proportional to the elevation difference.

TABLE 20 SUMMARY CURVE PARAMETERS FOR GROUP SDU.PT PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Tangent Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
5.3	-3.81	30	290	66.25
10.6	-5.9	31	289	72.56
15.9	-6.98	31	289	75.84

7.2.3 Experiment Group SDU.SP

The next series of experiments also involves increasing the tangent gradient in increments of 0.2 percent. In this process to keep Δd constant, the length of parabola is decreased and the length of the sag length is increased while keeping the tangent length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile in both directions.

Experiment SDU.SP.01: The first experiment is performed for Δd of 5.3 feet, which resulted in 30 profiles. There is very little variation in the Final-IRI value for the parabola length from 150 to 75 feet. When the parabola length is further decreased, the Final-IRI value increased considerably. The minimum value of Final-IRI is 69.66 which occurred at the parabola length of 134 feet. Figure 28 shows the plot of Final-IRI values.

Experiment SDU.SP.02: The same profile generating procedure results in 30 profiles for this setup. The minimum value of Final-IRI is 77.72 which occurs at the parabola length of 136 feet. The plot of Final-IRI values is depicted in Figure 28.

Experiment SDU.SP.03: The third group considers a Δd value of 15.9 feet, which resulted in 30 profiles. The parabola length of 137 feet gives the minimum value of Final-IRI. Figure 28 shows the plot of the Final-IRI values.

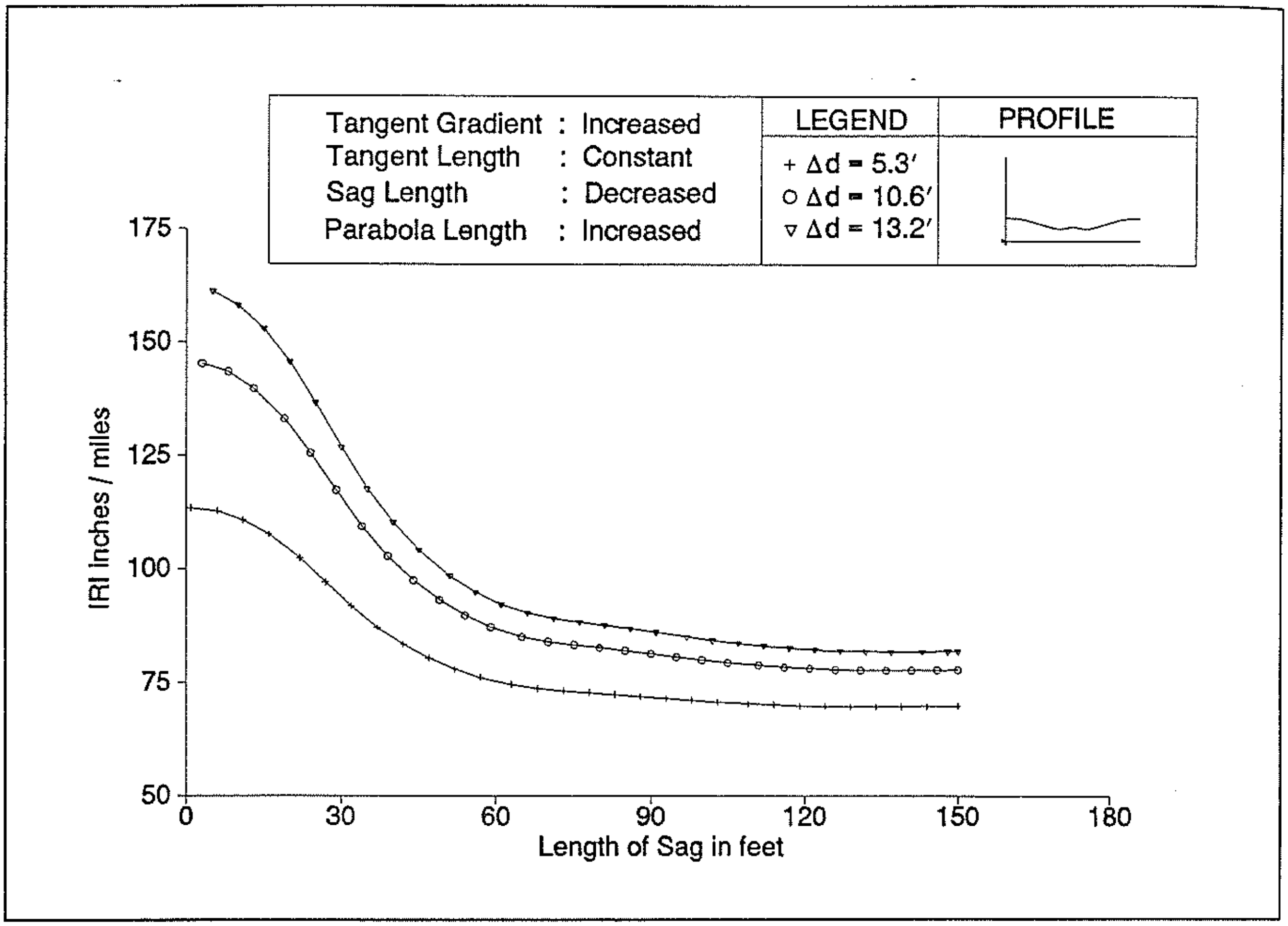

Figure 28 Final-IRI for experiment SDU.SP

Table 21 summarizes the curve parameters for minimum Final-IRI for the three elevation differences. Figures 26, 27, and 28 reveal that the shape of the Final-IRI curve is similar for the three elevation differences. The parabola length of around 135 feet gives lower Final-IRI values. It is also evident that Final-IRI is directly proportional to the elevation difference.

TABLE 21 SUMMARY CURVE PARAMETERS FOR GROUP SDU.PS PROFILES WITH LOWEST IRI

Δd	Tangent Gradient	Sag Curve Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
5.3	-2.49	134	166	69.66
10.6	-4.14	136	164	77.72
15.9	-4.98	137	163	81.82

7.2.4 Summary Results for Profile No. SDU

Study of Figures 26 and 28 reveals that Final-IRI value is directly proportional to the elevation difference. The Final-IRI value is less sensitive to variation in sag-tangent and parabola-tangent than to variation in sag-parabola length. Tangent lengths of 30 feet and parabola lengths of 135 feet give lower values of Final-IRI.

8 ANALYSIS OF ASYMMETRIC X INTERSECTIONS

This chapter describes simulation experiments performed on the asymmetrical profile XUU shown in Figure 29. The elevation difference of the secondary roadway and the main highway is kept the same on both sides of the main highway. Three sets of experiments are performed by increasing the tangent gradient and then varying the length of two of the three curves on the right side of the main highway to meet the elevation difference. Three elevation differences are considered for each set of experiments. The curve parameters on the left side of the main highway are kept constant for each set of experiments. The variation in the IRI value with changes in the curve parameters are depicted in graphical forms for each experiment.

Study of profile XDD reveals that the profile is exactly similar to profile XUU considered for the opposite direction. The results obtained from profile XUU also hold true for profile XDD with the exception that Final-IRI for XUU is the opposite of Final-IRI for XDD and vice versa. This chapter describes the profile generation procedure for each experiment and the results obtained for the profile XUU.

8.1 PROFILE XUU

A set of simulation experiments is performed on a unsymmetric profile (XUU) as depicted in Figure 29. The elevation difference on the left side of the main highway is always kept equal to the elevation difference on the right side of the main highway. The total horizontal length of the profile is 1060 feet. It starts with a tangent on the secondary roadway with a length of 36 feet and 0 percent gradient. The tangent is then joined to a sag curve of 150 feet in length. The sag curve is then joined to another tangent of 170 feet in length. Finally a parabola of 150 feet in length joins the tangent and the cross slope of the main highway. This setting on the left side of the main highway is kept constant throughout the experiment. The main highway is 48 feet wide with a cross slope of 2.5 percent from the center line. The right cross slope of the main highway is joined to the sag curve of 150 feet in length and start tangent gradient of -2.5 percent. The sag curve is joined to a tangent length of 170 feet which is joined to a parabola length of 150 feet and an end tangent gradient of 0 percent. The parabola is then joined to a tangent length of 36 feet and 0 percent gradient.

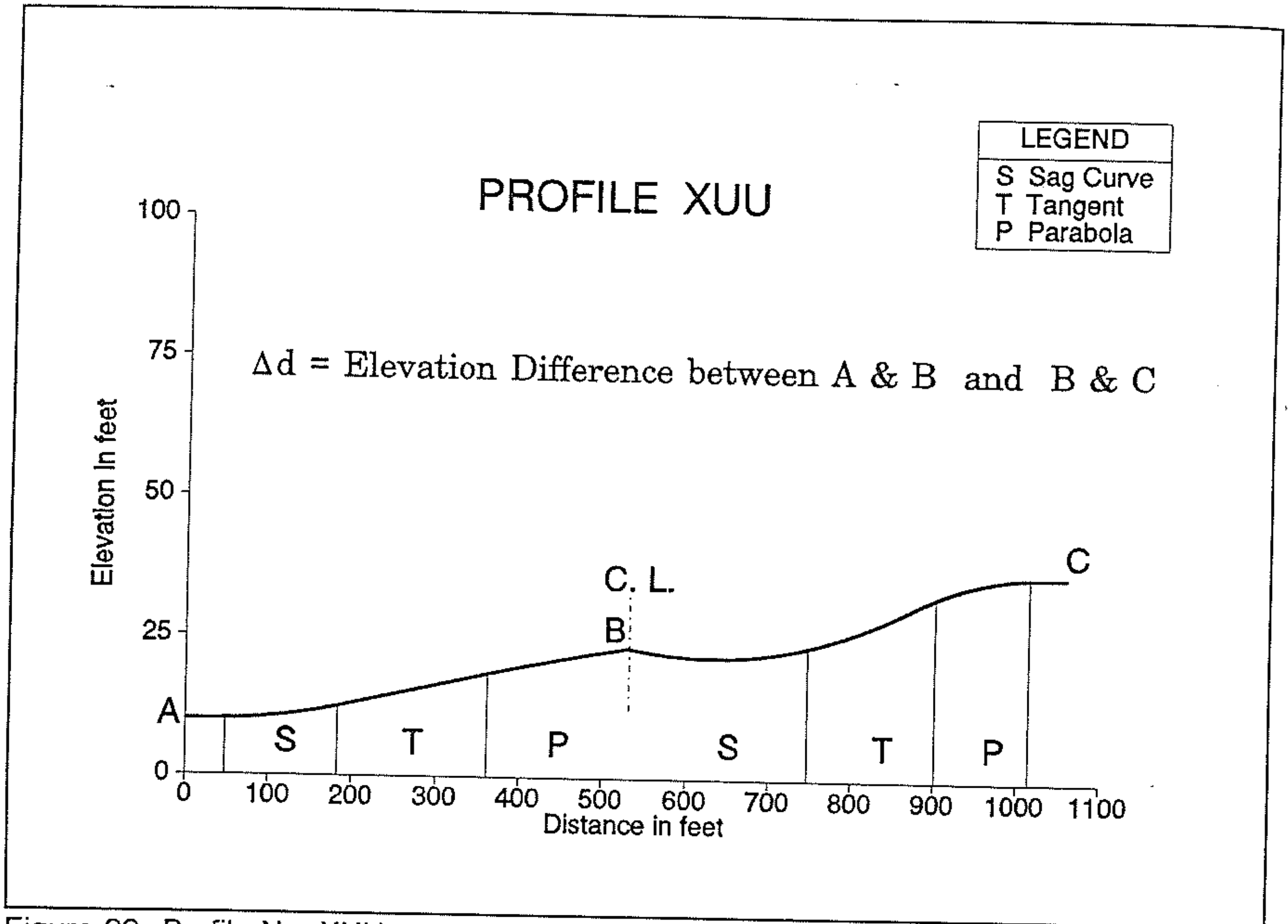

Figure 29 Profile No. XUU

Many experiments are performed on profile XUU by systematically varying two factors on the right side of the main highway: (1) the length of two of the three curves in S-T-P design, and (2) the elevation difference between the main highway and the secondary roadway. The possible pairs of curves from a S-T-P combination are: S-T, P-T and S-P. For the elevation difference, the selected values result in approximate grade changes of 1 percent, 2 percent and 2.5 percent on the intersection. Nine sets of experiments are required to consider all the possible combinations of the two factors. For each set, simulation experiments are performed by changing the length of two curves while keeping the length of the third curve constant for a given elevation difference. This is done by controlling the tangent gradient first: it is increased in increments of 0.02 percent for each experiment. To accommodate this change, the lengths of two of the three curves are then adjusted to maintain a constant elevation difference (Δd). The simulation stops when a feasible profile can not be obtained by changing the lengths of two curves. The width and the cross slope of the main highway is kept constant for all the experiments.

Table 22 shows the curve parameter setup by group. For example, Group XUU.ST is performed by reducing the tangent length and increasing the sag length to meet the 0.02 percent change in the tangent gradient. Each group of experiments is repeated using the same procedure for three different elevation differences (i.e. 5.3, 10.6 and 13.25 feet respectively.) The following sections present the descriptions and the results obtained from these experiments.

TABLE 22 XUU EXPERIMENT GROUPS

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

8.1.1 Experiment Group XUU.ST

In the first group of experiments the length of sag and the length of tangent on the right side of the main highway are systematically varied to determine their effects on the IRI. The tangent gradient is increased in increments of 0.02 percent. To keep the elevation difference between the secondary roadway and the main highway (Δd) constant, the length of the sag curve is increased and the length of the tangent is decreased. The length of the parabola is kept constant in the process. Once a feasible design is produced by a computer program, the program calculates the IRI of the resulting profile in both directions. The program terminates when the length of tangent can not be further reduced. Three sets of experiments are performed corresponding to different elevation differences.

Experiment XUU.ST.01: In this experiment, the elevation difference, Δd, is set at 5.3 feet for a 1 percent grade on the intersection. The secondary roadway starts with a tangent of 0 percent gradient and a length of 36 feet which is joined to a sag curve length of 150 feet with a start and an end tangent of 0 percent and 0.9 percent respectively. The sag curve is joined with a tangent length of 170 feet and a gradient of 0.9 percent. A parabola length of 150 feet with a start and end gradient of 0.9 percent and 2.5 percent respectively joins the tangent and the cross slope of the main highway. The right cross slope of the main highway is joined to a sag curve length of 150 feet and start tangent gradient of -2.5 percent. The sag curve is joined to a tangent length of 170 feet and gradient of 2.45 percent which is then joined to a parabola of 150 feet in length and end tangent gradient of 0 percent. The parabola is joined to a tangent length of 36 feet and gradient of 0 percent. Table 23 summarizes the parameters of the curve on the right side of the main highway.

TABLE 23 INPUT CURVE PARAMETERS FOR PROFILE XUU (Δd=5.3 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	-2.5%	2.45%	150
Tangent	2.45%	2.45%	170
Sag	2.45%	0%	150

Figure 30 is a plot of the calculated IRI from both directions of the profile XUU based on the curve parameters specified in Table 23.

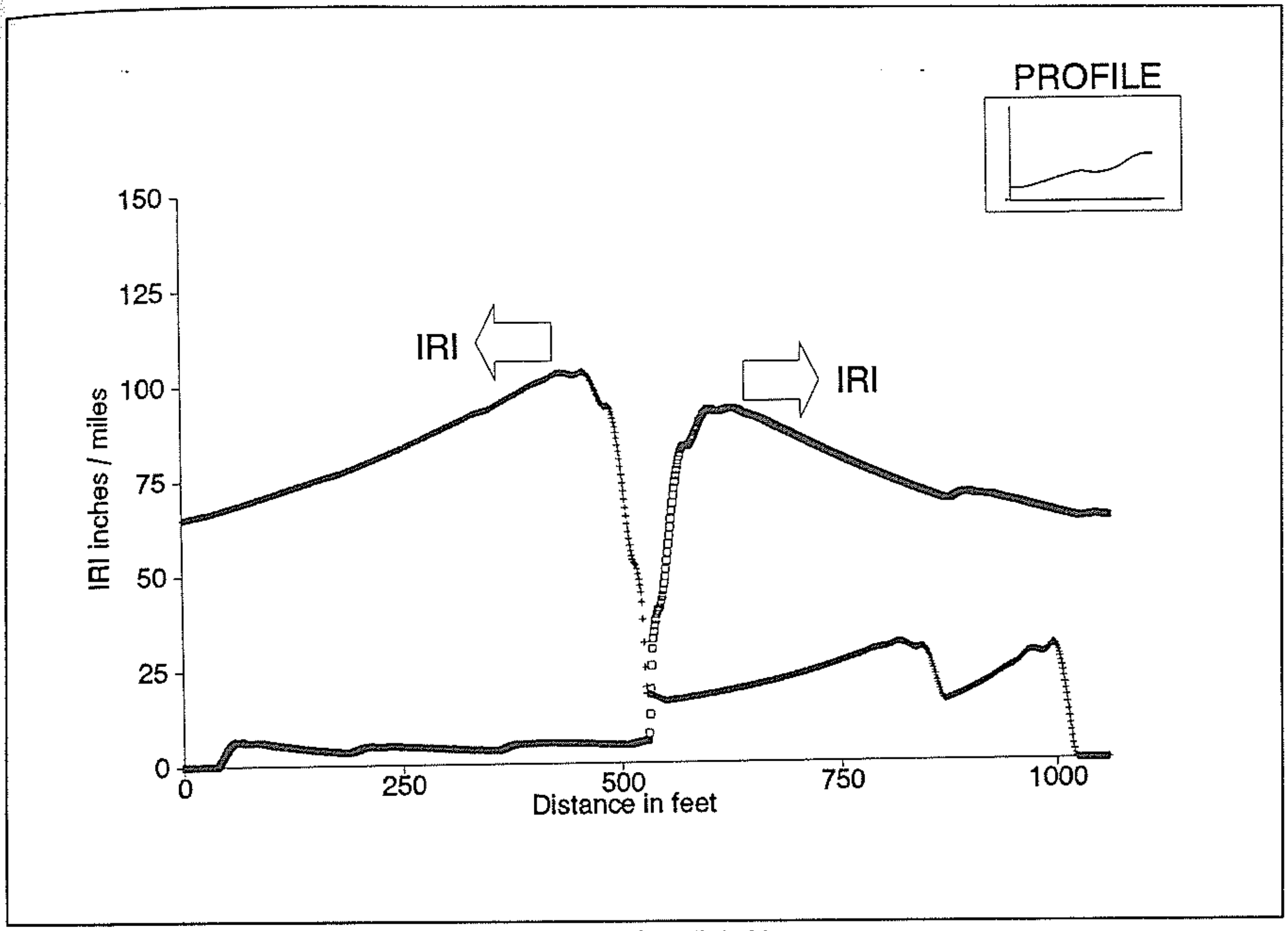

Figure 30 IRI Variation along Profile XUU (Δd=5.3 ft)

The Final-IRI is calculated for a total length of 1060 feet, 530 feet each side from the center line of the main highway. A total of 90 profiles is generated for this setup. Both the minimum Final-IRI and the minimum opposite Final-IRI occurs for the tangent length of 31 feet. The minimum value of the Final-IRI and the opposite Final-IRI is 61.95 and 62.74 respectively. The plot of the Final-IRI values is depicted in Figure 31.

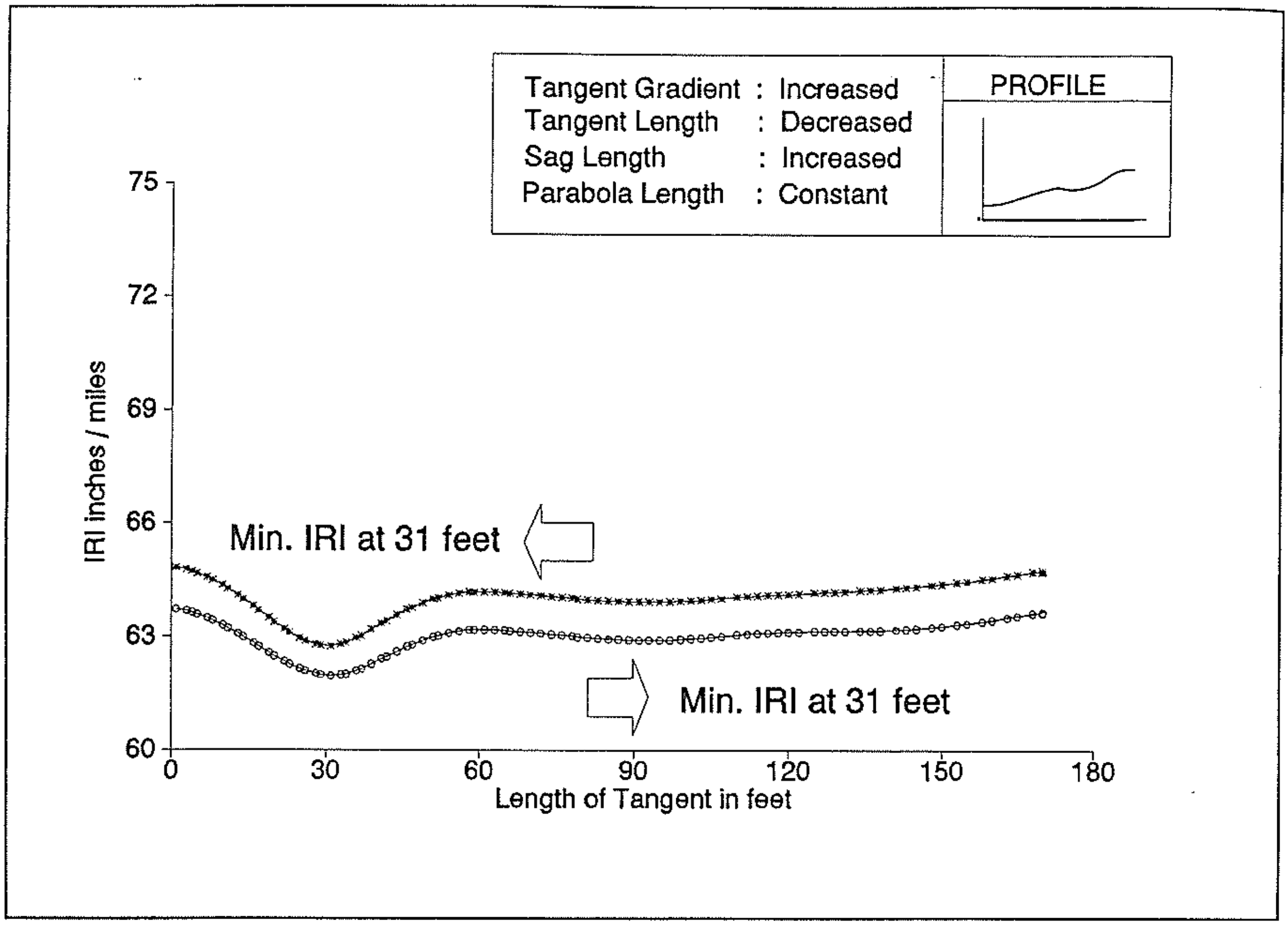

Figure 31 Final-IRI for experiment XUU.ST.01 (Δd=5.3 ft)

Experiment XUU.ST.02: The criteria for experiment XUU.ST.01 is repeated for an elevation difference of 2 percent (Δd=10.6). Figure 32 shows the calculated IRI along the profile for the initial setup shown in Table 24. The gradient of the tangent on the left side of the main highway is increased from 0.9 percent to 2.55 percent. The gradient of the tangent on the right side of the main highway is increased from 2.45 percent to 4.1 percent. A total of 119 profiles is generated for this experiment. The minimum value of Final-IRI and the opposite Final-IRI occurs for the tangent length of 31 feet. The minimum value of the Final-IRI and the opposite Final-IRI is 65.23 and 66.15 respectively. The plot of the Final-IRI values is depicted in Figure 33.

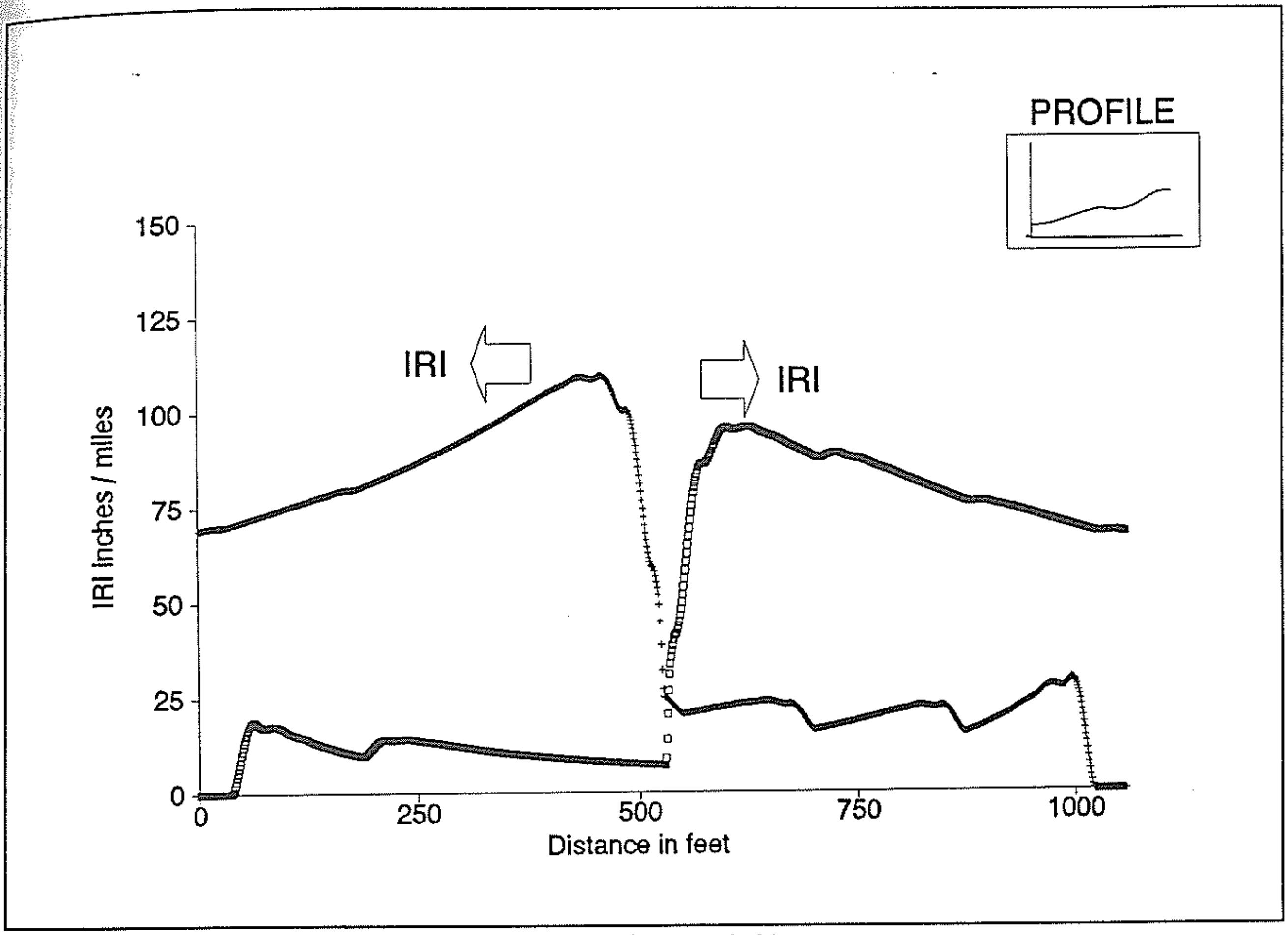

Figure 32 IRI variation along profile XUU (Δd=10.6 ft)

TABLE 24 INPUT CURVE PARAMETERS FOR PROFILE XUU (Δd=10.6 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	-2.5%	4.1%	150
Tangent	4.1%	4.1%	170
Parabola	4.1%	0%	150

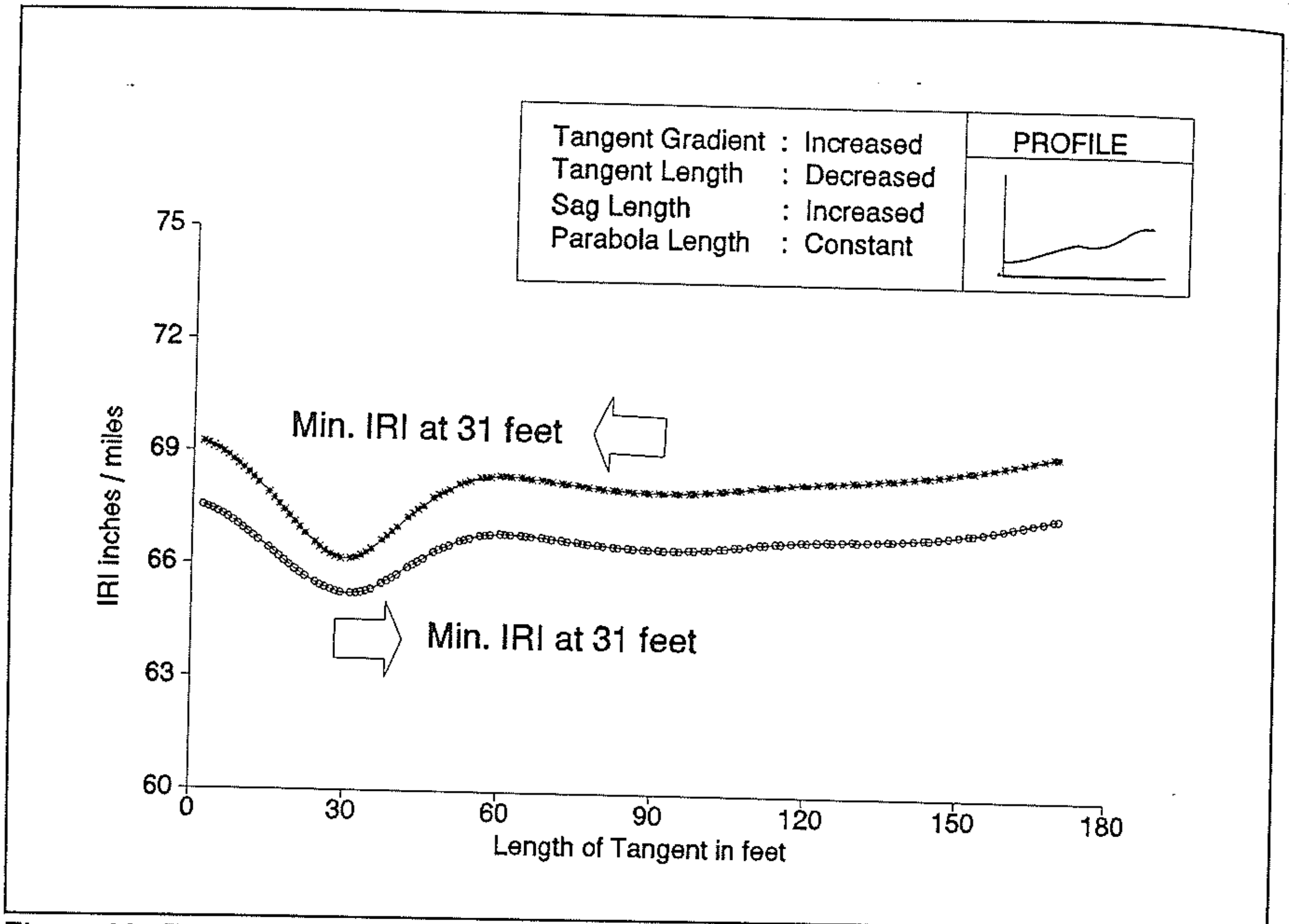

Figure 33 Final-IRI for experiment XUU.ST.02 (Δd=10.6 ft)

Experiment XUU.ST.03: The same profile generating procedure used in experiment XUU.ST.02 is repeated for an elevation difference of 13.25 feet (about 2.5 percent). Figure 34 shows the calculated IRI along the profile for the the initial setup shown in Table 25. The number of profiles generated for this setup is 135. The minimum value of Final-IRI (68.51) occurs at a tangent length of 31 feet. The minimum value of opposite Final-IRI is 68.52 and it occurs at tangent length of 30 feet. The plot of Final-IRI values is depicted in Figure 35.

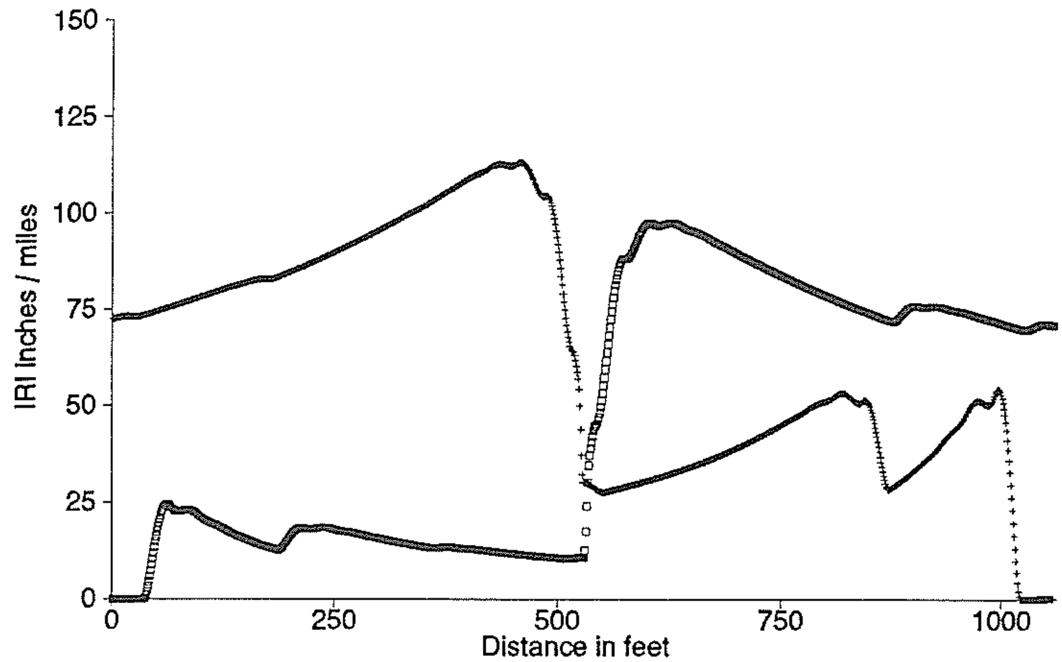

Figure 34 IRI variation along profile XUU (Δd=13.25 ft)

TABLE 25 INPUT CURVE PARAMETERS FOR PROFILE XUU (Δd=13.25 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag	-2.5%	4.92%	150
Tangent	4.92%	4.92%	170
Parabola	4.92%	0%	150

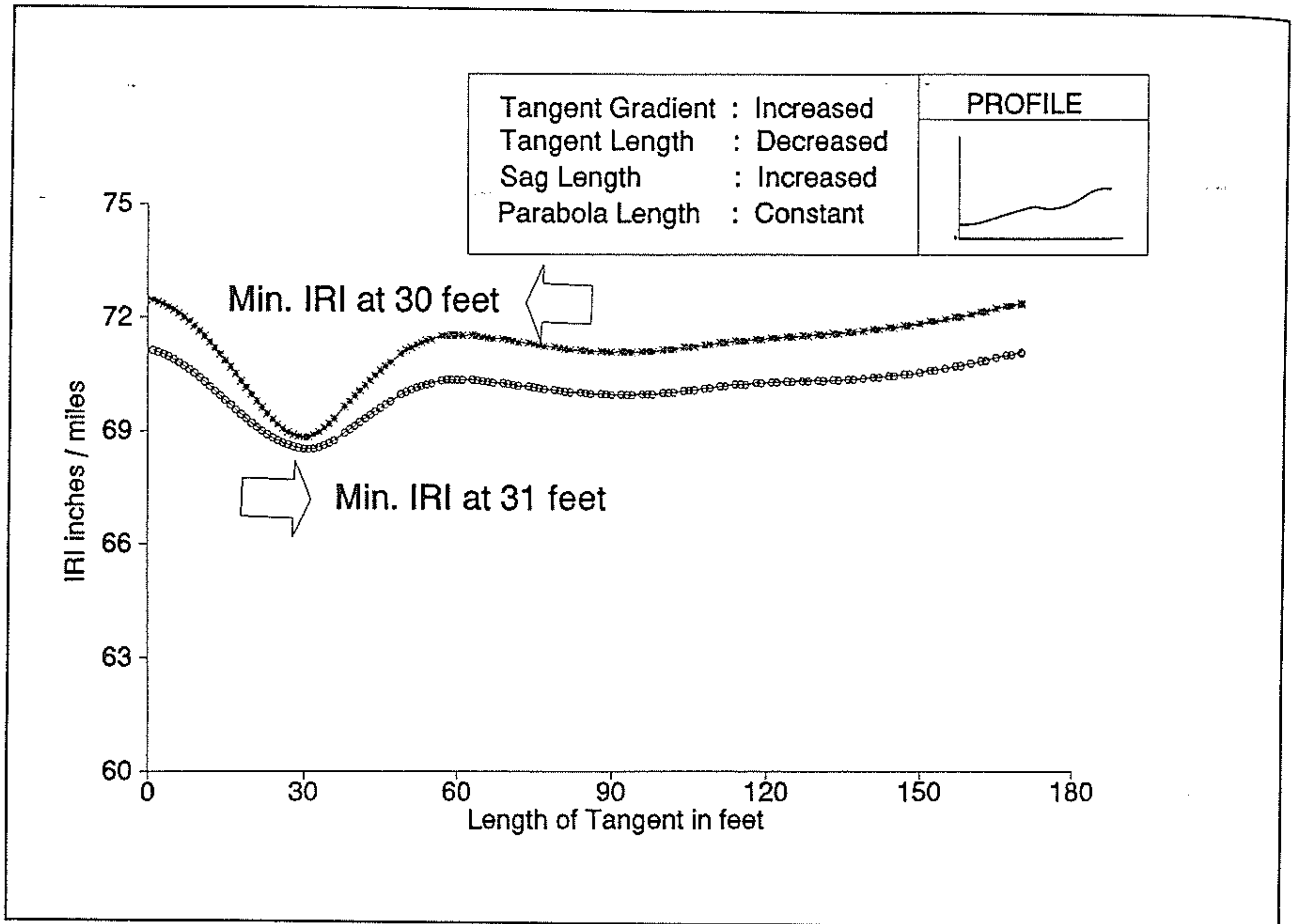

Figure 35 Final-IRI for experiment XUU.ST.03 plot (Δd=13.25 ft)

Table 26 summarizes the curve parameters for the minimum value of the Final-IRI and the opposite Final-IRI for the group XUU.ST. A review of this table reveals minimum Final-IRI and minimum opposite Final-IRI at a tangent length of approximately 30 feet. Observation of the IRI values also reveals that the Final-IRI values are not greatly affected by changes in Δd.

TABLE 26 SUMMARY OF CURVE PARAMETERS FOR GROUP XUU.ST

Δd	Tangent Gradient	Tangent Length (ft)	Sag Curve Length (ft)	Minimum Final-IRI (in/mile)	Minimum Opposite Final-IRI (in/mile)
5.3	3.84	31	289	61.95	
5.3	3.84	31	289		62.74
10.6	5.93	31	289	65.23	
10.6	5.93	31	289		66.15
13.25	7.01	31	289	68.51	
13.25	6.99	30	290		68.52

8.1.2 Experiment Group XUU.PT

The initial setup for the next group of experiments is also shown in Table 22. In this series of experiments, we increase the tangent gradient in increments of 0.02 percent. In the process, to keep Δd constant, the length of parabola is increased and the length of the tangent is decreased while the sag length is kept constant. Once a feasible design is produced, the program calculated the Final-IRI of the resulting profile in both the directions.

Experiment XUU.PT.01: The first set of experiments is performed for the initial setting of group XUU.PT.01, which resulted in 45 profiles. The minimum value of Final-IRI and the opposite Final-IRI occurs at the tangent length of 32 feet. The minimum value of the Final-IRI and the opposite Final-IRI is 61.34 and 63.82 respectively. Figure 36 depicts the plot of Final-IRI and opposite Final-IRI values of the generated profiles.

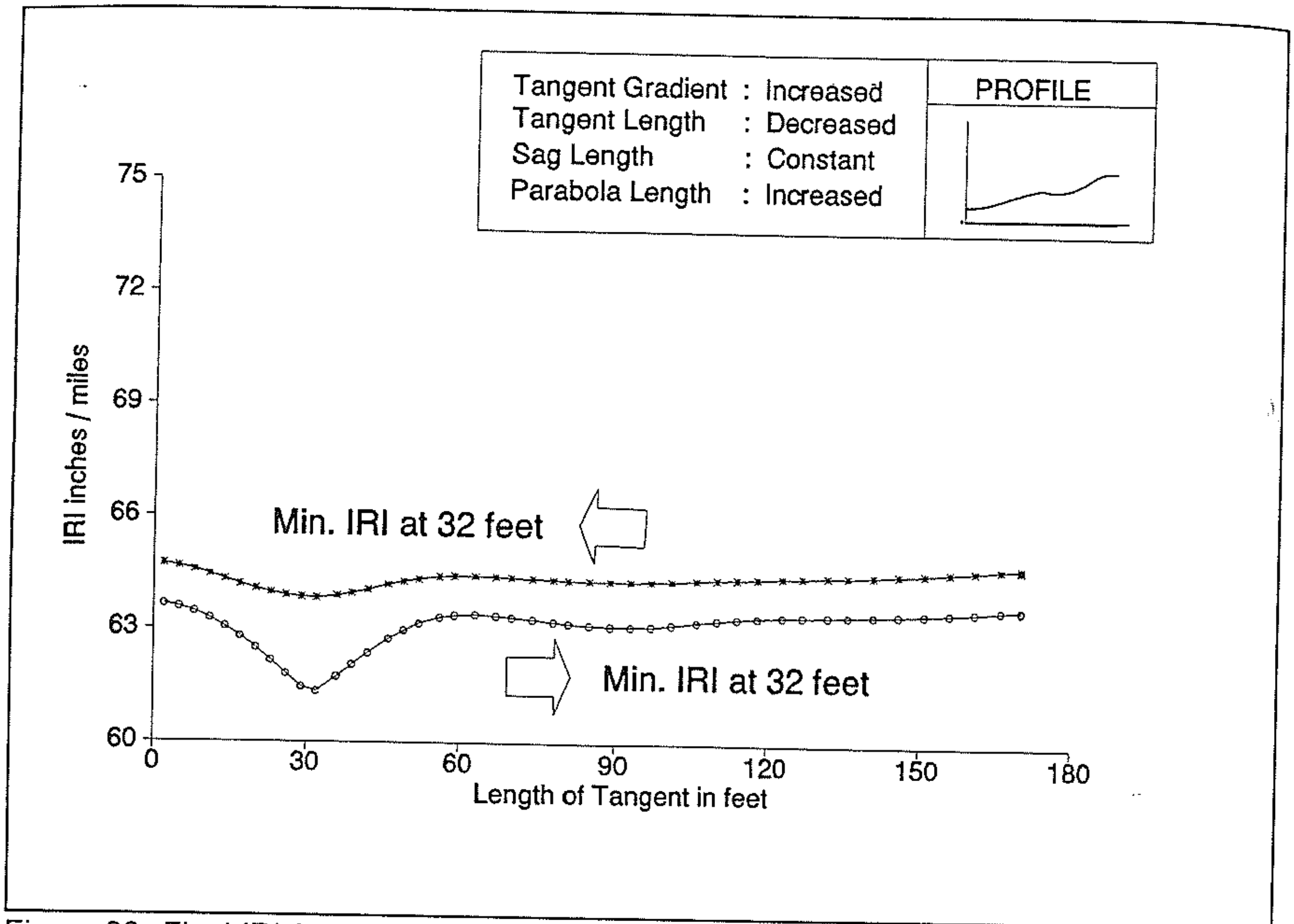

Figure 36 Final-IRI for experiment XUU.PT.01 (Δd=5.3 ft)

Experiment XUU.PT.02: The same procedure used in experiment XUU.PT.01 is repeated for the elevation difference of 10.6 feet, which generated 75 profiles. The minimum value of Final-IRI and the opposite Final-IRI occurs for the tangent length of 31 feet. The minimum value of the Final-IRI and the opposite Final-IRI is 63.82 and 67.64 respectively. Variation in the values of the Final-IRI as a function of tangent length is not significant in this case. The plot of Final-IRI and opposite Final-IRI values is depicted in Figure 37.

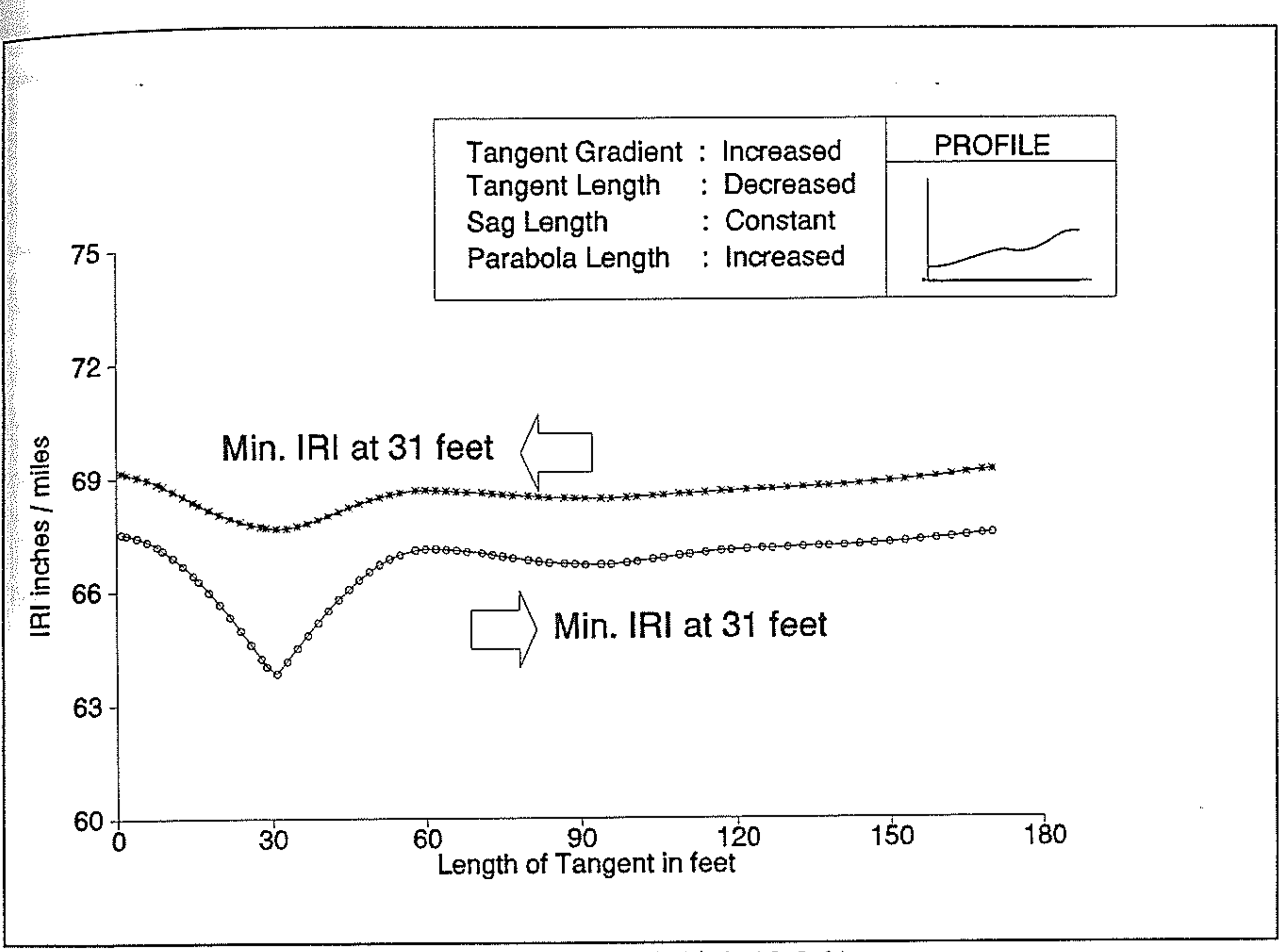

Figure 37 Final-IRI for experiment XUU.PT.02 (Δd=10.6 ft)

Experiment XUU.PT.03: The above criteria is repeated for the elevation difference of 13.25 feet which generated 90 profiles. The tangent length of 30 feet gives the lowest value of the Final-IRI and the opposite Final-IRI. Again the opposite Final-IRI value (70.54) is more than the Final-IRI value of 66.92. The plot of Final-IRI and opposite Final-IRI values is depicted in Figure 38.

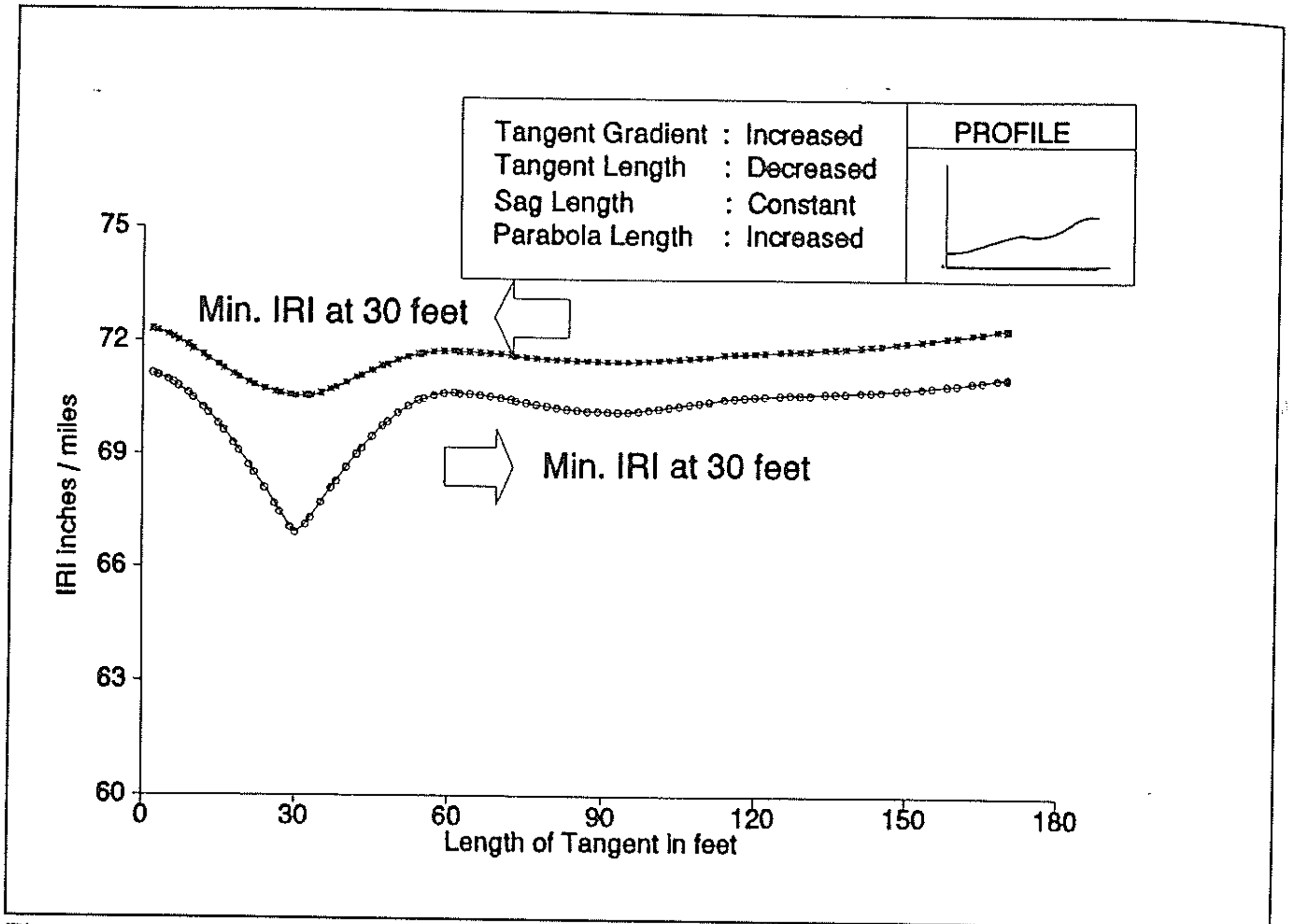

Figure 38 Final-IRI for experiment XUU.PT.03 (Δd=15.9 ft)

Table 27 summarizes the curve parameters for the minimum value of the Final-IRI and the opposite Final-IRI for the group XUU.PT. For each elevation difference(Δd) there are two sets of parameters, one for the minimum Final-IRI and the other for the minimum opposite Final-IRI. Observation of the Table reveals that variation of the Final-IRI as a function of the length of the tangent curve is not significant. A tangent of length around 31 feet gives a lower value of the Final-IRI and opposite Final-IRI for profile XUU.

TABLE 27 SUMMARY OF CURVE PARAMETERS FOR GROUP XUU.PT

Δd	Tangent Gradient	Tangent Length (ft)	Parabola Length (ft)	Minimum Final-IRI (in/mile)	Minimum Opposite Final-IRI (in/mile)
5.3	3.14	32	288	61.34	
5.3	3.14	32	288		63.82
10.6	5.23	31	289	63.82	
10.6	5.23	31	289		67.64
13.25	6.31	30	290	66.92	
13.25	6.31	30	290		70.54

8.1.3 Experiment Group XUU.SP

The next series of experiments also involves increasing the tangent gradient in increments of 0.02 percent. In this process to keep Δd constant, the length of parabola is decreased and the length of the sag is increased while the tangent length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile in both directions.

Experiment XUU.SP.01: The first experiment is performed for Δd of 5.3 feet. A total of 31 profiles is generated for this setup. The Final-IRI value remains almost constant from the parabola length of 100 to 150 feet. When the parabola length is further decreased, the IRI value increases. There is a significant increase in the Final-IRI value with a decrease in the parabola length below 50 feet. The lowest value of the Final-IRI and the opposite Final-IRI occurred at the tangent length of 130 feet. Figure 39 depicts the plot of Final-IRI and opposite Final-IRI values of the generated profiles.

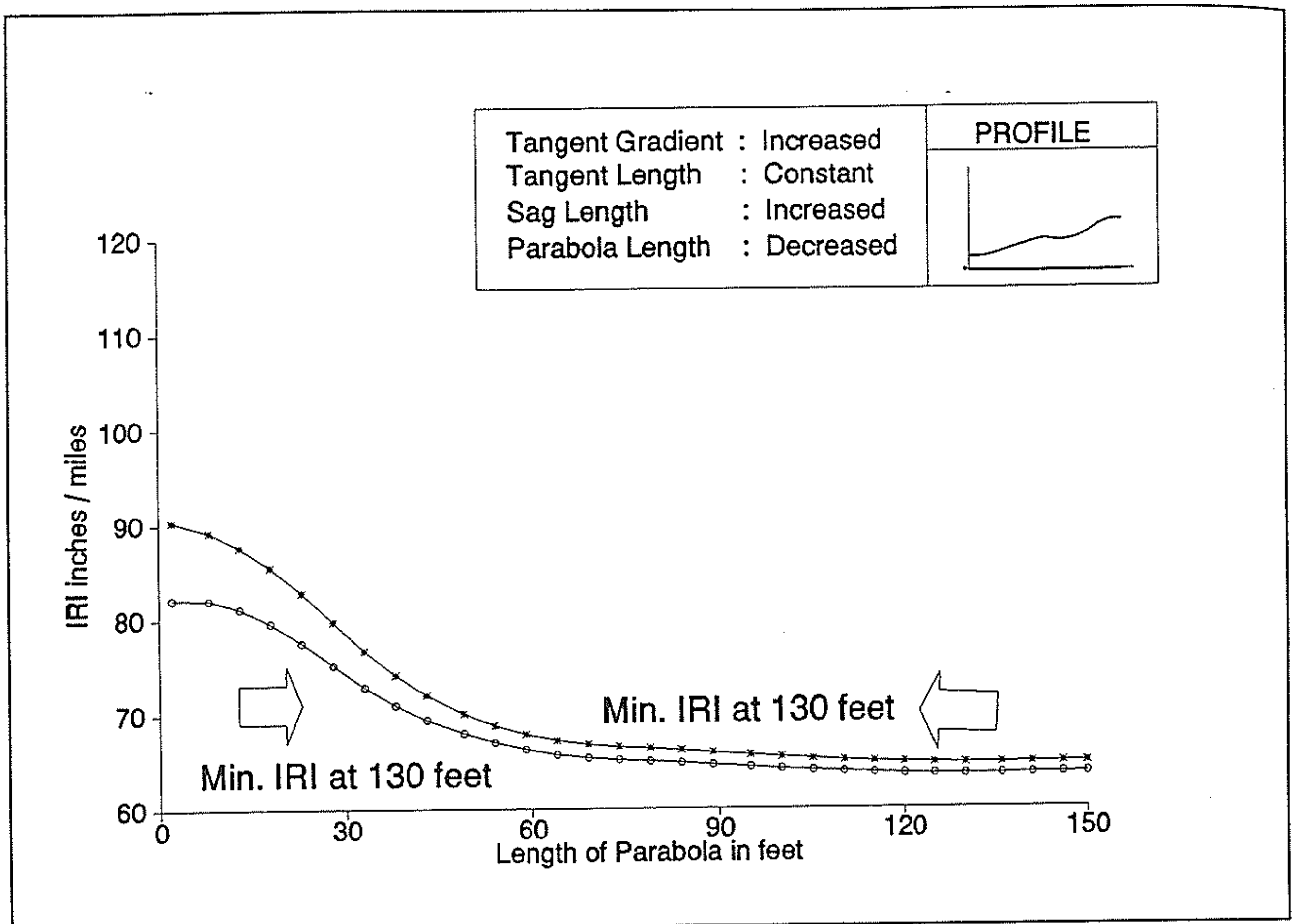

Figure 39 Final-IRI for experiment XUU.SP.01 (Δd=5.3 ft)

<u>Experiment XUU.SP.02:</u> The above profile generating criteria is repeated for Δd value of 10.6 feet which generated 30 profiles. The parabola length of 130 feet gives the lowest value of the Final-IRI and the opposite Final-IRI. The minimum value of the Final-IRI and the opposite Final-IRI is 63.52 and 64.68 respectively. Figure 40 depicts the plot of Final-IRI and opposite Final-IRI values of the generated profiles.

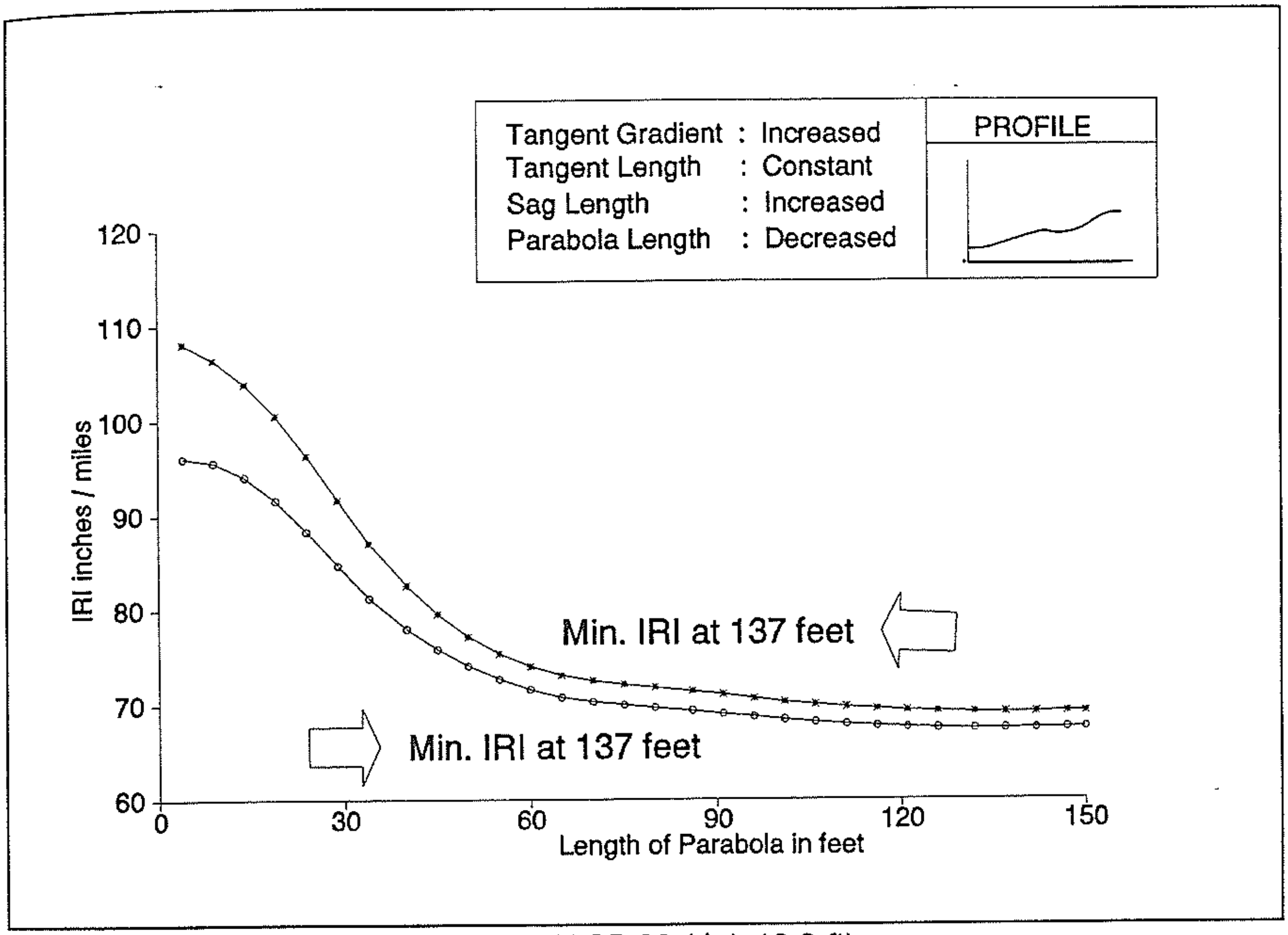

Figure 40 Final-IRI for experiment XUU.SP.02 (Δd=10.6 ft)

Experiment XUU.SP.03: The same procedure as experiment XUU.SP.02 is repeated for the Δd value of 13.25 feet. A total of 31 profiles is generated for this setup. The minimum value of the Final-IRI (71.01) occurs at the parabola length of 137 feet. The minimum value of the opposite Final-IRI is 72.34 and occurs at the parabola length of 136 feet. Figure 41 shows the plot of Final-IRI and opposite Final-IRI values .

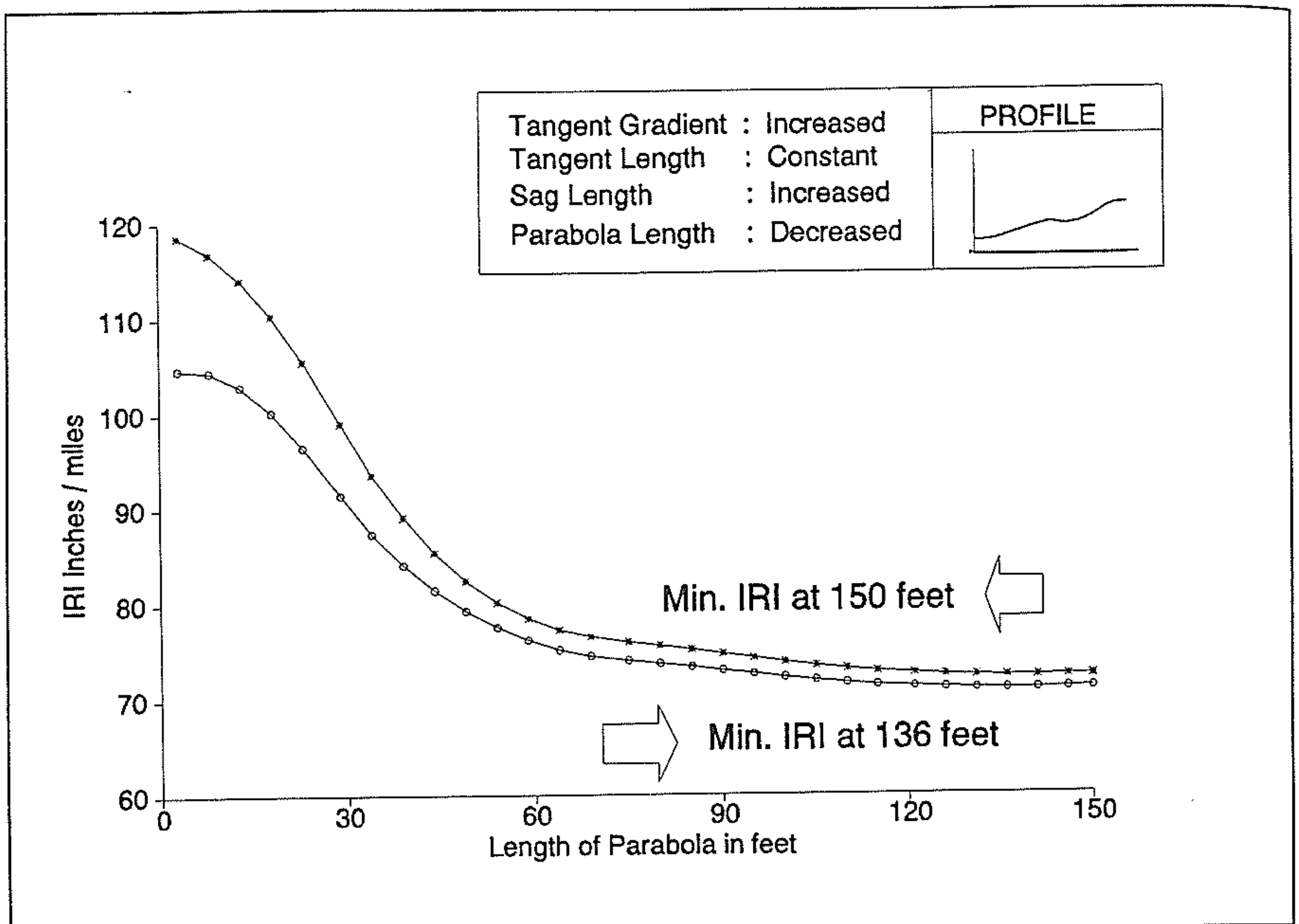

Figure 41 Final-IRI for experiment XUU.SP.03 (Δd=13.25 ft)

Table 28 summarizes the curve parameters for the minimum value of the Final-IRI and the opposite Final-IRI for the group XUU.SP. For each elevation difference (Δd) there are two sets of parameters, one for the minimum Final-IRI and the other for the minimum opposite Final-IRI. The variation in minimum IRI values is not significant in the parabola length.

TABLE 28 CURVE PARAMETERS FOR LOWEST Final-IRI AND OPPOSITE Final-IRI FOR THE GROUP XUU.SP

Δd	Tangent Gradient	Parabola Length (ft)	Sag Curve Length (ft)	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
5.3	2.53	130	174	63.52	
5.3	2.53	130	174		69.14
10.6	4.15	137	163	67.42	
10.6	4.15	137	163		69.14
13.25	5	136	164	71.01	
13.25	4.92	150	150		72.34

8.1.4 Summary Results for Profile No. XUU

For profile XUU, a tangent length of 30 feet and parabola length of about 130 feet result in lower values of the Final-IRI. The Final-IRI and the opposite Final-IRI values are directly proportional to the elevation difference (Δd). The Final-IRI and the opposite Final-IRI values are more sensitive to variation in parabola length than to variation in tangent length.

8.2 PROFILE XDD

The preliminary studies of profiles joining a secondary roadway to the main highway that is at a lower elevation, revealed that the combination of a parabola, tangent, and a sag results in the smoothest profile. While going downgrade from the main highway to the secondary roadway, the same combination of a parabola, tangent, and a sag also results in the smoothest profile. This observation leads to the conclusion of similarity between profiles XUU and XDD. The results of profile XUU also holds true for profile XDD except that the Final-IRI of XUU becomes opposite Final-IRI of XDD and the opposite Final-IRI XUU is the Final-IRI for XDD.

9 ANALYSIS OF COMPOUND X INTERSECTIONS

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

We have performed experiments on two symmetrical compound profiles SVV and SCC. Profile SVV shown in Figure 42 consists of convex curves on both sides of the main highway. Profile SCC shown in Figure 52 consists of concave curves on both sides of the main highway. Six group of experiments are performed for each profile by varying the parameters of two of the five curves. Each set of experiments is performed for three elevation differences. This section describes the profile generating procedure for all the experiments and the results obtained for both the profiles.

9.1 PROFILE SVV

A set of simulation experiments is performed on a symmetric profile as depicted in Figure 42. The design of the transition on the right side of the centerline of the main highway is a mirror image of the profile on the left side. This symmetrical property is not altered as various design parameters are considered.

A combination of parabola, tangent, sag, tangent, and parabola will produce the smoothest transition going downgrade and upgrade. The secondary roadway always starts with a tangent of length 36 feet and 0 percent gradient. The tangent is joined to a parabola with a length of 90 feet, which is joined to another tangent with a length of 100 feet. A sag of 90 feet in length joins this tangent to another tangent of 100 feet. A parabola of 90 feet joins the tangent and the cross slope of the main highway. The main highway is 48 feet wide and has a gradient of 2.5 percent on either side of the centerline. Width and cross slope of the main highway are kept constant for all experiments.

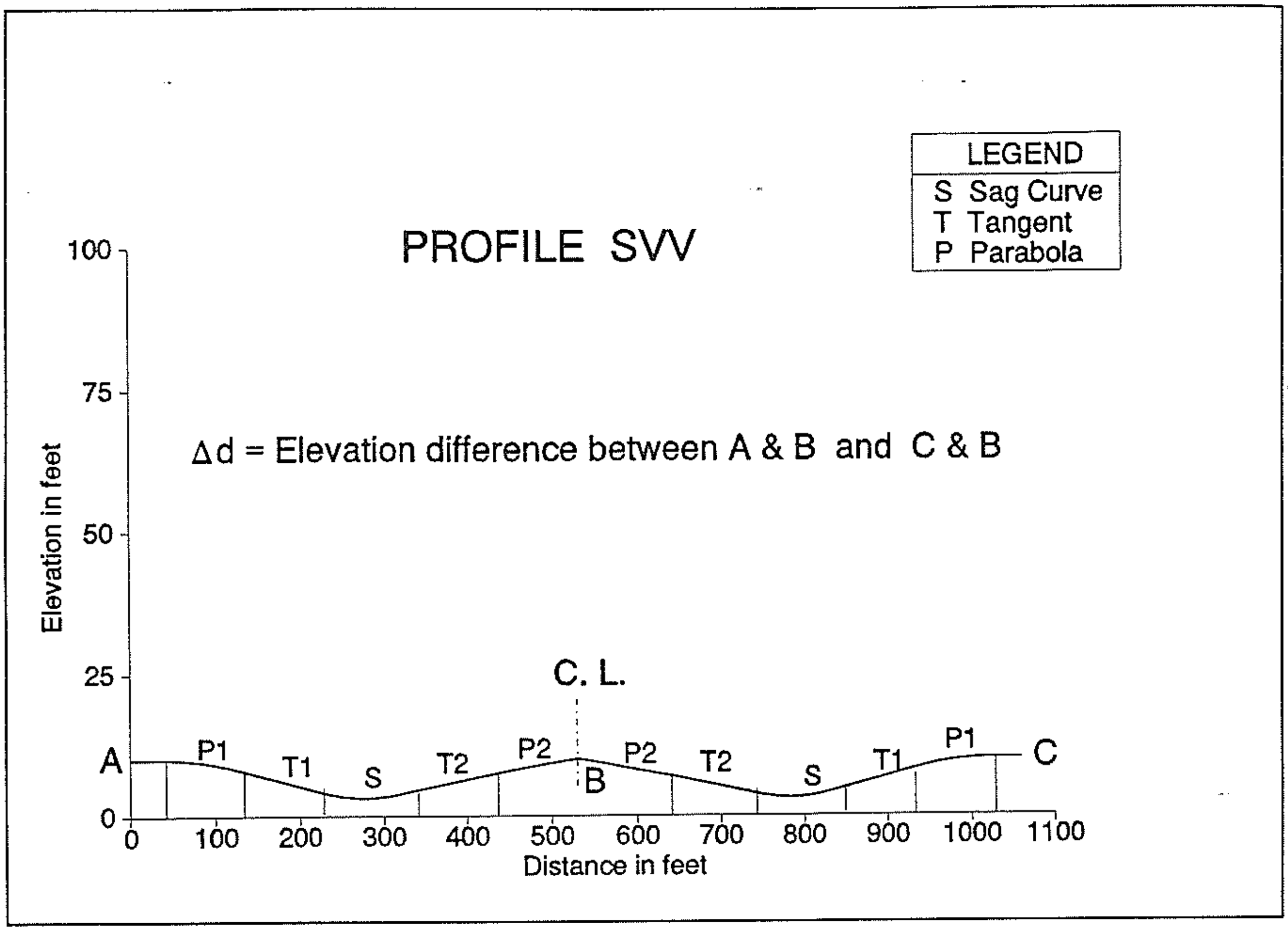

Figure 42 Profile No. SVV

A number of experiments is performed on profile SVV by systematically varying two factors: (1) the length of two of the five curves (P1,T1,S,T2,P2), and (2) the elevation difference between the main highway and the secondary roadway. Six curve combinations are possible: S-T1, P1-T1, S-P1, S-T2, P2-T2, S-P2, and three elevation differences -1, 0, and 1 feet are considered for all the combinations. Eighteen sets of experiments are required to consider all possible combinations of the two factors at three different levels. For each set, experiments are performed by changing the gradient of either tangent: it is increased in increments of 0.02 percent, after a feasible profile is generated. To accommodate for this change, the lengths of two of the five curves are then adjusted to maintain a constant elevation difference (Δd). The simulation is stopped when an additional feasible profile can not be obtained by changing the length of the two curves.

Table 29 shows the curve parameter setup by group. For example, Group SVV.SP1 is performed by reducing the parabola length and increasing the sag length to meet the 0.02 percent change in the gradient of the first tangent. In each group, experiments are repeated using the same procedure for three different elevation differences (i.e., -1, 0, and 1 feet). The following sections present the descriptions and the results obtained from these experiments.

TABLE 29 SVV EXPERIMENT SETUP BY GROUP

Experiment Group	Tangent Gradient	Tangent Length	Sag Length	Parabola Length
SVV.ST1	Increase	Decrease	Increase	Constant
SVV.P1T1	Increase	Decrease	Constant	Increase
SVV.SP1	Increase	Constant	Increase	Decrease
SVV.ST2	Increase	Decrease	Increase	Constant
SVV.P2T2	Increase	Decrease	Constant	Increase
SVV.SP2	Increase	Constant	Increase	Decrease

9.1.1 Experiment Group SVV.ST1

Experiments in this group are performed to study the effect of variation in sag and tangent-1 length on IRI. The tangent-1 gradient is increased by 0.2 percent after each feasible profile is generated. To keep Δd constant, the length of the sag curve is increased and the length of the tangent-1 is decreased, while the parabola length is kept constant. Once a feasible design is produced, the program calculates the IRI of the resulting profile. The program is terminated when the tangent-1 length is exhausted. Three sets of experiments are performed corresponding to various elevation differences.

Experiment SVV.ST1.01: For this set of experiments, the elevation difference Δd, is set at

-1 feet. The input profile starts with a tangent of 36 feet in length and 0 percent gradient on the secondary roadway. A parabola of 90 feet in length with a start and end tangent of 0 percent and -4 percent respectively is joined to the two tangents. A tangent-1 of 100 feet in length and a gradient of -4 percent joins the parabola to a sag curve of 90 feet in length with a start and end gradient of -4 percent and 2.57 percent respectively. The sag curve is joined to another tangent of 100 feet in length and 2.57 percent gradient. Then a parabola of 90 feet in length and start and end tangents of 2.57 percent and 2.5 percent respectively joins the tangent-2 to the cross slope of the main highway. Curve parameters for the input profile are summarized in Table 30.

TABLE 30 INPUT CURVE PARAMETERS FOR PROFILE SVV (Δd=-1 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Parabola-1	0%	-4%	90
Tangent-1	-4%	-4%	100
Sag	-4%	2.57%	90
Tangent-2	2.57%	2.57%	100
Parabola-2	2.57%	2.5%	90

Figure 43 shows the calculated IRI of the profile SVV for the parameters shown in Table 30. There is a little increase in IRI value at every curve junction, but there is a sudden rise in the IRI value at the intersection. This rise in IRI value at the center line of the main highway is due to the cross slope of the main highway.

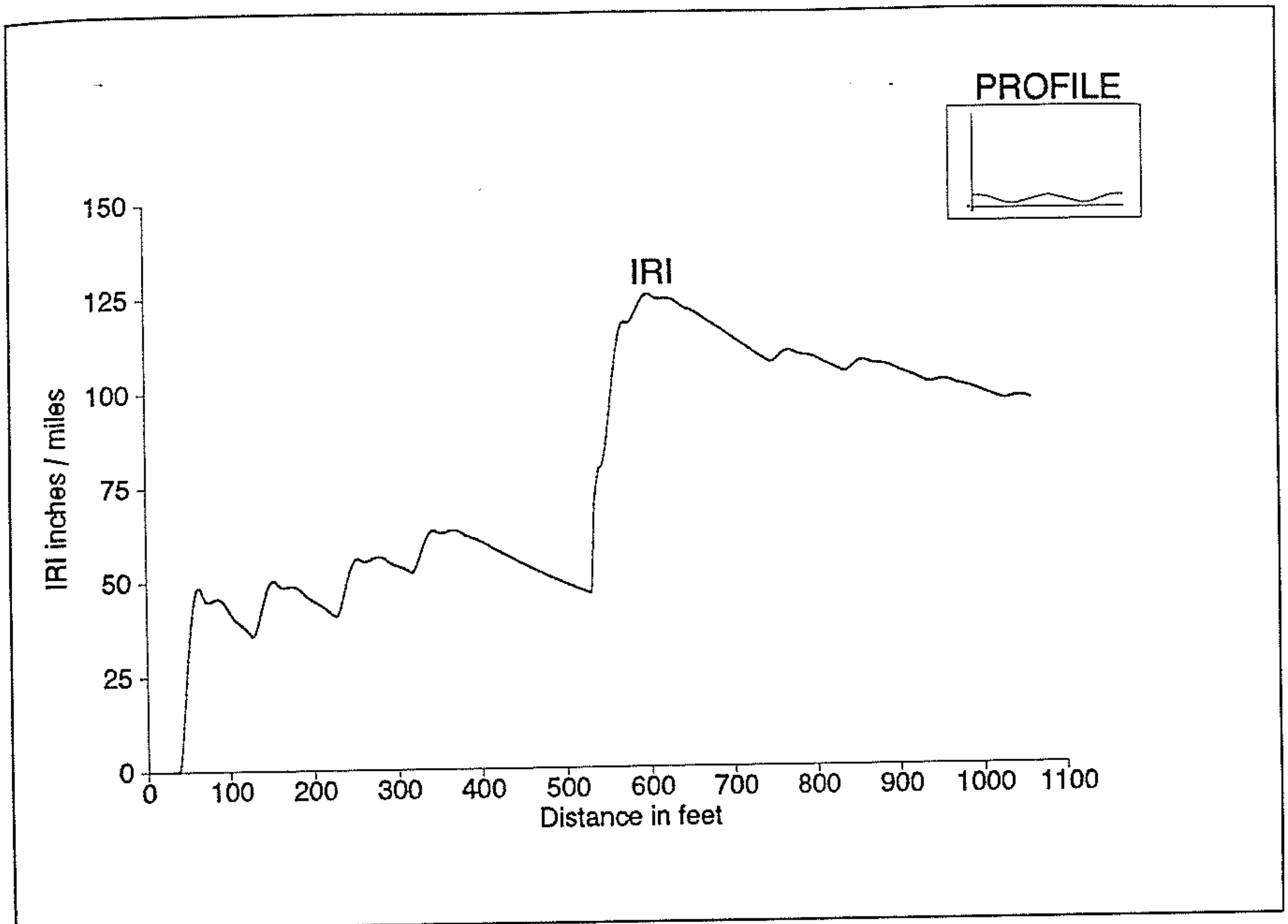

Figure 43 IRI variation along profile SVV (Δd=-1 ft)

Final-IRI is calculated for a total length of 1060 feet, 530 feet each side of the centerline of the main highway. This procedure of generating the profiles is continued until tangent-1 length is exhausted, which resulted in 116 profiles. The minimum value of Final-IRI is 87.16 and is obtained for a tangent-1 length of 31 feet. Plot of the Final-IRI values of the generated profiles is shown in Figure 46.

Experiment SVV.ST1.02: The criteria of generating profiles for experiment SVV.ST1.01 is repeated for an elevation difference of 0 feet. The gradient of tangent-2 is increased to 3.1 percent to make the elevation difference of 0 feet, and all other parameters are kept the same. Table 31 shows the initial setup for this experiment and Figure 44 shows the calculated IRI along the profile for the parameters of initial setup. A total of 126 profiles is generated for this experiment. The minimum value of the Final-IRI is 91.13 and is again obtained for the tangent-1 length of 31 feet. The plot of the Final-IRI values of the generated profiles is also depicted in Figure 46.

TABLE 31 INPUT CURVE PARAMETERS FOR PROFILE SVV (Δd=0 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Parabola-1	0%	-4%	90
Tangent-1	-4%	-4%	100
Sag	-4%	3.1%	90
Tangent-2	3.1%	3.1%	100
Parabola-2	3.1%	2.5%	90

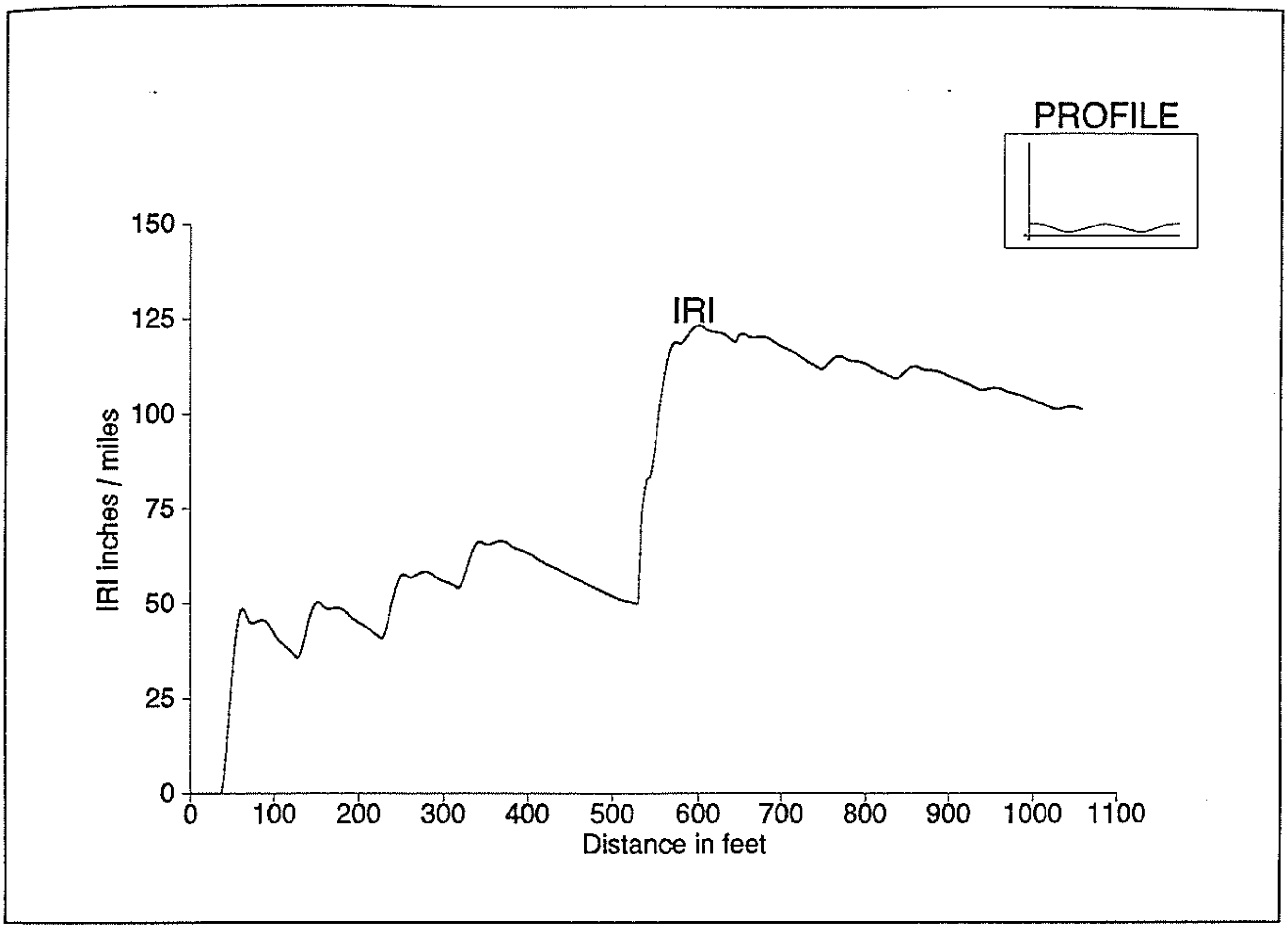

Figure 44 IRI variation along profile SVV (Δd=0 ft)

<u>Experiment SVV.ST1.03:</u> The same criterion as above is repeated for Δd of 1 foot, which results in 135 profiles. The gradient of tangent-2 is increased to 3.62 percent, keeping all other parameters unchanged. The parameters of initial setup are shown in Table 32 and Figure 45 shows the calculated IRI along the profile. The minimum value of Final-IRI is 96.40 and it is obtained for a tangent-1 length of 32 feet. Figure 46 depicts the plot of Final-IRI values of the generated profiles.

TABLE 32 INPUT CURVE PARAMETERS FOR PROFILE SVV (Δd=1 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Parabola-1	0%	-4%	90
Tangent-1	-4%	-4%	100
Sag	-4%	3.62%	90
Tangent-2	3.62%	3.62%	100
Parabola-2	3.62%	2.5%	90

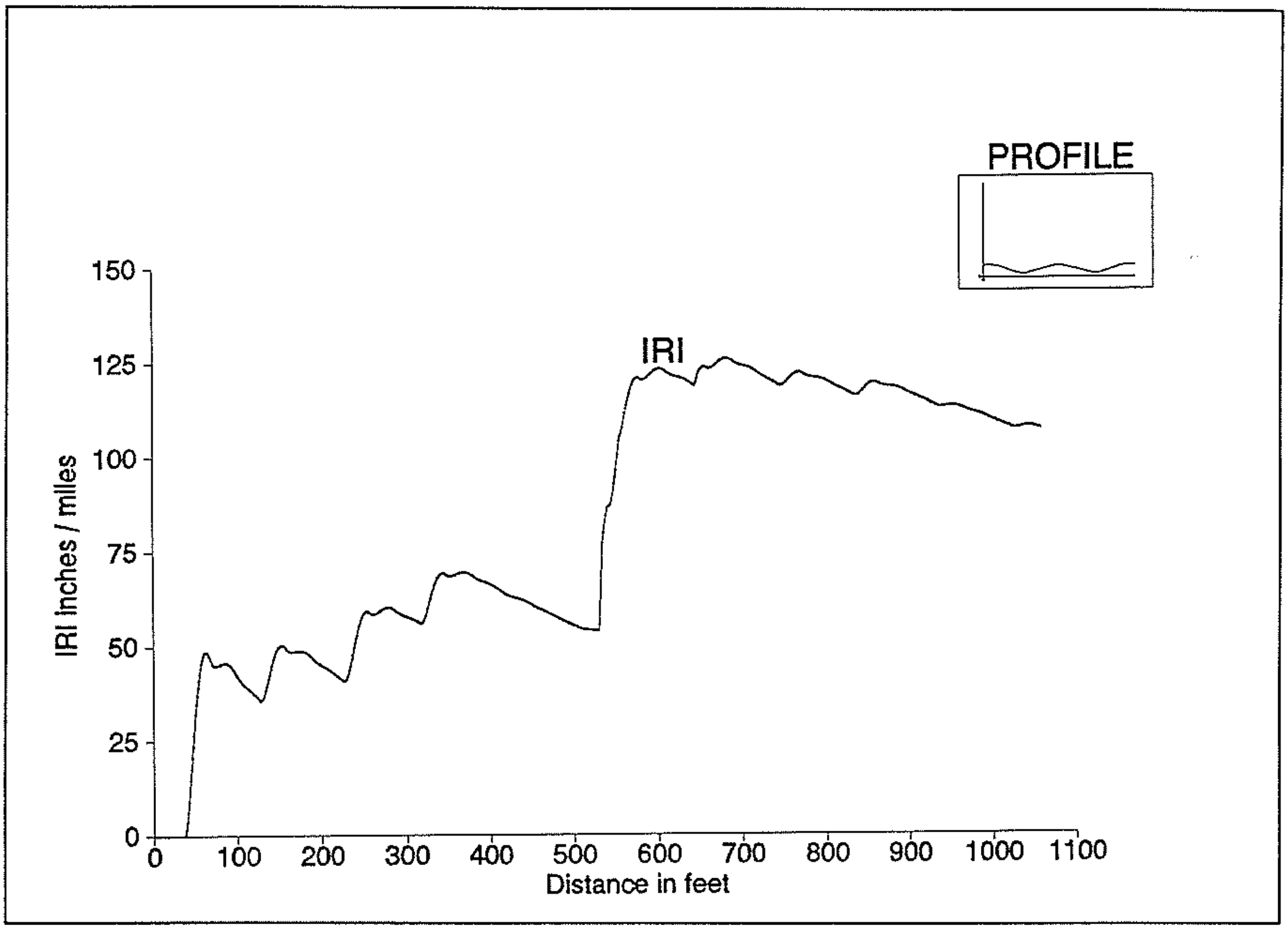

Figure 45 IRI variation along profile SVV (Δd=1 ft)

Table 33 summarizes the curve parameters for the minimum value of Final-IRI for all three elevation differences. Figure 46 reveals that the shape of the Final-IRI curve is similar for all three elevation differences, and Final-IRI is directly proportional to Δd. The tangent-1 length of around 30 feet produces lower Final-IRI values.

TABLE 33 CURVE PARAMETERS FOR SVV.ST1 PROFILES

Δd	Tangent-1 Gradient	Tangent-1 Length (ft)	Sag Curve Length (ft)	Minimum Final-IRI (in/mile)
-1	-5.43	31	159	87.16
0	-5.55	31	159	91.13
1	-5.63	32	158	96.40

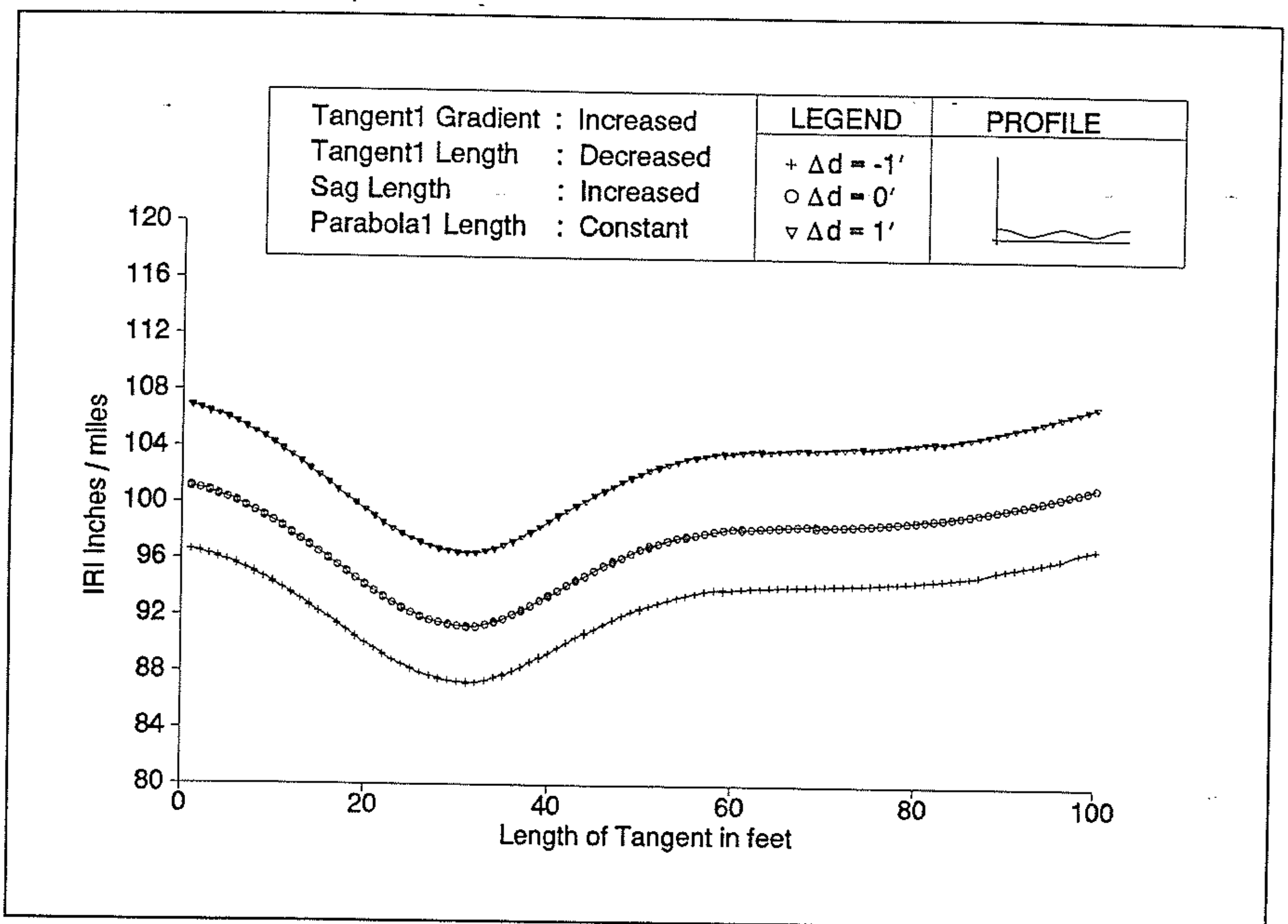

Figure 46 Final-IRI for experiment SVV.ST1

9.1.2 Experiment Group SVV.P1T1

Initial setup for the next group of experiments is also shown in Table 29. For this series of experiments, the tangent-1 gradient is increased in an increment of 0.2 percent. In the process, to keep Δd constant, the length of parabola-1 is increased and the length of the tangent-1 is decreased while the sag length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program terminates when no more feasible profiles could be generated by varying the length of parabola-1 and tangent-1.

Experiment SVV.P1T1.01: The first set of experiments was performed for the initial setting shown in Table 30, which resulted in 71 profiles. The minimum value of Final-IRI is 88.90 and is obtained for the tangent-1 length of 31 feet. Figure 47 depicts the plot of Final-IRI values of the generated profiles.

Experiment SVV.P1T1.02: The same profile generating procedure used in experiment SVV.P1T1.01 is repeated for the elevation difference of 0 feet. The curve parameters shown in Table 32 are used as the input profile, which also resulted in 71 profiles. The minimum value of the Final-IRI is 93.25 and occurs for the tangent-1 length of 32 feet. Variation in the values of the Final-IRI as a function of tangent-1 length is not significant in this case. Figure 47 depicts the plot of Final-IRI values of the generated profiles.

Experiment SVV.P1T1.03: The above criterion of generating profiles is repeated for the elevation difference of 1 feet. Input parameters for this experiment are shown in Table 33, the experiment resulted in 71 profiles. Again the minimum Final-IRI value occurs for the tangent length of 32 feet. The plot of Final-IRI values of the generated profiles is depicted in Figure 47.

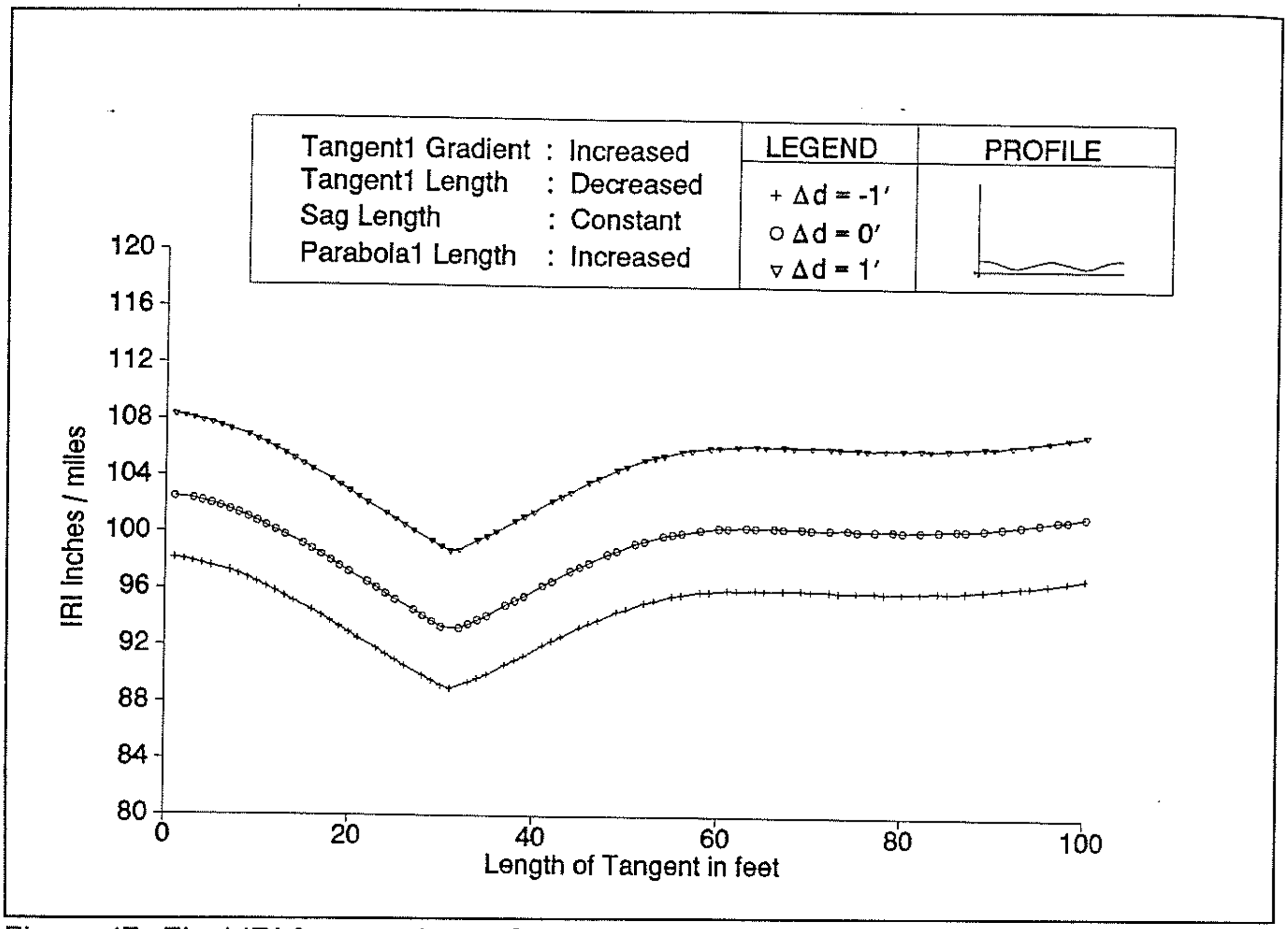

Figure 47 Final-IRI for experiment SVV.P1T1

Table 34 summarizes the curve parameters for the minimum value of Final-IRI for all three elevation differences. Figure 47 reveals that the shape of the Final-IRI curve is similar for all three elevation differences. In this group also the tangent-1 length around 31 feet gives a lower value of the Final-IRI. It is also evident from Figure 47 that the Final-IRI is directly proportional to Δd.

TABLE 34 CURVE PARAMETERS FOR SVV.P1T1 PROFILES

Δd	Tangent-1 Gradient	Tangent-1 Length (ft)	Parabola-1 Length (ft)	Minimum Final-IRI (in/mile)
-1	-4.87	31	159	88.90
0	-4.87	32	158	93.25
1	-4.87	32	158	98.71

9.1.3 Experiment Group SVV.SP1

This series of experiments also involves increasing the tangent-1 gradient in increments of 0.2 percent. In this process to keep Δd constant, the length of parabola-1 is decreased and the length of the sag curve is increased while keeping the tangent-1 length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program stops when the parabola-1 length is exhausted.

Experiment SVV.SP1.01: The first experiment is performed for Δd of -1 feet, which resulted in 31 profiles. Initial setup is shown in Table 30. There is very little variation in the Final-IRI value for the length of parabola-1 from 90 to 60 feet. When the parabola-1 length is further decreased, the Final-IRI value increases considerably. The minimum value of Final-IRI is 95.74 and it occurs for the parabola-1 length of 70 feet. Figure 48 shows the plot of Final-IRI values.

Experiment SVV.SP1.02: The same profile generation procedure used in experiment SVV.SP1.01 results in 37 profiles for Δd of 0 feet. Initial setup shown in Table 31 is used as the input profile for this experiment. The minimum value of Final-IRI is 100.02 and occurs for the parabola-1 length of 71 feet. Figure 48 shows the plot of Final-IRI values of the generated profiles.

Experiment SVV.SP1.03: The third setup of groups considers the Δd value of 1 foot. The initial setup shown in Table 32 was used as the input profile for this experiment and it resulted in generation of 43 profiles. The parabola-1 length of 69 feet gives the minimum value of Final-IRI i.e., 105.60. Figure 48 shows the plot of Final-IRI values of the generated profiles.

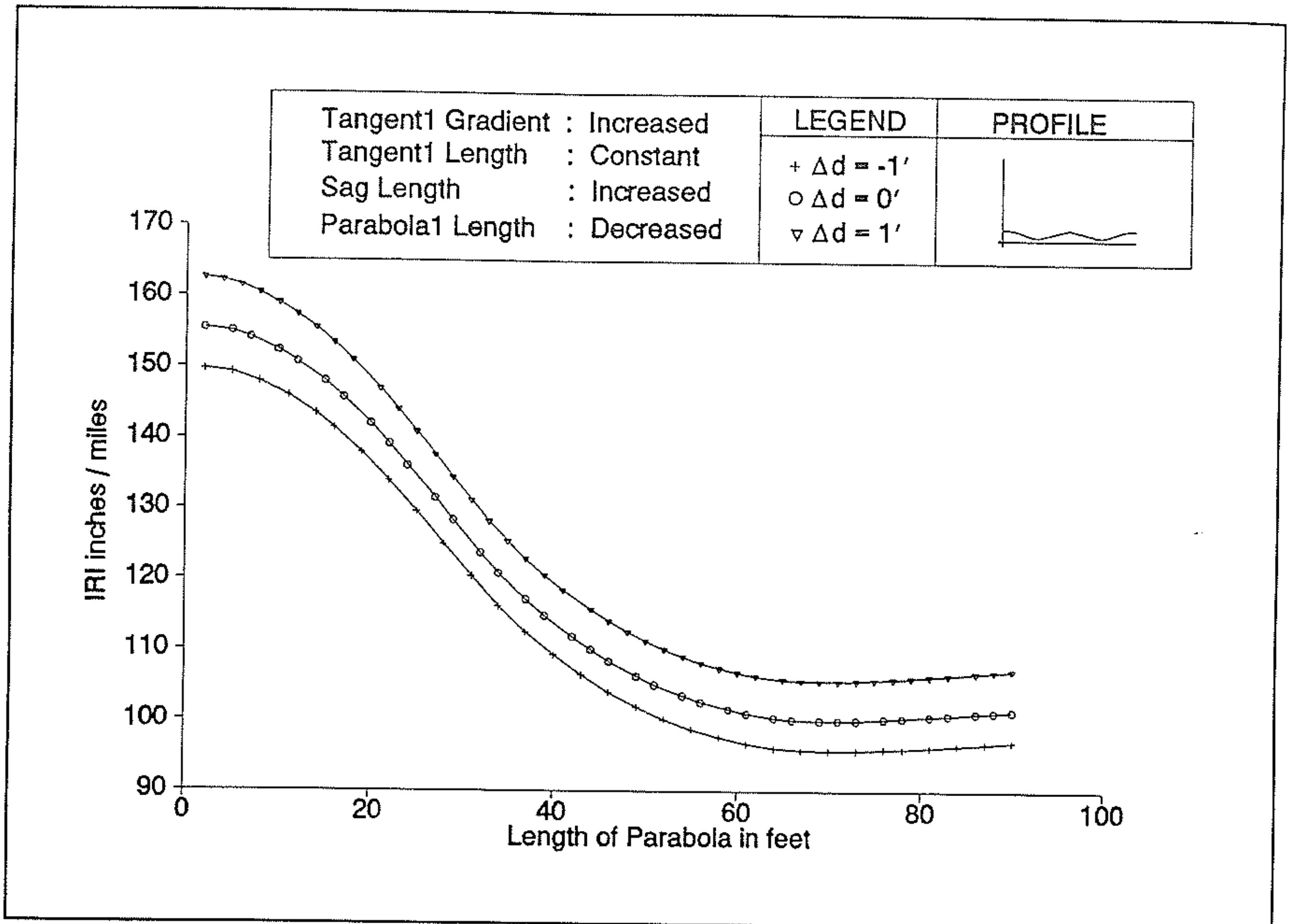

Figure 48 Final-IRI for experiment SVV.SP1

Table 35 summarizes the curve parameters for the minimum value of Final-IRI for all three elevation differences. Figure 48 reveals that the shape of the Final-IRI curve is similar for all three elevation differences. It is also evident that Final-IRI value is directly proportional to Δd. The parabola-1 length of around 70 feet produces lower Final-IRI values.

TABLE 35 CURVE PARAMETERS FOR SVV.SP1 PROFILES

Δd	Tangent-1 Gradient	Sag Curve Length (ft)	Parabola-1 Length (ft)	Minimum Final-IRI (in/mile)
-1	-4.14	70	110	95.74
0	-4.15	71	109	100.02
1	-4.12	69	111	105.60

9.1.4 Experiment Group SVV.ST2

Experiments in this group are performed to study the effect of variation in sag and tangent-2 length on IRI. The tangent-2 gradient is increased by 0.2 percent after each feasible profile is generated. To keep Δd constant, the length of the sag curve is increased and the length of the tangent-2 is decreased, while keeping the parabola-2 length constant. Once a feasible design is produced, the program calculated the IRI of the resulting profile. This procedure is continued till the tangent-2 length is exhausted. Three sets of experiments are performed corresponding to Δd value of -1, 0 and 1 feet.

Experiment SVV.ST2.01: For this set of experiments, the elevation difference Δd, is set at -1 feet. Initial setup is shown in Table 30. The gradient of tangent-2 is increased in increments of .02 percent after a feasible profile is produced. Then to meet Δd the length of tangent-2 is decreased and the length of sag curve is increased. This procedure of generating the profiles is continued until tangent-2 length is exhausted. A total of 119 profiles is generated for this setup. The minimum value of Final-IRI (90.39) occurs for a tangent-2 length of 42 feet. A plot of the Final-IRI values of the generated profiles is shown in Figure 49.

Experiment SVV.ST2.02: The criteria of generating profiles for experiment SVV.ST2.01 is repeated for Δd value of 0 feet, which resulted in 128 profiles. Initial setup shown in Table 31 is used. The minimum value of the Final-IRI is 95.93 and is obtained for a tangent-2 length of 44 feet. The plot of the Final-IRI values of the generated profiles is also depicted in Figure 49.

Experiment SVV.ST2.03: The same procedure of generating profiles used in experiment SVV.ST2.02 is repeated for Δd value of 1 feet, which results in 138 profiles. Initial setup for this experiment is shown in Table 32. The minimum value of Final-IRI is 96.40 and is again obtained for a tangent-2 length of 44 feet. Figure 49 depicts the plot of the Final-IRI values of the generated profiles.

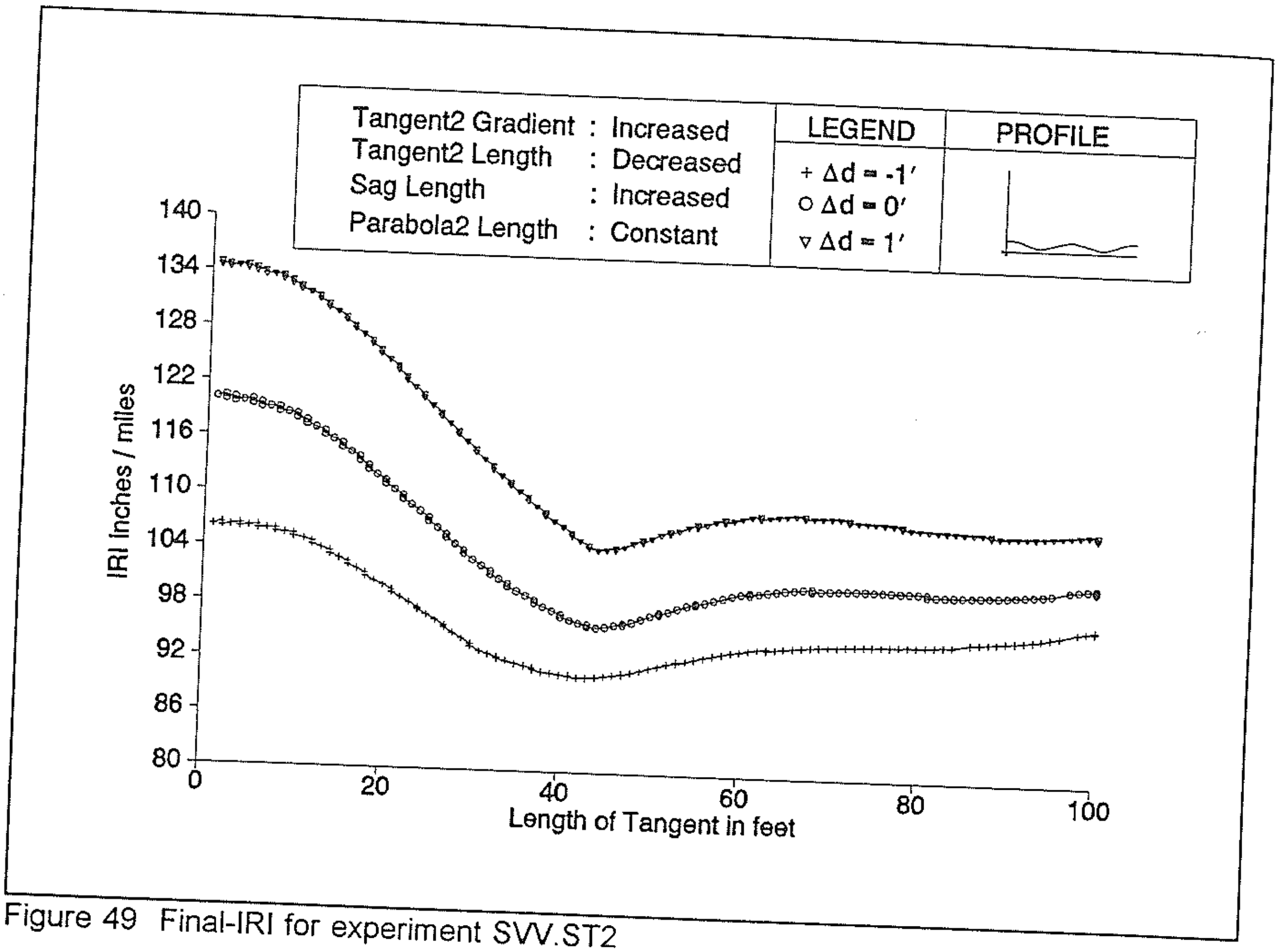

Figure 49 Final-IRI for experiment SVV.ST2

Table 36 summarizes the curve parameters for minimum values of Final-IRI for three elevation differences. Figure 49 reveals that the shape of the Final-IRI curve is similar for all three elevation differences, and the Final-IRI value is directly proportional to Δd. The tangent-2 length of around 44 feet produces lower Final-IRI values. There is a considerable increase in Final-IRI value when the tangent-2 length is reduced below 40 feet.

TABLE 36 CURVE PARAMETERS FOR SVV.ST2 PROFILES

Δd	Tangent-2 Gradient	Tangent-2 Length (ft)	Sag Curve Length (ft)	Minimum Final-IRI (in/mile)
-1	3.78	42	148	90.39
0	4.35	44	146	95.93
1	4.97	44	146	96.40

9.1.5 Experiment Group SVV.P2T2

This set of experiments is performed to study the effect of variation in parabola-2 and tangent-2 length on IRI. The experiments involves increasing the tangent-2 gradient in an increment of 0.2 percent. In the process, to keep Δd constant, the length of parabola-2 is increased and the length of the tangent-2 is decreased while the sag length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program is terminated when no more feasible profiles can be generated by varying the length of parabola-2 and tangent-2.

Experiment SVV.P2T2.01: The first set of experiments was performed for the initial setting shown in the Table 30, which resulted in 5 profiles. The minimum value of Final-IRI was 96.98 and was obtained for the tangent-2 length of 100 feet. Figure 50 depicts the plot of the Final-IRI values of the generated profiles.

Experiment SVV.P2T2.02: The same profile generating procedure was repeated for Δd of 0 feet, which resulted in 14 profiles. The minimum value of the Final-IRI was 99.55 and it occured for the tangent-2 length of 41 feet. Variation in the values of the Final-IRI as a function of tangent-2 length is not significant in this case. The plot of Final-IRI values of the generated profiles is depicted in Figure 50.

Experiment SVV.P2T2.03: The above criterion of generating profiles was repeated for Δd of 1 feet, which generated 24 profiles. The tangent-2 of 42 feet in length provides the minimum value of Final-IRI. Figuree 50 shows the plot of Final-IRI values of the generated profiles.

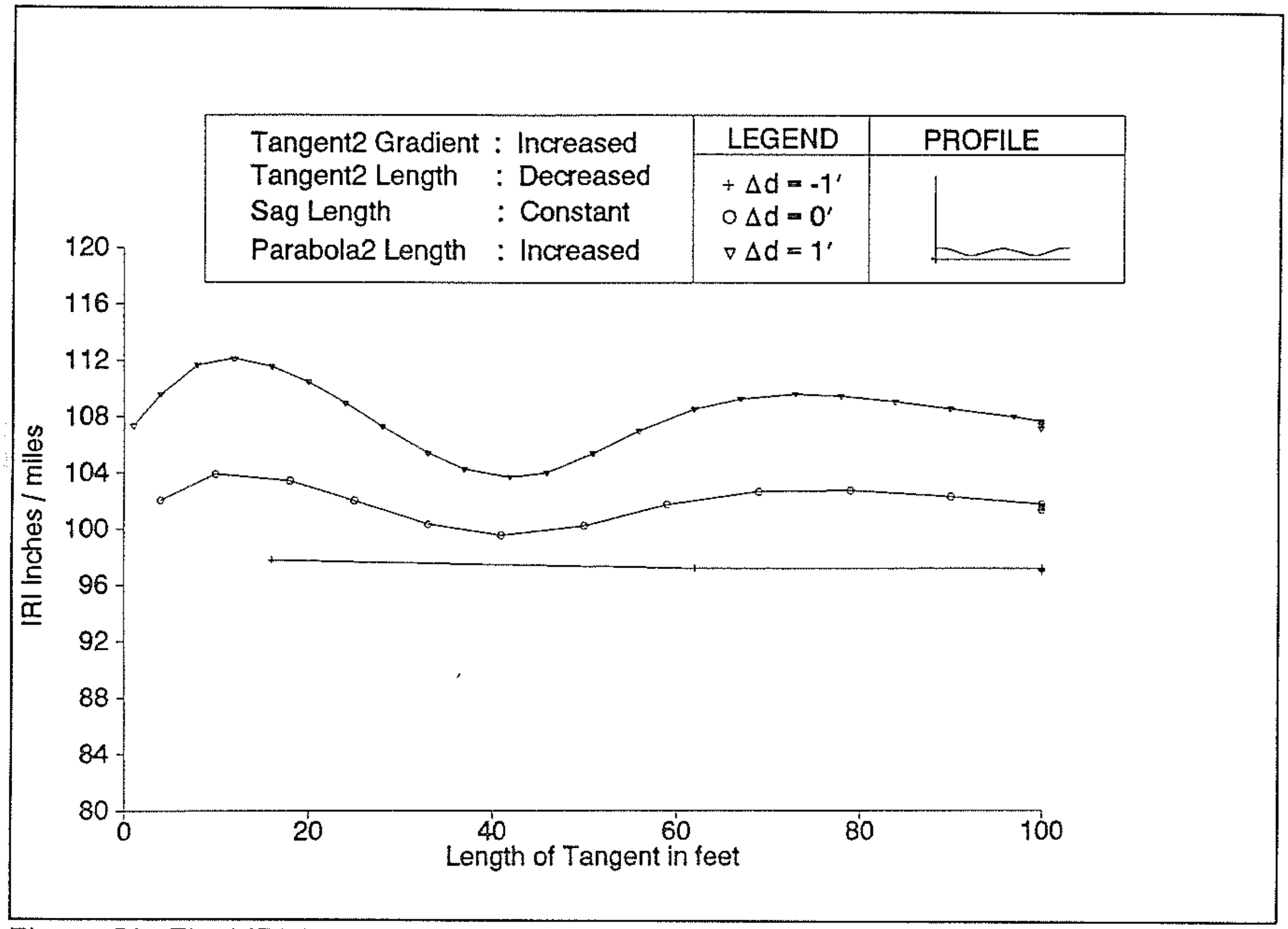

Figure 50 Final-IRI for experiment SVV.P2T2

Table 37 summarizes the curve parameters for the minimum value of Final-IRI for the three elevation differences. In this group, a tangent-2 length of around 42 feet produces lower values of Final-IRI. It is also evident that the Final-IRI is directly proportional to the elevation difference.

TABLE 37 CURVE PARAMETERS FOR SVV.P2T2 PROFILES

Δd	Tangent-2 Gradient	Tangent-2 Length (ft)	Parabola-2 Length (ft)	Minimum Final-IRI (in/mile)
-1	2.57	100	90	96.98
0	3.25	41	149	99.95
1	3.87	42	148	103.72

9.1.6 Experiment Group SVV.SP2

The next series of experiments also involves increasing the tangent-2 gradient in increments of 0.2 percent. In this process to keep Δd constant, the length of parabola-2 is decreased and the length of the sag curve is increased while the tangent-2 length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program terminates when parabola-2 length is exhausted.

Experiment SVV.SP2.01: The first experiment is performed for Δd of -1 feet, using the curve parameters shown in Table 30 as the input profile. A total of 79 profiles is generated for this setup. The minimum value of Final-IRI is 77.59 and is obtained for a parabola-2 length of 6 feet. Figure 51 shows the Final-IRI value of the input profile.

Experiment SVV.SP2.02: The same profile generation criterion is repeated for Δd of 0 feet, which also results in 79 profiles. The input profile for this experiment is shown in Table 31. The parabola-2 length of 3 feet provides the minimum value of Final-IRI i.e., 79.50. The plot of Final-IRI value of the input profile is depicted in Figure 51.

Experiment SVV.SP2.03: The third setup of the group considers the Δd value of 1 feet, using curve parameters shown in Table 32 as the input profile. This experiment also results in 79 profiles and the minimum Final-IRI value of 84.90 obtained at the parabola-2 length of 3 feet. Figure 51 shows the plot of Final-IRI of the input profile.

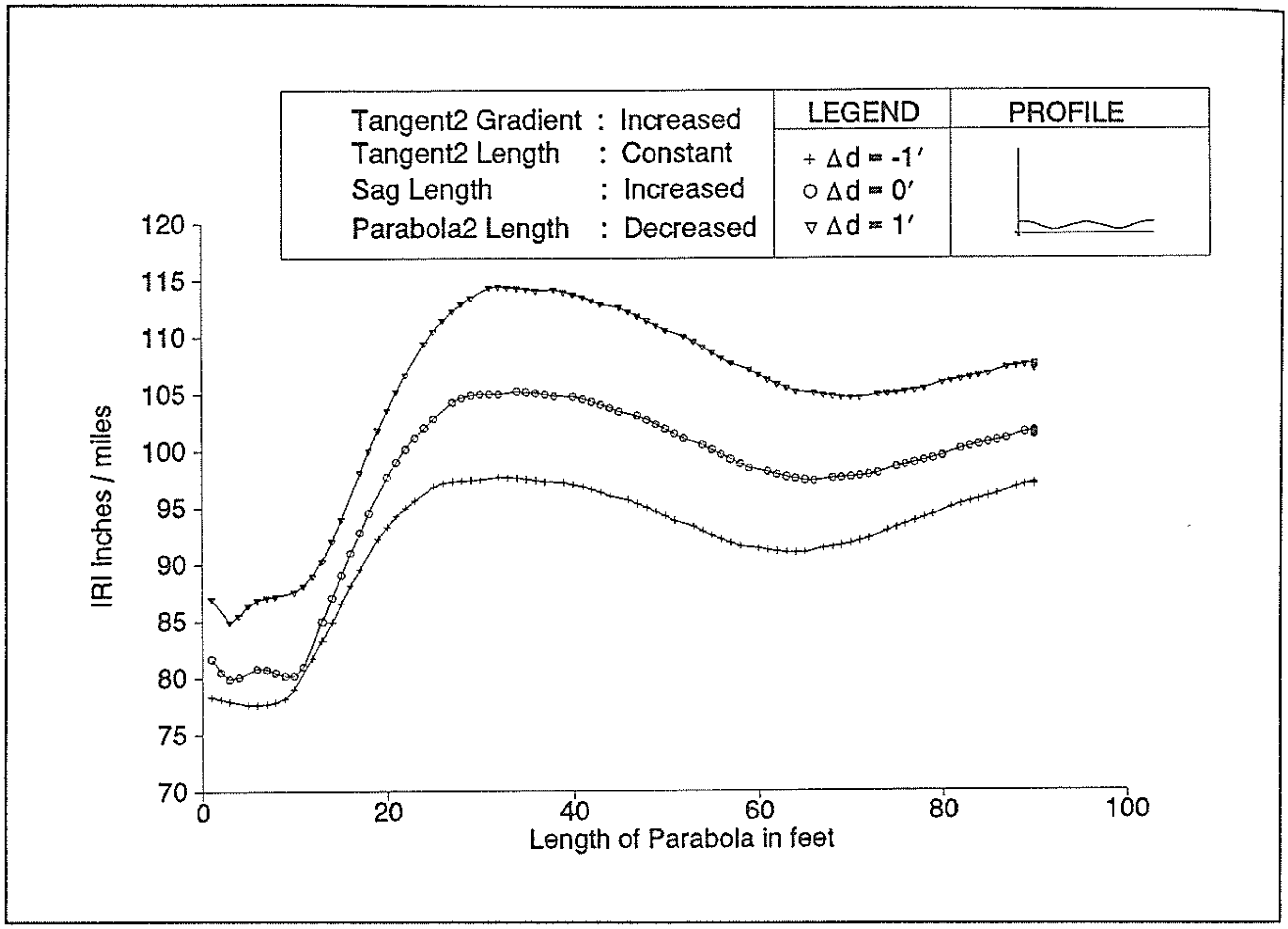

Figure 51 Final-IRI for experiment SVV.SP2

Table 38 summarizes the curve parameters for the minimum value of Final-IRI for three elevation differences. The parabola-2 length of less then 10 feet provides the minimum value of the Final-IRI. It is evident that the Final-IRI is very sensitive to variations in the length of parabola-2.

TABLE 38 CURVE PARAMETERS FOR SVV.SP2 PROFILES

Δd	Tangent-2 Gradient	Parabola-2 Length (ft)	Sag Length (ft)	Minimum Final-IRI (in/mile)
-1	4.04	6	174	77.59
0	4.61	3	177	79.90
1	5.15	3	177	84.90

9.1.7 Summary Results for Profile No. SVV

A study of the plots reveals that Final-IRI value is directly proportional to Δd. Tangent-1 length of around 30 feet and parabola-1 length of around 60 feet gives lower values of Final-IRI. Tangent-2 length of around 44 feet and the parabola-2 length of less then 10 feet gives lower Final-IRI value. The Final-IRI value is more sensitive to variation in parabola-2 then all other curves.

9.2 PROFILE SCC

A set of simulation experiments is performed on a symmetrical profile as depicted in Figure 52. The design of the transition on the right side of the main highway is a mirror image of the profile on the left side. This symmetrical property is not altered as various design parameters are considered.

The profile starts with a tangent length of 36 feet and 0 percent gradient. The tangent is joined to a sag curve of 90 feet in length, which is joined to another tangent with a length of 100 feet. A parabola of 90 feet joins one tangent to another tangent with a length of 100 feet. A sag curve of 90 feet joins the tangent and the cross slope of the main highway. The main highway is 48 feet wide and has a gradient of 2.5 percent on both sides of the centerline. The width and the cross slope of the main highway are kept constant for all experiments.

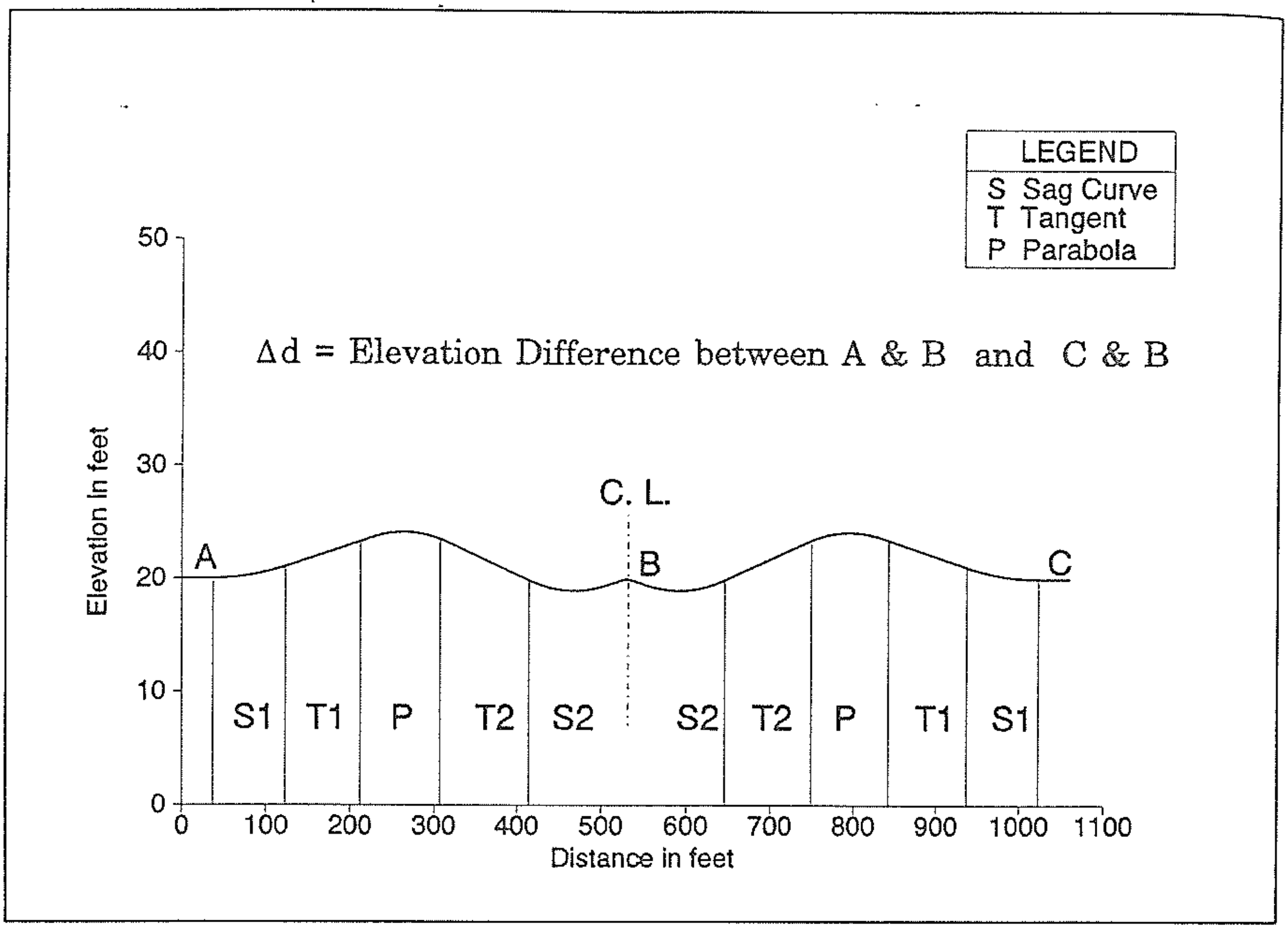

Figure 52 Profile No. SCC

A number of experiments is performed on profile SCC by systematically varying two factors: (1) the length of two of the five curves (S1,T1,P,T2,S2), and (2) the elevation difference between the main highway and the secondary roadway. Six curve combinations are possible: S1-T1, P-T1, P-S1, S2-T2, P-T2, P-S2. Three elevation differences: -1, 0, and 1 feet are considered for all combinations. Eighteen sets of experiments are required to consider all possible combinations of the two factors at three different levels. For each set, experiments are performed by controlling the gradient of either tangent: it is increased in increments of 0.02 percent, after a feasible profile is generated. To accommodate this change, the lengths of two of the five curves are then adjusted to maintain a constant elevation difference (Δd). The simulation is stopped when a feasible profile can not be obtained by changing the length of two curves.

On the basis of curves with adjustable length, six groups are formed from the nine sets. Table 39 shows the curve parameter setup by group. For example, for group SCC.PS1, experiments are performed by reducing the sag-1 curve length and increasing the parabola length to meet the 0.02 percent change in the tangent gradient. In each group, experiments are repeated using the same procedure for three different elevation differences (i.e., -1, 0, and 1 feet). The following sections present the descriptions and the results obtained from these experiments.

TABLE 39 SCC EXPERIMENT GROUPS

Experiment Group	Tangent Gradient	Tangent Length	Sag Length	Parabola Length
SCC.S1T1	Increase	Decrease	Increase	Constant
SCC.PT1	Increase	Decrease	Constant	Increase
SCC.S1P	Increase	Constant	Decrease	Increase
SCC.S2T2	Increase	Decrease	Increase	Constant
SCC.PT2	Increase	Decrease	Constant	Increase
SCC.PS2	Increase	Constant	Decrease	Increase

9.2.1 Experiment Group SCC.S1T1

Experiments in this group are performed to study the effect of variation in sag-1 and tangent-1 lengths on IRI. The tangent-1 gradient is increased by 0.2 percent after each feasible profile is generated. To keep Δd constant, the length of the sag-1 curve is increased and the length of the tangent-1 is decreased, while keeping the parabola length constant. Once a feasible design is produced, the program calculates the IRI of the resulting profile. The program terminates when the tangent-1 length is exhausted. Three sets of experiments are performed corresponding to different elevation differences.

Experiment SCC.S1T1.01: For this set of experiments, the elevation difference Δd is set at -1 feet. The input profile starts with a tangent length of 36 feet and 0 percent gradient on the secondary roadway. A sag-1 curve of 90 feet with a start and an end tangent of 0 percent and 2.5 percent respectively is joined to the tangent. A tangent-1 length of 100 feet and a gradient of 2.5 percent joins the sag-1 curve to a parabola of 90 feet with a start and an end gradient of 2.5 percent and -3.93 percent respectively. Then a tangent-2 of 100 feet and gradient -3.93 percent joins the parabola to a sag-2 curve. The sag-2 curve of 90 feet and start and end gradient of -3.93 percent and 2.5 percent respectively is joined to the cross slope of the main highway. Curve parameters for the input profile are summarized in Table 40.

TABLE 40 INPUT CURVE PARAMETERS FOR PROFILE SCC (Δd=-1 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag-1	0%	2.5%	90
Tangent-1	2.5%	2.5%	100
Parabola	-2.5%	-3.93%	90
Tangent-2	-3.93%	-3.93%	100
Sag-2	-3.93%	2.5%	90

Figure 53 shows the calculated IRI of the profile SCC along the profile for parameters shown in Table 40. There is little increase in IRI value at every curve junction, but there is a sudden rise in the IRI value at the intersection. This rise in IRI value at the centerline of the main highway is due to the cross slope of the main highway.

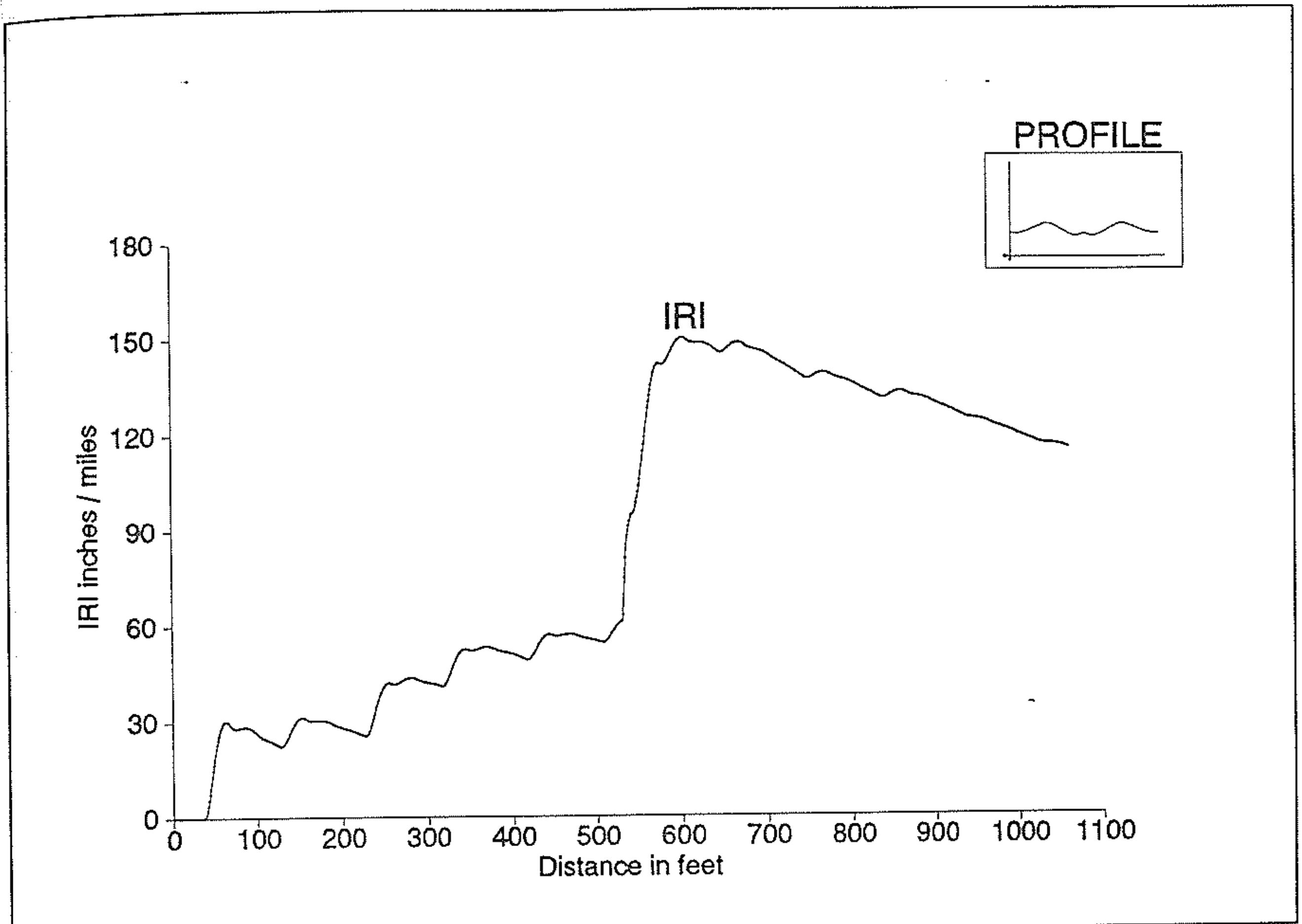

Figure 53 IRI variation along profile SCC (Δd=-1 ft)

The Final-IRI value is calculated for a total length of 1060 feet, 530 feet each side of the center line of the main highway. This procedure for generating profiles is continued until tangent-1 length is exhausted, which results in 48 profiles. The minimum value of Final-IRI is 109.93 and is obtained for a tangent length of 32 feet. The plot of the Final-IRI values is shown in Figure 56.

Experiment SCC.S1T1.02: The criteria of generating profiles for experiment SCC.S1T1.01 is repeated for an elevation difference of 0 feet. The gradient of tangent-2 is decreased to -3.4 percent to make the elevation difference of 0 feet. All other parameters are kept constant. Table 41 shows the initial setup for this experiment and Figure 54 shows the calculated IRI along the profile for the parameters of initial setup. A total of 48 profiles is generated for this experiment. The minimum value of the Final-IRI is 105.49 and is obtained for a tangent length of 31 feet. The plot of the Final-IRI values for the generated profiles is depicted in Figure 56.

TABLE 41 INPUT CURVE PARAMETERS FOR PROFILE SCC (Δd=0 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag-1	0%	2.5%	90
Tangent-1	2.5%	2.5%	100
Parabola	-2.5%	-3.4%	90
Tangent-2	-3.4%	-3.4%	100
Sag-2	-3.4%	2.5%	90

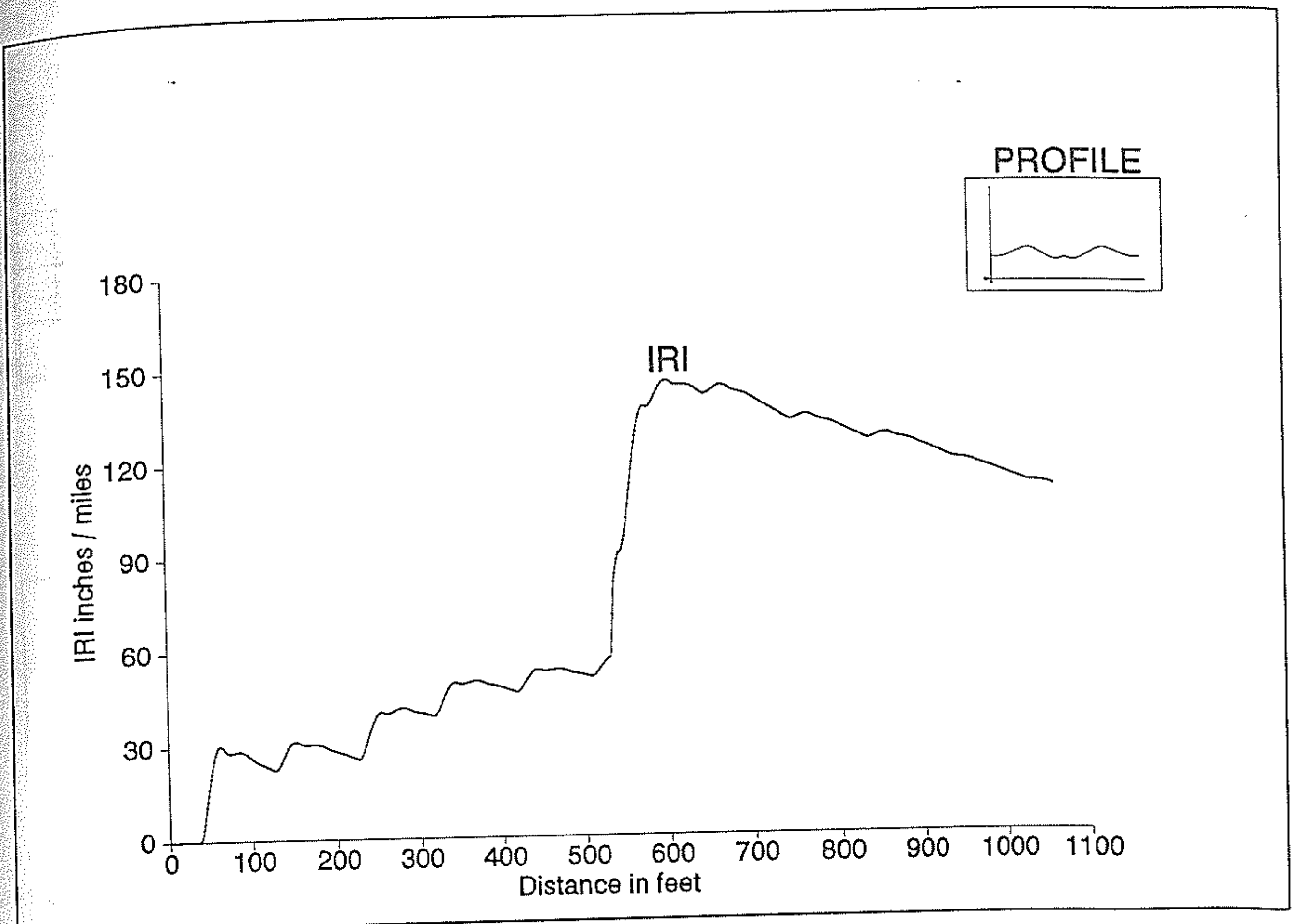

Figure 54 IRI variation along profile SCC (Δd=0 ft)

<u>Experiment SCC.S1T1.03:</u> The above criterion for generating profiles is repeated for Δd of 1 feet which results in 48 profiles. The gradient of tangent-2 is decreased to -2.88 percent. All other parameters are kept unchanged. Figure 55 shows the calculated IRI along the profile for the parameters of initial setup shown in Table 42. The minimum value of Final-IRI is 101.19 and it is obtained for a tangent-1 length of 32 feet. Figure 56 depicts the plot of Final-IRI values.

TABLE 42 INPUT CURVE PARAMETERS FOR PROFILE SCC (Δd=1 ft)

Curve Type	Start Gradient	End Gradient	Curve Length (ft)
Sag-1	0%	2.5%	90
Tangent-1	2.5%	2.5%	100
Parabola	-2.5%	-2.88%	90
Tangent-2	-2.88%	-2.88%	100
Sag-2	-2.88%	2.5%	90

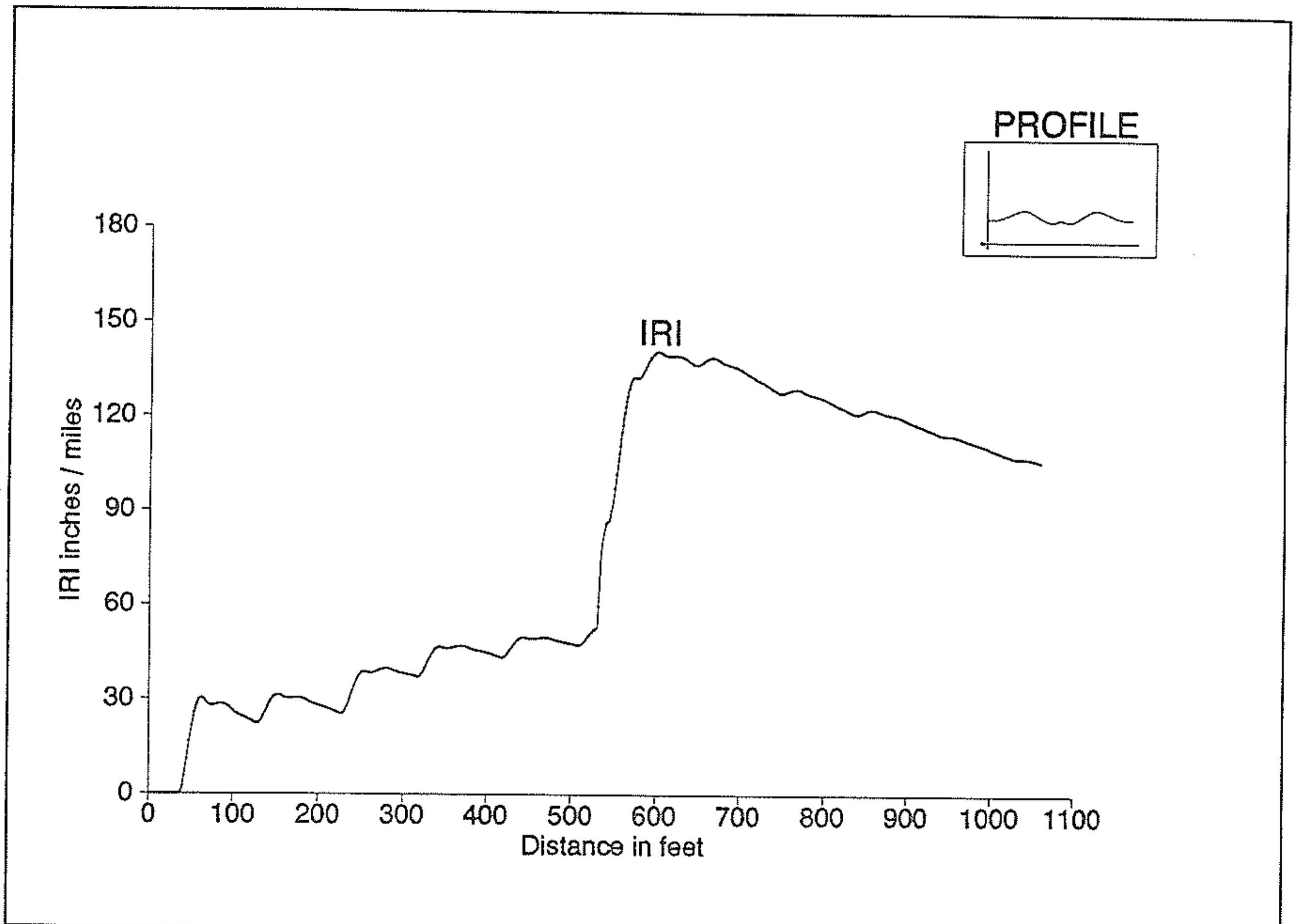

Figure 55 IRI variation along profile SCC (Δd = 1 ft)

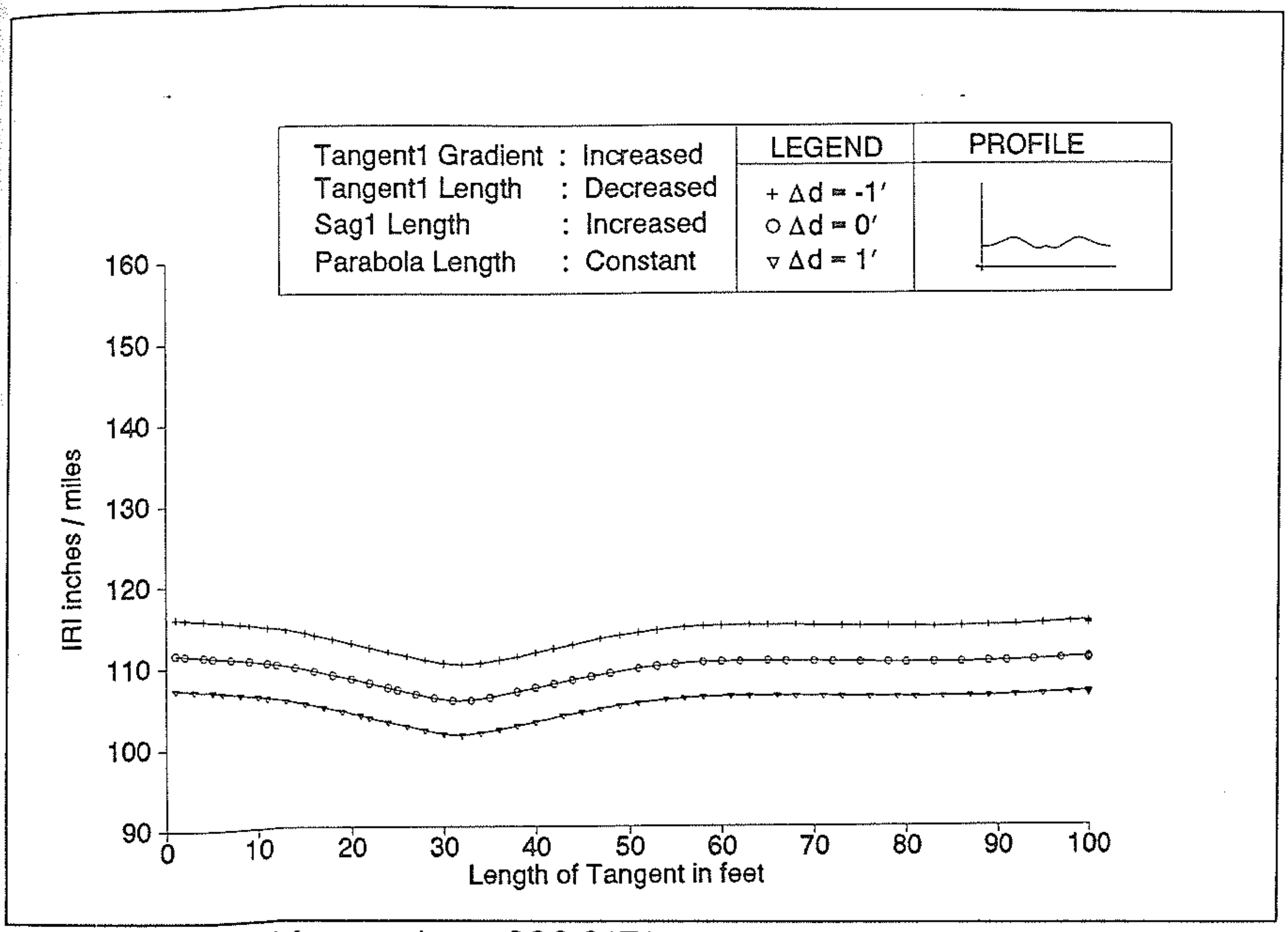

Figure 56 Final-IRI for experiment SCC.S1T1

Table 43 summarizes the curve parameters for the minimum value of Final-IRI for the three elevation differences. Figure 56 reveals that the shape of the Final-IRI curve is similar for all three elevation differences, and Final-IRI is inversely proportional to Δd. The tangent length of around 30 feet produces lower Final-IRI values.

TABLE 43 CURVE PARAMETERS FOR SCC.S1T1 PROFILES

Δd	Tangent-1 Gradient	Tangent-1 Length (ft)	Sag-1 Curve Length (ft)	Final-IRI (in/mile)
-1	3.1	32	158	109.93
0	3.1	31	159	105.49
1	3.1	32	158	101.19

9.2.2 Experiment Group SCC.PT1

Initial setup for the next group of experiments is also shown in Table 39. This series of experiments involves increasing the tangent-1 gradient in increments of 0.2 percent. In the process, to keep Δd constant, the length of parabola is increased and the length of the tangent-1 is decreased while the sag-1 length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program stops when no more feasible profiles can be generated by varying the length of parabola and tangent-1.

Experiment SCC.PT1.01: The first set of experiments is performed for the initial setting shown in Table 40, which resulted in 117 profiles. The minimum value of Final-IRI is 106.63 and is obtained for the tangent-1 length of 31 feet. Figure 57 depicts the plot of Final-IRI values of the generated profiles.

Experiment SCC.PT1.02: The same profile generating procedure is used in experiment SCC.PT1.01 for the elevation difference of 0 feet. The curve parameters shown in Table 42 are used as the input profile, which results in 107 profiles. Again the minimum value of the Final-IRI is 102.79 and occurs for the tangent length of 31 feet. The variation in the values of the Final-IRI as a function of tangent-1 length is not significant in this case. Figure 57 depicts the plot of Final-IRI values of the generated profiles.

Experiment SCC.PT1.03: The above criterion is repeated for the elevation difference of 1 foot. Input parameters for this experiment are shown in Table 43. The experiment resulted in 99 profiles. Once again the minimum Final-IRI value occurs for the tangent length of 31 feet. The plot of Final-IRI values of the generated profiles is depicted in Figure 57.

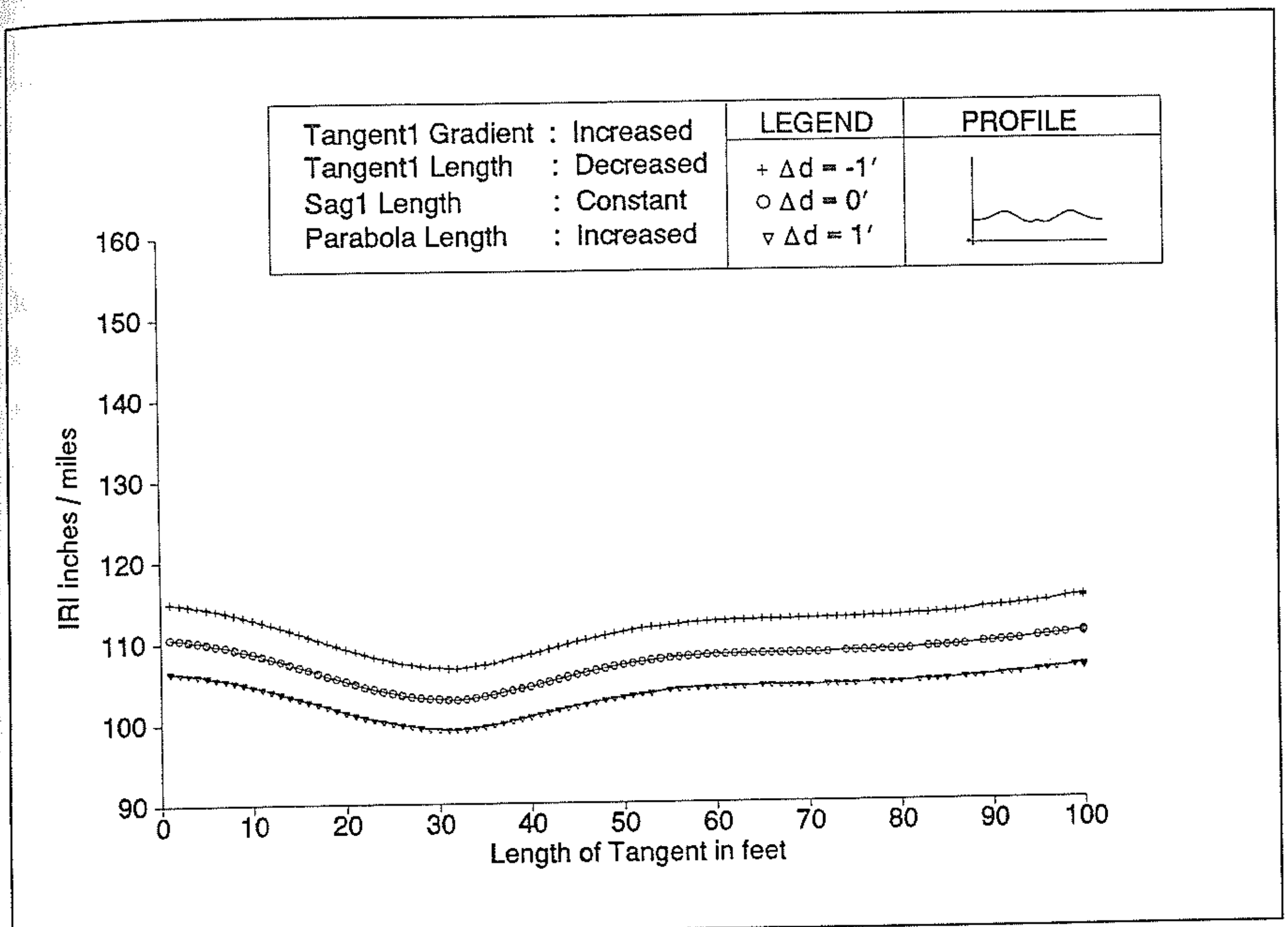

Figure 57 Final-IRI for experiment SCC.PT1

Table 44 summarizes the curve parameters for the minimum value of Final-IRI for all three elevation differences. Figure 57 reveals that the shape of the Final-IRI curve is similar for all three elevation differences. In this group also the tangent-1 length of around 31 feet gives a lower value for the Final-IRI. It is also evident from Figure 57 that the Final-IRI is inversely proportional to Δd.

TABLE 44 CURVE PARAMETERS FOR SCC.PT1 PROFILES

Δd	Tangent-1 Gradient	Tangent-1 Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
-1	3.96	31	159	106.63
0	3.84	31	159	102.79
1	3.74	31	159	99.11

9.2.3 Experiment Group SCC.PS1

This series of experiments also involves increasing the tangent-1 gradient in increments of 0.2 percent. In this process to keep Δd constant, the length of sag-1 curve is decreased and the length of the parabola is increased while keeping the tangent-1 length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program terminates when sag-1 length is exhausted.

Experiment SCC.PS1.01: The first experiment is performed for Δd of -1 feet, which results in 49 profiles. Initial setup shown in Table 40 is used as the input profile for this experiment. There is very little variation in the Final-IRI value for the length of sag-1 curve from 90 to 60 feet. When the sag-1 length is further decreased, the Final-IRI value increases considerably. The minimum value of Final-IRI is 113.61 and occurs at the sag length of 69 feet. Figure 58 shows the plot of Final-IRI values of the generated profiles.

Experiment SCC.PS1.02: The same profile generation procedure used in experiment SCC.PS1.01 results in 43 profiles for this setup. The setup shown in Table 41 is used as the initial setup for this experiment. The minimum value of Final-IRI is 109.42 and occurs at the sag length of 70 feet. Figure 58 shows the plot of Final-IRI values of the generated profiles.

Experiment SCC.PS1.03: The third setup considers the Δd value of 1 foot. Initial setup shown in Table 42 is used as the input profile for this experiment and it results in 30 profiles.

The sag-1 length of 72 feet gives the minimum value of Final-IRI i.e., 105.37. Figure 58 shows the plot of Final-IRI values of the generated profiles.

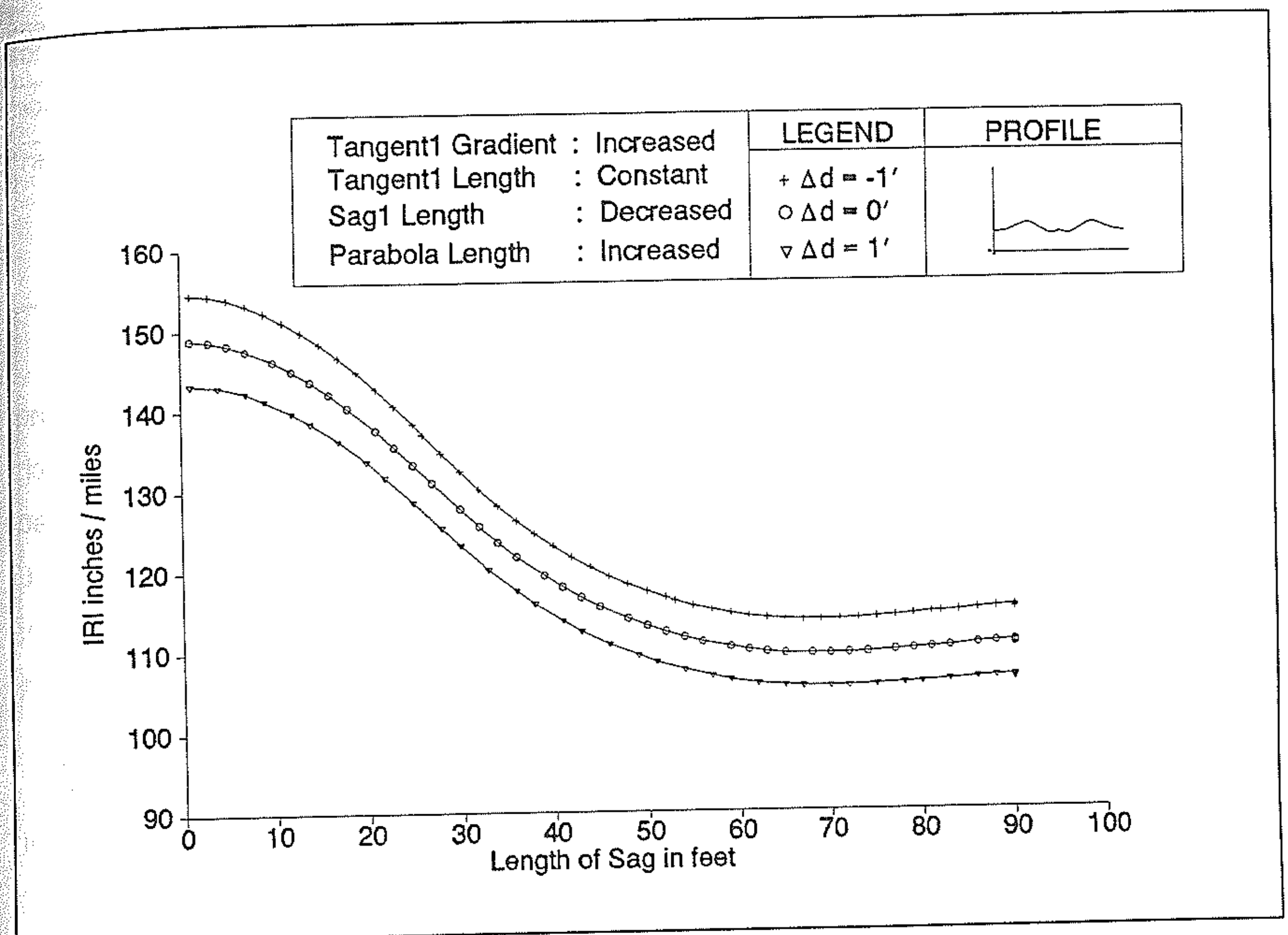

Figure 58 Final-IRI for experiment SCC.SP1

Table 45 summarizes the curve parameters for the minimum value of Final-IRI for three elevation differences. Figure 58 reveals that the shape of the Final-IRI curve is similar for all three elevation differences. It is also evident that the Final-IRI value is inversely proportional to Δd. The sag-1 length of around 70 feet results in lower Final-IRI values.

TABLE 45 CURVE PARAMETERS FOR SCC.PS1 PROFILES

Δd	Tangent-1 Gradient	Sag-1 Curve Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
-1	2.76	69	111	113.61
0	2.72	70	110	109.42
1	2.68	72	108	105.37

9.2.4 Experiment Group SCC.S2T2

Experiments in this group are performed to study the effect of variation in sag-2 and tangent-2 lengths on IRI. The tangent-2 gradient is increased by 0.2 percent after each feasible profile is generated. To keep Δd constant, the length of the sag-2 curve is increased and the length of the tangent-2 is decreased, while keeping the parabola length constant. Once a feasible design is produced, the program calculates the IRI of the resulting profile. This procedure is continued till the tangent-2 length is exhausted. Three sets of experiments are performed corresponding to Δd values of -1, 0, and 1 feet.

Experiment SCC.S2T2.01: For this set of experiments, the elevation difference Δd, is set at -1 feet. Initial setup is shown in Table 40 and is used as the input profile for this setup. The gradient of tangent-2 is increased in increments of .02 percent after a feasible profile is produced. Then to meet Δd requirements, the length of tangent-2 is decreased and the length of sag-2 curve is increased. This procedure of generating the profiles is continued until tangent-2 length is exhausted. A total of 10 profiles is generated for this setup. The minimum value of Final-IRI is 112.90 and is obtained for a tangent-2 length of 89 feet. A plot of the Final-IRI values of the generated profiles is shown in Figure 59.

Experiment SCC.S2T2.02: The criteria of generating profiles for experiment SCC.S2T2.01 is repeated for Δd value of 0 feet, which results in 10 profiles. Initial setup shown in Table 41 is used as an input profile for this experiment. The minimum value of the Final-IRI is 108.76 and is again obtained for the tangent-2 length of 89 feet. The plot of the Final-IRI values of the generated profiles is also depicted in Figure 59.

Experiment SCC.S2T2.03: The same procedure of generating profiles used in experiment SCC.S2T2.02 is repeated for Δd value of 1 feet, which also results in 10 profiles. Initial setup for this experiment is shown in Table 42. The minimum value of Final-IRI is 104.30 and is obtained for a tangent-2 length of 87 feet. Figure 59 depicts the plot of Final-IRI values of the generated profiles.

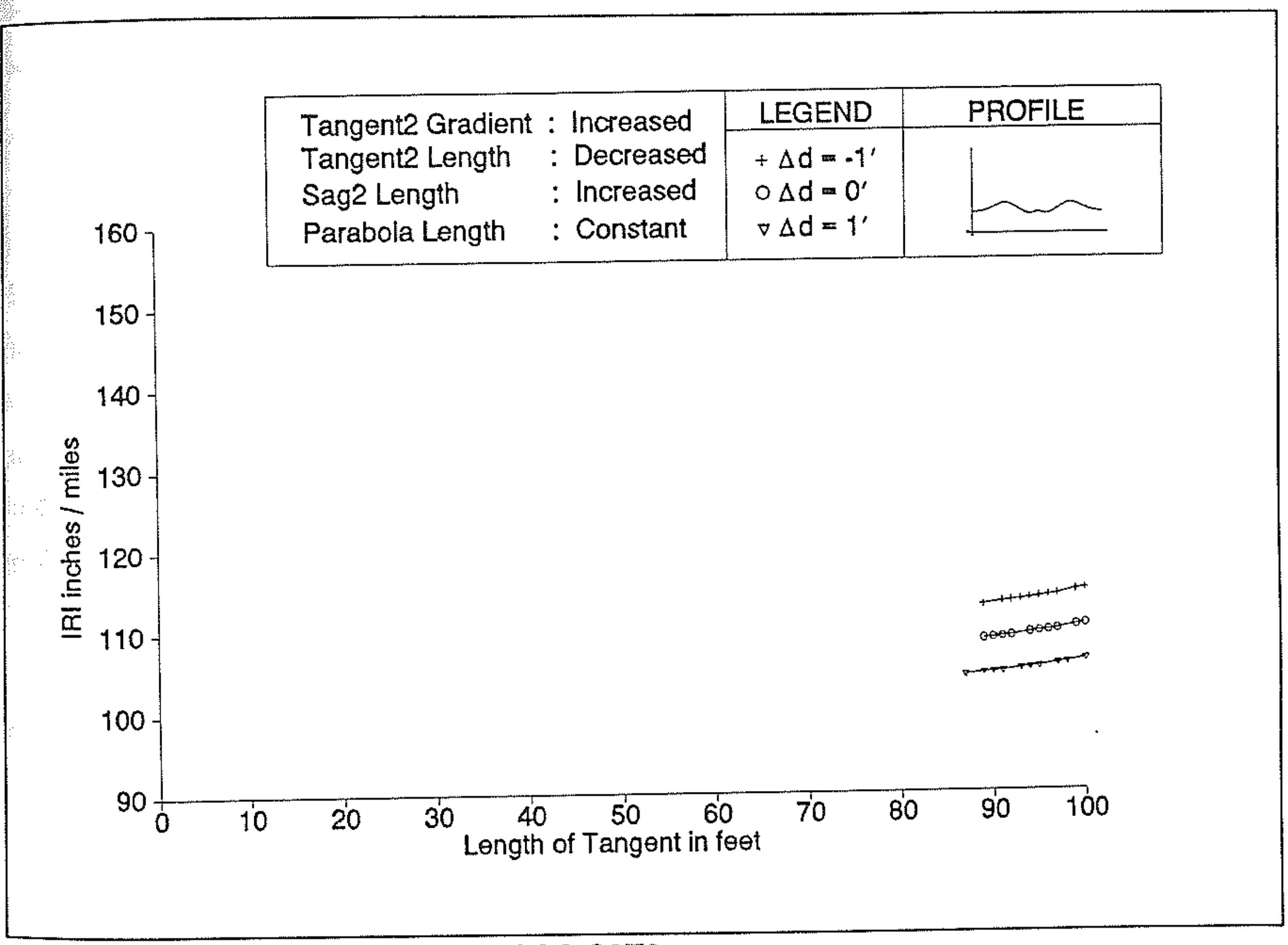

Figure 59 Final-IRI for experiment SCC.S2T2

Table 46 summarizes the curve parameters for the minimum value of Final-IRI for the three elevation differences. Figure 59 reveals that the shape of the Final-IRI curve is similar for the three elevation differences. No profiles are generated when the tangent-2 length is reduced below 85 feet. The tangent-2 length around 90 feet results in lower Final-IRI values.

TABLE 46 CURVE PARAMETERS FOR SCC.S2T2 PROFILES

Δd	Tangent-2 Gradient	Tangent-2 Length (ft)	Sag-2 Curve Length (ft)	Final-IRI (in/mile)
-1	-4.11	89	101	112.90
0	-3.58	89	101	108.76
1	-3.06	87	103	104.30

9.2.5 Experiment Group SCC.PT2

This set of experiments is performed to study the effect of variation in parabola and tangent-2 length on IRI. The experiments involve increasing the tangent-2 gradient in increments of 0.2 percent. In the process, to keep Δd constant, the length of parabola is increased and the length of the tangent-2 is decreased while the sag-2 length is kept constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program stops when no more feasible profiles can be generated by varying the length of parabola and tangent-2.

Experiment SCC.PT2.01: The first set of experiments is performed for the initial setting shown in Table 40, which resulted in 10 profiles. The minimum value of Final-IRI is 113.13 and is obtained for the tangent-2 length of 89 feet. Figure 60 depicts a plot of the Final-IRI values of the generated profiles.

Experiment SCC.PT2.02: The same profile generating procedure is repeated for the elevation difference of 0 feet, which also resulted in 10 profiles. The minimum value of the Final-IRI is 109.01 and also occurs for the tangent-2 length of 89 feet. Variation in the values of the Final-IRI as a function of tangent-2 length is not significant in this case. The plot of Final-IRI values of the generated profiles is depicted in Figure 60.

Experiment SCC.PT2.03: The above criterion is repeated for the elevation difference of 1 feet, which again generated 10 profiles. The tangent-2 of 87 feet provides the minimum value of Final-IRI. Figure 60 shows the plot of Final-IRI values of the generated profiles.

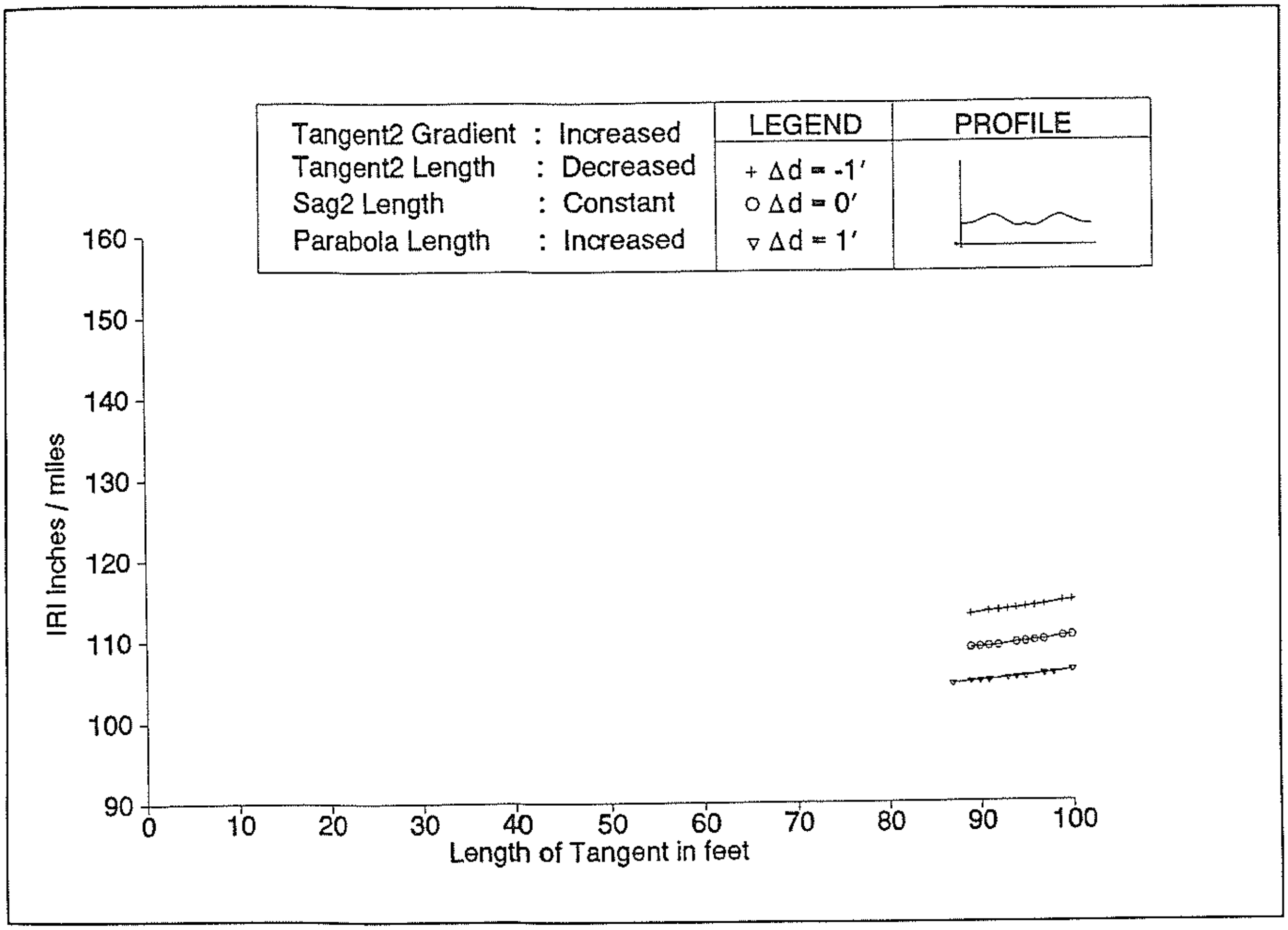

Figure 60 Final-IRI for experiment SCC.PT2

Table 47 summarizes the curve parameters for the minimum value of Final-IRI for the three elevation differences. Figure 60 reveals that the shape of the Final-IRI curve is similar for all three elevation differences. In this group also the tangent-2 length of around 90 feet produces lower values of Final-IRI. It is also evident from Figure 57 that the Final-IRI is inversely proportional to the elevation difference.

TABLE 47 CURVE PARAMETERS FOR SCC.PT2 PROFILES

Δd	Tangent-2 Gradient	Tangent-2 Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
-1	-4.11	89	101	113.13
0	-3.58	89	101	109.01
1	-3.06	87	103	104.56

9.2.6 Experiment Group SCC.PS2

The next series of experiments also involves the increase in the tangent-2 gradient in increments of 0.2 percent. In this process to keep Δd constant, the length of sag-2 curve is decreased and the length of the parabola is increased while keeping the tangent-2 length constant. Once a feasible design is produced, the program calculates the Final-IRI of the resulting profile. The program stops when sag-2 length is exhausted.

Experiment SCC.PS2.01: The first experiment is performed for Δd of -1 feet, using the curve parameters shown in Table 40 as the input profile. The program is not able to generate more profiles because after increasing the tangent-2 gradient by .02 percent, no combination of parabola and sag-2 length could meet the requirement for Δd. Figure 61 shows the Final-IRI value of the input profile.

Experiment SCC.PS2.02: The same profile generation criterion is repeated for Δd of 0 feet. Input profile for this experiment is shown in Table 41. This experiment could generate no more profiles. The plot of Final-IRI value of the input profile is depicted in Figure 61.

Experiment SCC.PS2.03: The third setup considers the Δd value of 1 feet, using curve parameters shown in Table 42. This experiment is also a failure because no more profiles are generated. Figure 61 shows the plot of Final-IRI of the input profile.

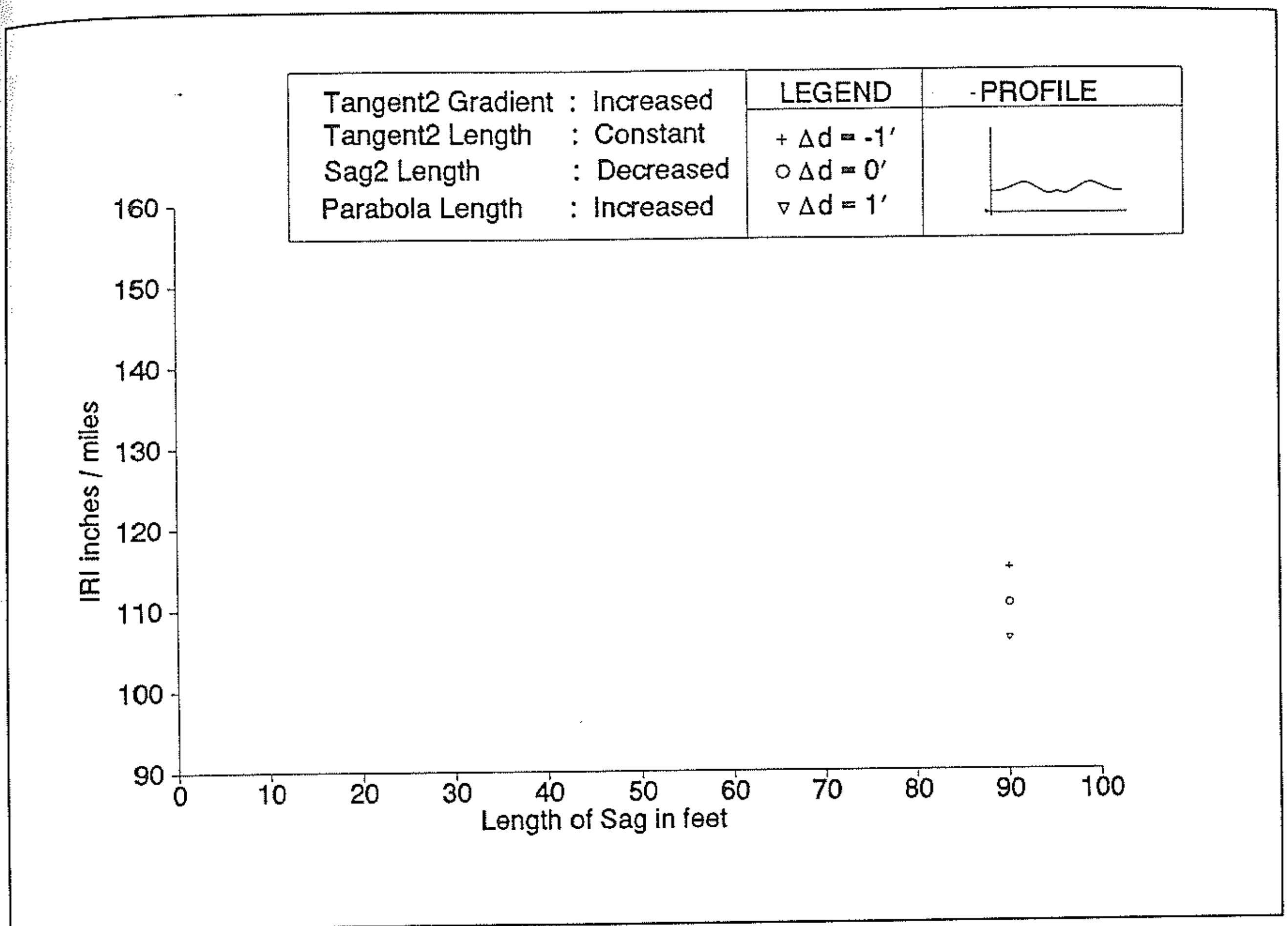

Figure 61 Final-IRI for experiment SCC.PS2

Table 48 summarizes the curve parameters for the minimum value of Final-IRI for the three elevation differences. These parameters are the same as the parameters of the input profile because no more profiles are generated. It is evident from Figure 58 that the Final-IRI value is inversely proportional to the elevation difference.

TABLE 48 CURVE PARAMETERS FOR SCC.PS2 PROFILES

Δd	Tangent-2 Gradient	Sag-2 Curve Length (ft)	Parabola Length (ft)	Final-IRI (in/mile)
-1	-3.93	90	90	114.84
0	-3.4	90	90	110.46
1	-2.88	90	90	106.16

9.2.7 Summary Results for Profile No. SCC

Study of the plots reveals that the Final-IRI value is inversely proportional to the elevation difference. Tangent-1 length of around 30 feet and sag-1 length of around 60 feet gives a lower value of Final-IRI. Tangent-2 length of around 90 feet gives a lower Final-IRI value, but from Figure 59 and 60 no profiles can be generated for tangent length below 85 feet.

10 DEVELOPMENT OF SIDRA

This chapter describes the heuristic procedures developed in this research. As decision support rules, they can be used to generate intersection profiles at the design stage. The logic and the developmental procedures for the heuristics are discussed in the first section. The second section summarizes the implementation of SIDRA and the available functions in the software.

10.1 HEURISTICS FOR INTERSECTION DESIGN

Six heuristic procedures are developed for six types of intersections based on the results from the simulation experiments discussed in the previous chapters. The objective of the heuristic procedure is to generate feasible profiles with low levels of roughness based on the following input data: (1) elevations of the secondary roadway and the main highway, (2) the selected distance (between the secondary roadway and the main highway) for roughness calculation and (3) the cross slope and the width of the main highway. The heuristic procedures are described below.

10.1.1 Heuristic T-STP for TINT Profile

The basic design of the T-Intersection consists of a sag, a tangent and a parabola (S-T-P sequence) joined to the cross slope of the main highway. The heuristic procedure involves the determination of parameters for the S-T-P, such that a profile with a reasonably low IRI value is generated. Each curve can be specified by three curve parameters: start gradient, end gradient and length of the curve. Table 50 shows the variable names used to represent the curve parameters. To provide smooth transition from one curve to other, the end gradient of a curve must be the same as the start gradient of the following curve. As shown in the table, the same variable name is used for the end gradient of the sag curve as well as the start gradient of the tangent.

TABLE 50 VARIABLES USED FOR PROFILE TINT

Curve	Start Gradient	End Gradient	Length
Sag Curve	ISG	ESG	SL
Tangent	ESG	ESG	TL
Parabola	ESG	EPG	PL
Main Highway	EPG	EPG	ML

Results of simulation experiments on T-intersection indicate that the tangent length (TL) around 30 feet gives a lower value of IRI. The optimal tangent length does not change with an increase in the total curve length (up to 2,200 feet). However, the optimal tangent length decreases to about 20 feet when the total curve length is below 300 feet. For the parabola, a length of 23 percent of the total curve length tends to give a lower value of IRI. Once the tangent and parabola length are determined, length of the sag curve is computed by subtracting the sum of all other curve lengths from the total intersection length. Starting gradient of the secondary roadway and the gradient of the tangent is set at 0 percent. An iterative procedure is used to match the gradient of the curves to the elevation of the centerline of the main highway, and the elevation points are computed at every foot. This heuristic, named T-STP, is summarized below:

<u>Heuristic T-STP</u>

1. Initialization. Set ISG at 0 percent.
2. Determination of Curve Length. Let TTL represent the total curve length from the start of the secondary roadway to the centerline of the main highway.
   - 2a. If TTL ≤ 300 feet then set TL = 20 feet else set TL = 30 feet.
   - 2b. Set PL = 0.23 * TTL.
   - 2c. Set SL = TTL - TL - PL - ML.
3. Determination of Curve Gradients.
   - 3a. Set ESG at 0 percent.
   - 3b. Compute the elevation points; check if the final elevation is equal to the elevation

of the centerline of the main highway. If Yes then goto step 4, otherwise goto step 3c.

3c. Let ESG = ESG + .02; goto step 3b.

4. Stop

10.1.2 Heuristic SUD-STPPTS for SUD Profile

The basic design of profile SUD comprises a sag curve, a tangent and a parabola joined to the cross slope of the main highway, and a parabola, a tangent, and a sag curve joining the cross slope to the secondary roadway on the right side of the main highway (S-T-P-P-T-S sequence). Table 51 shows the variable names used to represent the curve parameters on both sides of the main highway. In addition to the curve variables, TTLLEFT and TTLRIGHT are used to represent the total curve lengths on the left and the right sides of the centerline of the main highway respectively.

TABLE 51 VARIABLES USED FOR PROFILE SUD

Curve	Start Gradient	End Gradient	Length
Left Side of the Main Highway			
Sag Curve	LSG	LGA	LSL
Tangent	LGA	LGA	LTL
Parabola	LGA	MG	LPL
Main Highway	MG	MG	ML
Right Side of the Main Highway			
Parabola	MG	RGA	RPL
Tangent	RGA	RGA	RTL
Sag Curve	RGA	RSG	RSL

The results from the simulation experiments on profile SUD are somewhat similar to the results from TINT experiments. A tangent length around 30 feet gives a lower value of IRI, and this optimal tangent length decreases to about 20 feet when curve length on one side of the main highway (TTLLEFT or TTLRIGHT) is below 300 feet. For the parabola length, the optimal value is around 10 feet. Since profile SUD is symmetrical on both sides of the main highway, the resulting curve parameters from one side also apply to the other side.

To generate a feasible design, the tangent gradient on the left hand side is increased in increments of 0.02 percent and elevation points are computed at every foot until the computed elevation is equal to the actual elevation of the centerline of the main highway. The tangent gradient on the right side of the main highway is increased in increments of -0.02 percent till the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. The procedure SUD-STPPTS is summarized below.

<u>Heuristic SUD-STPPTS</u>

1. Initialization. Set LSG and RSG at 0 percent.
2. Determination of Curve Length.
   - 2a. If TTLLEFT ≤ 300 feet then set LTL = 20 feet else set LTL = 30 feet.
   - 2b. Set LPL = 10 feet.
   - 2c. Set LSL = TTLLEFT - LTL - LPL - ML.
   - 2d. If TTLRIGHT ≤ 300 feet then set RTL = 20 feet else set RTL = 30 feet.
   - 2e. Set RPL = 10 feet.
   - 2f. Set RSL = TTLRIGHT - RTL - RPL - ML.
3. Determination of Curve Gradients.
   - 3a. Set LGA at 0 percent.
   - 3b. Compute the elevation points, check if the computed elevation of the main highway is equal to the elevation of the centerline of the main highway. If Yes then goto step 3d, otherwise goto step 3c.
   - 3c. Let LGA = LGA + .02; goto step 3b.
   - 3d. Set RGA at 0 percent.
   - 3e. Compute the elevation points, check if the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. If Yes then goto step 4, otherwise goto step 3f.
   - 3f. Let RGA = RGA - .02; goto step 3e.
4. Stop

10.1.3 Heuristic SDU-PTSSTP for SDU Profile

Profile SDU consists of a parabola, a tangent, and a sag curve joined to the cross slope of the main highway, and a sag curve, a tangent, and a parabola joining the cross slope to the secondary roadway on the right side of the main highway (P-T-S-S-T-P sequence). Similar to profile SUD, TTLLEFT and TTLRIGHT are the total curve lengths on the left and right sides of the main highway respectively. The same variable names TTLLEFT and TTLRIGHT will be used for the total curve length for all the intersections. Variable names used to represent the curve parameters are shown in Table 52.

TABLE 52 VARIABLES USED FOR PROFILE SDU

Curve	Start Gradient	End Gradient	Length
Left Side of the Main Highway			
Parabola	LPG	LGA	LPL
Tangent	LGA	LGA	LTL
Sag Curve	LGA	MG	LSL
Main Highway	MG	MG	ML
Right Side of the Main Highway			
Sag Curve	MG	RGA	RSL
Tangent	RGA	RGA	RTL
Parabola	RGA	RPG	RPL

The optimum tangent length for profile SDU is the same as the optimum tangent length for profile TINT and SUD. The parabola length should be around 25 percent of TTLLEFT or TTLRIGHT. Values of these optimum curve parameters are kept the same for curves on both sides of the main highway.

The heuristic procedure starts by setting the left side tangent gradient to 0 percent and increasing it in increments of -0.02 percent while computing the elevation points at every foot. This process continues until the computed elevation is equal to the given elevation of the centerline of the main highway. The right side of the main highway is increased in increments of 0.02 percent and the elevation points are computed at every one foot. This procedure is continued till the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. A summary of steps for heuristic SDU-PTSSTP is presented below.

<u>Heuristic SDU-PTSSTP</u>

1. Initialization. Set LPG and RPG at 0 percent.
2. Determination of Curve Length.
   - 2a. If TTLLEFT ≤ 300 feet then set LTL = 20 feet else set LTL = 30 feet.
   - 2b. Set LPL = 0.25 * TTLLEFT.
   - 2c. Set LSL = TTLLEFT - LTL - LPL - ML.
   - 2e. If TTLRIGHT ≤ 300 feet then set RTL = 20 feet else set RTL = 30 feet.
   - 2f. Set RPL = 0.25 * TTLRIGHT.
   - 2g. Set RSL = TTLRIGHT - RTL - RPL - ML.
3. Determination of Curve Gradients.
   - 3a. Set LGA at 0 percent.
   - 3b. Compute the elevation points, check if the computed elevation of the main highway is equal to the elevation of the centerline of the main highway. If Yes then goto step 3d, otherwise goto step 3c.
   - 3c. Let LGA = LGA - .02; goto step 3b.
   - 3d. Set RGA at 0 percent.
   - 3e. Compute the elevation points, check if the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. If Yes then goto step 4, otherwise goto step 3f.
   - 3f. Let RGA = RGA + .02; goto step 3e.
4. Stop

10.1.4 Heuristic XUU-STPSTP for XUU Profile

The design of profile XUU consists of a sag curve, a tangent, and a parabola joined to the cross slope of the main highway, and a sag curve, a tangent, and a parabola joining the cross slope to the secondary roadway on the right side of the main highway (S-T-P-S-T-P sequence). Table 53 shows the variable names used to represent the curve parameters.

TABLE 53 VARIABLES USED FOR PROFILE XUU

Curve	Start Gradient	End Gradient	Length
Left Side of the Main Highway			
Sag Curve	LSG	LGA	LPL
Tangent	LGA	LGA	LTL
Parabola	LGA	MG	LSL
Main Highway	MG	MG	ML
Right Side of the Main Highway			
Sag Curve	MG	RGA	RSL
Tangent	RGA	RGA	RTL
Parabola	RGA	RPG	RPL

The results of the simulation runs performed on profile XUU reveal that a tangent length of around 30 feet gives a lower value of IRI when the total curve length on one side of the main highway is more than 300 feet. The simulation runs on XUU also indicate that the parabola length of around 25 percent of the total curve length gives a lower value of IRI. The length of the sag curve is then determined by subtracting all other curve lengths from the total length on one side of the main highway. These parameters are kept constant for curves on both sides of the main highway. Gradient of tangent on both sides of the main highway is initialized to 0 percent and then an iterative procedure is used to match the gradient of the curves to the elevation of the centerline of the main highway and the secondary roadway. This procedure is implemented in the heuristic XUU-STPSTP as presented below.

<u>Heuristic XUU-STPSTP</u>

1. Initialization. Set LSG and RPG at 0 percent.
2. Determination of Curve Length.
   2a. If TTLLEFT $\leq$ 300 feet then set LTL = 20 feet else set LTL = 30 feet.

2b. Set LPL = 0.25 * TTLLEFT.

2c. Set LSL = TTLLEFT - LTL - LPL - ML.

2e. If TTLRIGHT ≤ 300 feet then set RTL = 20 feet else set RTL = 30 feet.

2f. Set RPL = 0.25 * TTLRIGHT.

2g. Set RSL = TTLRIGHT - RTL - RPL - ML.

3. Determination of Curve Gradients.

3a. Set LGA at 0 percent.

3b. Compute the elevation points, check if the computed elevation of the main highway is equal to the elevation of the centerline of the main highway. If Yes then goto step 3d, otherwise goto step 3c.

3c. Let LGA = LGA - .02; goto step 3b.

3d. Set RGA at 0 percent.

3e. Compute the elevation points, check if the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. If Yes then goto step 4, otherwise goto step 3f.

3f. Let RGA = RGA + .02; goto step 3e.

4. Stop

10.1.5 Heuristic SVV-PTSTP for SVV Profile

The basic design of profile SVV consists of a P-T-S-T-P sequence on both sides of the main highway. Table 53 shows the variable names used to represent the curve parameters. There are two parabolas and two tangents on one side of the main highway, so they have been numbered as 1 and 2.

The results of simulation experiments on profile SVV reveal that a tangent-1 length of around 30 feet and a tangent-2 length of around 40 feet give a lower value of IRI. The experiments on SVV also indicate that the parabola-1 length of around 13 percent of the total curve length (TTLLEFT or TTLRIGHT) gives a lower value of IRI, and a parabola-2 length of around 10 feet gives a lower value of IRI. The sag length is determined by subtracting the length of all other curves from the total length (TTLLEFT or TTLRIGHT) on one side of the main highway. The values of these parameters are kept constant for curves on both sides of the main highway.

TABLE 54 VARIABLES USED FOR PROFILE SDU

Curve	Start Gradient	End Gradient	Length
Left Side of the Main Highway			
Parabola-1	LP1G	LGA1	LPL1
Tangent-1	LGA1	LGA1	LTL1
Sag Curve	LGA1	LGA2	LSL
Tangent-2	LGA2	LGA2	LTL2
Parabola-2	LGA2	MG	LPL2
Main Highway	MG	MG	ML
Right Side of the Main Highway			
Parabola-2	MG	RGA2	RPL2
Tangent-2	RGA2	RGA2	RTL2
Sag Curve	RGA2	RGA1	RSL
Tangent-1	RGA1	RGA1	RTL1
Parabola-1	RGA1	RP1G	RPL1

Similar to all other heuristics discussed earlier, the start and the end gradients of the secondary roadway are set to 0 percent. The gradient of tangent-1 is set according to the elevation difference between the secondary roadway and the main highway, for example: if the elevation difference is between 0 and 5 feet the gradient is set at -2.5 percent. The gradient of tangent-2 is set at 0 percent and the elevation points are computed at every foot. The tangent-2 gradient is increased in increments of 0.02 percent and elevation points are computed at every foot till the computed elevation is equal to the actual elevation of the centerline of the main highway. The tangent-1 gradient on the right side is set depending on the elevation difference between the main highway and the right side secondary roadway. Then the tangent-2 gradient on the right side of the main highway is set to 0 percent and the elevation points are computed at every foot. This gradient is increased in increments of -0.02 percent to match the computed final elevation to the elevation of the secondary roadway on the right side of the main highway. This procedure is implemented in the heuristic called

SVV-PTSTP as given below.

<u>Heuristic SVV-PTSTP</u>

1. Initialization. Set LP1G and RP1G at 0 percent.
2. Determination of Curve Length.
   - 2a. Set LPL1 = (70/530) * TTLLEFT.
   - 2b. Set LTL1 = 30.
   - 2c. Set LPL2 = 10.
   - 2e. Set LTL2 = 40.
   - 2f. Set LSL = TTLLEFT - LPL1 - LTL1 - LPL2 - LTL2 - ML.
   - 2g. Set RPL1 = (70/530) * TTLLEFT.
   - 2h. Set RTL1 = 30.
   - 2i. Set RPL2 = 10.
   - 2j. Set RTL2 = 40.
   - 2k. Set RSL = TTLRIGHT - RPL1 - RTL1 - RPL2 - RTL2 - ML.
3. Determination of Curve Gradients.
   - 3a. Let x be the elevation difference between the left side secondary roadway and the main highway.

     IF x ≥ 10 THEN Set LGA1 = -4.

     IF x < 10 AND x ≥ 5 THEN Set LGA1 = -3.

     IF x < 5 AND x ≥ 0 THEN Set LGA1 = -2.5.

     IF x < 0 AND x ≥ -5 THEN Set LGA1 = -2.

     IF x < -5 AND x > -10 THEN Set LGA1 = -1.

     IF x ≤ -10 THEN Set LGA1 = -0.5.
   - 3b. Set LGA2 at 0 percent.
   - 3c. Compute the elevation points, check if the computed elevation of the main highway is equal to the elevation of the centerline of the main highway. If Yes then goto step 3e, otherwise goto step 3d.
   - 3d. Let LGA2 = LGA2 + .02; goto step 3c.
   - 3e. Let w be the elevation difference between the right side secondary roadway and the main highway.

     IF w ≥ 10 THEN Set RGA1 = 4.

IF w < 10 AND w ≥ 5 THEN Set RGA1 = 3.

IF w < 5 AND w ≥ 0 THEN Set RGA1 = 2.5.

IF w < 0 AND w ≥ -5 THEN Set RGA1 = 2.

IF w < -5 AND w > -10 THEN Set RGA1 = 1.5.

IF w ≤ -10 THEN Set RGA1 = .5.

3f. Set RGA2 at 0 percent.

3g. Compute the elevation points, check if the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. If Yes then goto step 4, otherwise goto step 3h.

3h. Let RGA2 = RGA2 - .02; goto step 3G.

4. Stop

10.1.6 Heuristic SCC-STPTS for SCC Profile

The basic design of profile SCC consists of a S-T-P-T-S sequence on both sides of the main highway. Table 55 shows the variable names used to represent the curve parameters.

The results of simulation experiments on profile SCC indicate that the optimum tangent-1 and tangent-2 lengths are around 30 feet. The results also reveal that the sag-1 and sag-2 lengths are around 13 percent of the total length (TTLLEFT or TTLRIGHT) for a lower value of IRI. The parabola length is computed by subtracting the sum of all curve lengths on one side from the total length of the intersection on one side of the main highway. The values of curve parameters are the same for both sides of the main highway.

TABLE 55 VARIABLES USED FOR PROFILE SCC

Curve	Start Gradient	End Gradient	Length
Left Side of the Main Highway			
Sag1	LS1G	LGA1	LS1L
Tangent-1	LGA1	LGA1	LT1L
Parabola	LGA1	LGA2	LPL
Tangent-2	LGA2	LGA2	LT2L
Sag2	LGA2	MG	LS2L
Main Highway	MG	MG	ML
Right Side of the Main Highway			
Sag2	MG	RGA2	RS2L
Tangent-2	RGA2	RGA2	RT2L
Parabola	RGA2	RGA1	RPL
Tangent-1	RGA1	RGA1	RT1L
Sag1	RGA1	RS1G	RS1L

The gradient of the left side tangent-1 is set according to the elevation difference between the left side secondary roadway and the main highway, for example: if the elevation difference is between 0 and 5 feet, the gradient is set at 1.5 percent. Gradient of left side tangent-2 is set at 0 percent and the elevation points are computed at every foot. This gradient is then increased in increments of -0.02 percent till the computed elevation is equal to the actual elevation of the centerline of the main highway. The tangent-1 gradient on the right side is set depending on the elevation difference between the main highway and the right side secondary roadway. The tangent-2 gradient on the right side of the main highway is set at 0 percent and the elevation points are computed at every foot. Then this gradient is increased in increments of 0.02 percent and elevation points are computed at every foot. This procedure is continued till the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. This procedure is implemented in the heuristic SCC-STPTS which is summarized below.

Heuristic SCC-STPTS

1. Initialization. Set LS1G and RS1G at 0 percent.
2. Determination of Curve Length.
   - 2a. Set LSL1 = (70/530) * TTLLEFT.
   - 2b. Set LTL1 = 30.
   - 2c. Set LSL2 = (70/530) * TTLLEFT.
   - 2e. Set LTL2 = 30.
   - 2f. Set LPL = TTLLEFT - LSL1 - LTL1 - LSL2 - LTL2 - ML.
   - 2g. Set RSL1 = (70/530) * TTLLEFT.
   - 2h. Set RTL1 = 30.
   - 2i. Set RSL2 = (70/530) * TTLLEFT.
   - 2j. Set RTL2 = 40.
   - 2k. Set RPL = TTLRIGHT - RSL1 - RTL1 - RSL2 - RTL2 - ML.
3. Determination of Curve Gradients.
   - 3a. Let x be the elevation difference between the left side secondary roadway and the main highway.

     IF $x \geq 10$ THEN Set LGA1 = 0.5.

     IF $x < 10$ AND $x \geq 5$ THEN Set LGA1 = 0.75.

     IF $x < 5$ AND $x \geq 0$ THEN Set LGA1 = 1.5.

     IF $x < 0$ AND $x \geq -5$ THEN Set LGA1 = 2.5.

     IF $x < -5$ AND $x > -10$ THEN Set LGA1 = 3.5.

     IF $x \leq -10$ THEN Set LGA1 = 4.5.
   - 3b. Set LGA2 at 0 percent.
   - 3c. Compute the elevation points, check if the computed elevation of the main highway is equal to the elevation of the centerline of the main highway. If Yes then goto step 3e, otherwise goto step 3d.
   - 3d. Let LGA2 = LGA2 - .02; goto step 3c.
   - 3e. Let w be the elevation difference between the right side secondary roadway and the main highway.

     IF $w \geq 10$ THEN Set RGA1 = -0.5.

     IF $w < 10$ AND $w \geq 5$ THEN Set RGA1 = -0.75.

IF w < 5 AND w ≥ 0 THEN Set RGA1 = -1.5.

IF w < 0 AND w ≥ -5 THEN Set RGA1 = -2.5.

IF w < -5 AND w > -10 THEN Set RGA1 = -3.5.

IF w ≤ -10 THEN Set RGA1 = -4.5.

3f. Set RGA2 at 0 percent.

3g. Compute the elevation points, check if the computed final elevation is equal to the elevation of the secondary roadway on the right side of the main highway. If Yes then goto step 4, otherwise goto step 3h.

3h. Let RGA2 = RGA2 + .02; goto step 3G.

4. Stop

10.2 SOFTWARE IMPLEMENTATION

The decision support system SIDRA (Software for Intersection Design and Roughness Analysis) is written in QuickBASIC language on an IBM Compatible PC. The current version of the program contains approximately 11,000 lines of code, with 8 modules and 90 subprograms.

The INPUT module provides the user interface and decides which other module is to be executed after reading the input data. This module also calculates the roughness of a profile when the elevation points are provided in an ASCII file. The elevation points can be provided in feet or inches.

When provided with the elevation difference and the length between the secondary roadway and the main highway, the GENERATE module can generate a feasible profile with low IRI value for all six types of intersections based on the heuristic procedures discussed earlier.

One module is written for each of the six types of intersections dipicted in Figure 1. These modules generate alternative profiles by varying curve parameters when provided with the curve parameters of an input profile. The roughness of the input profile can be compared with the alternative profile and the profile generated by heuristics. SIDRA selects few profiles with lower IRI values and displays them on the screen for the designer to make a transportation choice.

11 ANALYSIS OF DATA

This chapter presents the analysis of data related to output of SIDRA. In the first section the IRI computation method used in SIDRA is verified by comparing SIDRA output to the IRI measured by two road roughness measuring devices. After the verification process, performance of the heuristic procedures in SIDRA is evaluated in the next section by comparing IRI measures of SIDRA generated profiles and randomly generated feasible profiles using a t-test. Finally, in the last section a regression model is developed to examine the relationship between IRI and SI (Serviceability Index).

11.1 VALIDATION OF IRI COMPUTATION

To validate the accuracy of SIDRA, a series of IRI values was generated for two existing intersections in Baton Rouge, Louisiana. The generated data is compared with the IRI values obtained from two road roughness measuring devices. The roughness measuring devices used are the K. J. Law model 8300 Roughness Surveyor and the Face Dipstick. The K. J. Law surveyor can readily be installed on most vehicles and uses an ultrasonic road sensor and an accelerometer to measure the longitudinal profile of the road. The measured profile is used to compute Mays Index which is identical to the IRI (10). The Face Dipstick measures the profile by automatically recording change in elevation at every foot. An on-board computer system is used to compute IRI values of the profile.

For each intersection, the elevations of two lanes are measured resulting in a total of four different profiles. The profiles considered are: east bound lane of Pecue Lane (PECUE-E), west bound lane of Pecue Lane (PECUE-W), north bound lane of highway LA #1 at the railroad crossing (LA1-N), and south bound lane of highway LA #1 at the railroad crossing (LA1-S). The road test was conducted by the technical staff of the Louisiana Transportation Research Center.

The measured elevation points of the profiles are used as input data and SIDRA produced IRI values that are very close to the values produced by the two roughness measuring devices. Table 56 summarizes the IRI values obtained by the various approaches. The last columns of the table show the ratios of the IRI values obtained by three methods. The ratios are in the range of 0.994 and 1.05 which indicate a close correlation between the three methods.

TABLE 56 IRI COMPARISON WITH INSTRUMENT READINGS

Profile	K.J.Law	Dipstick	SIDRA	K.J.Law / SIDRA	Dipstick / SIDRA
LA1-NO	147	141.43	140.9	1.04	1.003
LA1-SO	210	208.73	208.8	1.005	0.999
PICOUE	278	261.18	262.7	1.05	0.994
PICOUW	278	267.08	266.5	1.04	1.002

The IRI estimated by SIDRA is considered as the theoretical IRI and includes the roughness induced due to construction. To provide a better estimation on the roughness of an intersection generated in the design stage, comparison between the theoretical IRI and the actual IRI must be made. One approach is to smooth the existing intersection profile and then calculate a theoretical IRI for the smoother profile. The comparison of theorectical and actual IRI will produce a multiplier that can be used to obtain real IRI values.

The four profiles considered in the validation process, are smoother using a cubic spline smoothing procedure (14). SIDRA is then used to calculate the IRI of the smoother profiles. Table 57 shows the actual IRI of the profiles, the theoretical IRI from the smoother profile, and the ratio between the two IRI values. The ratio is not consistent for the four profiles because the degree that a profile can be smoother depends on the original characteristics of the profile. It should be noted that the route LA-1 intersection involves the crossing of a railroad track.

TABLE 57 COMPARISON BETWEEN ACTUAL AND SMOOTHED PROFILE

Profile	Actual-IRI (in/mile)	Smoother-IRI (in/mile)	Actual-IRI/ Smooth-IRI (in/mile)
LA1-N	140.9	53.80	2.61
LA1-S	208.8	62.32	3.35
PICOU-E	262.7	138.52	1.89
PICOU-W	266.5	137.33	1.94

11.2 PERFORMANCE EVALUATION OF HEURISTICS

This section compares the profiles generated by SIDRA with randomly generated feasible profiles. A t-test is performed to see whether the profile generated by SIDRA provides lower roughness than the profile randomly generated for each of the six intersections.

For each type intersection, a profile is generated from SIDRA based on a given total length of the profile and elevation difference. For the same length and elevation difference 30 profiles are generated by randomly selecting feasible curve lengths for sag, tangent, and parabola. Cross slope and width of the main highway are kept constant. IRI of the resulting profile is calculated in both directions.

A total length of 1060 feet and an elevation difference of 21.2 feet are used to generate profiles for the T-intersection. Table 58 summarizes the curve parameters of the profile generated by heuristic T-STP and its Final-IRI and opposite Final-IRI value. It also shows the curve parameters and the IRI values for the randomly generated profiles which gives minimum and maximum values of the Final-IRI and the opposite Final-IRI. The symbol "R-Min, F" represents the randomly generated profile with a minimum Final-IRI value. The symbol "R-Max, O" represents the randomly generated profile with a maximum opposite Final-IRI value. The length of the sag curve (TL), tangent (TB), and parabola (TL1) for all the five profiles is shown in the table.

TABLE 58 COMPARISON OF IRI VALUES FOR PROFILE TINT

Profile Type	TL	TL1	TB	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
T-STP	720	30	250	1.23	5.87
R-Min, F	536	170	294	1.3	
R-Max, F	18	59	923	15.42	
R-Min, O	651	48	301		6.11
R-Max, O	18	59	923		17.51
Mean IRI for Random Profiles				3.46	8.13

Using data from all 30 profiles, a t-test is then performed using NCSS software (15) to check whether the difference between the Final-IRI value of the profile generated by heuristic and the mean of Final-IRI values of the randomly generated profile is significant. The result of the test shows that the difference between the two values is significant at the 0.01 level. The same test is performed for opposite Final-IRI values which also shows that the difference of the mean of the opposite Final-IRI for randomly generated profile and the opposite Final-IRI generated by heuristics is significant. The results of the t-test are shown in Table 64, the last column in the table shows the significance level of the t-value. The table also shows the percentage differences between the IRI values obtained from heuristic and mean of randomly generated profiles. The mean of the Final-IRI value of a randomly generated profile is 3.46 which is 181 percent higher than the Final-IRI value (1.23) obtained for the profile generated by heuristic as shown in Table 58. The minimum value of Final-IRI obtained from simulation experiments for profile TINT is 4.73 (Table 641) which is more then 300 percent of the Final-IRI value for the profile generated by the heuristic.

The above procedure is repeated for profile SUD to evaluate the performance of heuristic SUD-STPPTS. A profile with an elevation difference of 10.6 feet, and a length of 530 feet on both sides of the main highway is generated using this heuristic SUD-STPPTS. For the same topography 30 profiles are generated by randomly selecting the curve lengths for sag, tangent, and parabola on both sides of the main highway. The gradients of tangent on both sides of the main highway are computed for the curve parameters to meet the required elevation difference between the secondary roadway and the main highway.

The length of the curves and the IRI values of the profile generated by heuristic SUD-STPPTS is shown in Table 59. The lengths of the curves and the IRI values of the randomly generated profiles which gives minimum and maximum Final-IRI and opposite Final-IRI values are also shown in the table. A common variable name (SUDL) has been used to represent the length of the curves on both sides of the main highway.

TABLE 59 COMPARISON OF IRI VALUES FOR PROFILE SUD

Profile Type	Side of M.H.	SUDL	SUDB	SUDL1	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
SUD - STPPTS	Left	430	30	10	45.17	44.76
	Right	430	30	10		
R-Min, F	Left	76	368	26	48.8	
	Right	410	49	11		
R-Max, F	Left	6	153	311	76.97	
	Right	99	97	274		
R-Min, O	Left	318	151	1		51.87
	Right	158	225	87		
R-Max, O	Left	6	153	311		72.66
	Right	99	97	274		

The results of the t-test (Table 64) show that the difference between the mean of the Final-IRI and the opposite Final-IRI values for randomly generated profiles and the profiles generated by the heuristic is significant at the 0.01 level. Table 64 also shows the percentage difference between the IRI values.

Heuristic SDU-PTSSTP is used to generate a profile for the same topography used for SUD-STPPTS. For the same length and elevation difference, 30 profiles are generated by randomly selecting the curve lengths for the parabola, tangent, and the sag on both sides of the main highway. Table 60 shows the length of the curves on both sides of the main highway and the IRI values for the randomly generated profiles with minimum and maximum values of Final-IRI and opposite Final-IRI. The table also shows the curve lengths and the IRI values of the profile generated by the heuristic.

TABLE 60 COMPARISON OF IRI VALUES FOR PROFILE SDU

Profile Type	Side of M.H.	SDUL	SDUL1	SDUB	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
SDU-PTSSTP	Left	135	30	305	73.57	73.56
	Right	136	30	304		
R-Min, F	Left	169	7	294	74.89	
	Right	177	47	246		
R-Max, F	Left	93	331	46	130.67	
	Right	96	356	18		
R-Min, O	Left	169	7	294		74.81
	Right	177	47	246		
R-Max, O	Left	318	151	1		131.77
	Right	158	225	87		

The t-value shows that the difference between the mean of the Final-IRI values and the opposite Final-IRI values of the profiles randomly generated and those generated by the heuristic is significant. Table 64 shows that the IRI generated by SDU-PTSSTP is about 30 percent lower.

Heuristic XUU-STPSTP is used to generate a profile for the same topography described earlier. A total of 30 profiles is generated by randomly selecting the lengths of the various curves. The length of the curves and the IRI values of the randomly generated profiles are shown in Table 61. The comparison of the Final-IRI of the profile generated by heuristic XUU-STPSTP with the minimum Final-IRI value of the profiles randomly generated indicates that the heuristic generates a profile with a lower IRI value.

TABLE 61 COMPARISON OF IRI VALUES FOR PROFILE XUU

Type	Side of M.H.	XUUL	XUUL1	XUUB	Final-IRI (in/mile)	Opposite Final-IRI (in/mile)
XUU-STPSTP	Left	305	30	135	61.91	62.22
	Right	305	30	135		
R-Min, F	Left	215	160	95	63.63	
	Right	232	37	201		
R-Max, F	Left	76	368	26	110.21	
	Right	11	49	410		
R-Min, O	Left	318	151	1		65
	Right	87	225	158		
R-Max, O	Left	76	368	26		121.22
	Right	11	49	410		

The result of the t-test indicates that there is a significant difference between the IRI value of a profile generated by heuristic and the ones randomly generated. Table 64 shows the test results. The mean of the Final-IRI value of a randomly generated profile is 98.37, which is 33 percent higher then the Final-IRI value of 73.57 obtained for the profile generated by the heuristic.

The above procedure of generating profiles is repeated for heuristic SVV-PTSTP. The length of the curves and the IRI values of these profiles are shown in Table 62. The Final-IRI value of the profile generated by heuristic SVV-PTSTP is greater than the minimum Final-IRI value for a randomly generated profile. In this case, the heuristic SVV-PTSTP doesn't generate the profile with minimum IRI.

TABLE 62 COMPARISON OF IRI VALUES FOR PROFILE SVV

Profile Type	Side of M.H.	SVVL1	SVVB2	SVVL2	SVVB3	SVVL3	FIRI	OIRI
SVV-PTSTP	Left	70	30	320	40	10	74.3	74.7
	Right	70	30	320	40	10		
R-Min, F	Left	37	54	56	183	140	71	
	Right	149	28	256	1	36		
R-Max, F	Left	231	7	123	65	44	195	
	Right	172	187	23	68	20		
R-Min, O	Left	37	54	56	183	140		75.2
	Right	149	28	256	1	36		
R-Max, O	Left	231	7	123	65	44		186
	Right	172	187	23	68	20		

The t-test to evaluate heuristic SVV-PTSTP shows that the difference between the mean of the Final-IRI values of the profile randomly generated and the Final-IRI value of the profile generated by heuristic is significant at the 0.01 level. The same conclusion holds for the opposite Final-IRI value. Table 64 shows the test results and the mean Final-IRI and opposite Final-IRI values of the randomly generated profiles.

Finally, heuristic SCC-STPTS is evaluated in the same manner. The lengths of the curves and the IRI values of the profiles generated by the heuristic are shown in Table 63. The curve parameters and the IRI values of the randomly generated profiles are also shown in Table 63.

The Final-IRI and the opposite Final-IRI values generated by the heuristic SCC-STPTS are greater than the minimum Final-IRI and the opposite Final-IRI values obtained for randomly generated profiles. But the maximum value of the Final-IRI and the opposite Final-IRI for randomly generated profiles are more then 300 percent of the values generated by the heuristic. The result of the t-test also shows that the difference between IRI values obtained by the heuristic and the random process is significant at the 0.01 level.

TABLE 63 COMPARISON OF IRI VALUES FOR PROFILE SCC

Profile Type	Side of M.H.	SCCL1	SCCB2	SCCL2	SCCB3	SCCL3	FIRI	OIRI
SCC-STPTS	Left	70	30	270	30	70	90	90
	Right	70	30	270	30	70		
R-Min, F	Left	148	50	92	9	171	88.1	
	Right	2	274	78	10	106		
R-Max, F	Left	75	295	1	89	10	346	
	Right	6	53	134	124	153		
R-Min, O	Left	148	50	92	9	171		88.4
	Right	6	53	134	124	153		
R-Max, O	Left	75	295	1	89	10		347
	Right	6	53	134	124	153		

Table 64 shows the Final-IRI and opposite Final-IRI values of the profiles generated by heuristics. It also shows the mean IRI values of randomly generated profiles and the percentage difference of these values with the IRI values obtained by the profile generating heuristics. For profile SCC the mean of the Final-IRI values of randomly generated profiles is 160.67 which is 78 percent higher than the Final-IRI value of 90.02 obtained for the heuristic profile.

The figures in the last column of the table are the minimum IRI values obtained for the simulation experiments. Comparison of these values with the IRI values obtained by the heuristic indicate that the heuristics generate profiles with reasonably lower IRI values.

TABLE 64 RESULTS OF T-TEST

Profile	IRI Direction	IRI profile produced by Heuristic (in/mile)	IRI (mean value) prduced randomly (in/mile)	% Diff.	Prob.	Minimum from Simulation Experiment
TINT	FIRI	1.23	3.46	181	.01	4.73
	OIRI	5.87	·8.13	38	.001	13.69
SUD	FIRI	45.17	61.55	36	.001	51.89
	OIRI	44.76	61.31	36	.001	51.89
SDU	FIRI	73.57	98.37	33	.001	72.56
	OIRI	73.56	96.17	30	.001	72.56
XUU	FIRI	61.91	74.50	20	.001	63.82
	OIRI	62.22	77.09	23	.001	66.15
SVV	FIRI	74.38	117.65	58	.001	91.13
	OIRI	74.75	119.83	60	.001	91.13
SCC	FIRI	90.02	160.67	78	.001	102.79
	OIRI	90	157.46	75	.001	102.79

11.3 RELATIONSHIP OF SI TO IRI AT INTERSECTION

The concept of Serviceability Index was first introduced at the AASHTO Road Test in the late 1950's. The basic concept is that a panel of users will rate 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 zero being impassable and a pavement with a rating of five as being perfectly smooth. On the other hand, an IRI value is the measure of roadway roughness and can be measured by several instruments. In contrast to SI, the IRI value doesn't clearly express the comfort of the rider. Since the Road Test, the SI of the roads has been routinely correlated with the output of various roughness measuring devices. In one such study, the relationship of SI to IRI (as measured with the K.J. Law 8300 Roughness Surveyor) has been documented by Cumbaa (10). The study concluded that:

> 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 our knowledge, the SI concept has never been applied to the geometric design of intersections. What has not been verified is the propriety of extending the established relationships to intersections, where a panel of motorists may rate intersection roughness in a manner that differs from normal highway roughness. A section of highway and an intersection may have the same measured roughness over a given length, but a panel may subjectively rate them with differing SI values.

Panel rating of intersections was not performed in this study; however, ten existing intersections in Baton Rouge, Louisiana, were rated by a knowledgeable and experienced team of LTRC (Louisiana Transportation Research Center) staff while taking measurements of IRI with the K.J. Law Roughness Surveyor. Table 65 summarizes the data for the ten intersections.

TABLE 65 COMPARISON OF IRI AND SI AT INTERSECTIONS

Intersection	IRI (in/mile)	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	-0.77	-
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 linear regression was performed on the measured IRI and the rated SI values (columns 2 and 4 in the above table), with IRI as the independent variable. The following relationship resulted:

$$SI = 4.46 - .00592 * IRI$$

Coefficient of determination (R^2) of the regression is 0.8, which indicates that there is a strong 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 ten intersections. The estimated SI and the percent difference between the rated and the estimated SI are presented in the last two columns of the table. For example, at the first intersection, the measured IRI is 562 and the rated SI is 0.5. The estimated SI value based on the regression is 1.13 which is 126 percent higher then the assigned value.

To further study the relationship between the SI of roadways and intersections, the rated SI of the ten intersections were plotted against the measured IRI. The data reported by Cumbaa (10) for rigid pavements was also included on that plot. Figure 62 depicts the relationships.

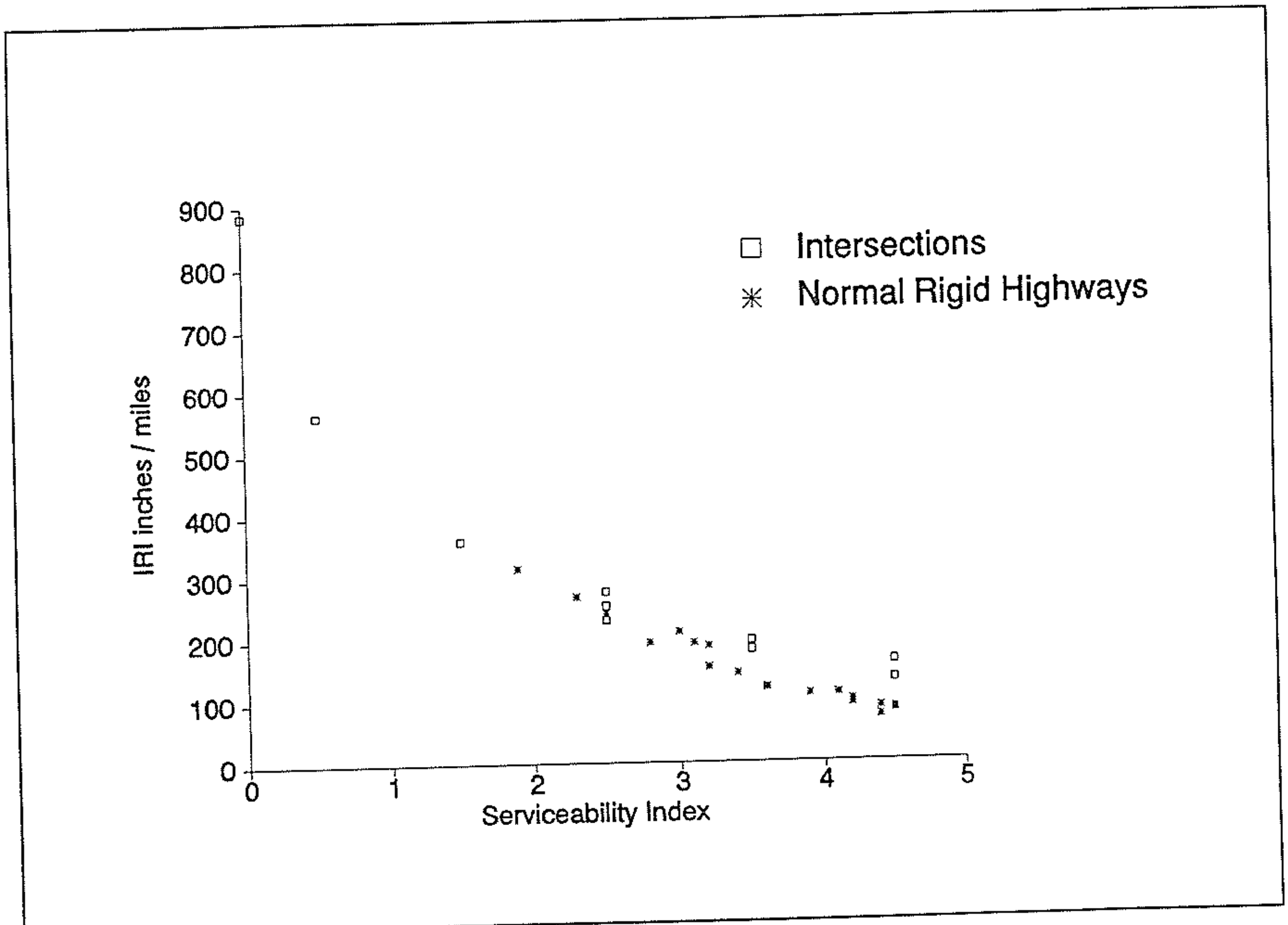

Figure 62 Relationship of IRI to SI

A review of the figure 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 the ratings assigned to highway segments.

The actual IRI of any roadway segment consists of two parts: IRI due to the design and 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 the construction. The LTRC technical staff has recommend that the values shown in Table 66 be used as guides for the IRI values of an intersection due to design. For example, if a final SI of 3 or greater (fair to good) is desired, then the geometric design should contribute an IRI of less than 90 inches/mile.

TABLE 66 RECOMMENDED UPPER LIMITS FOR DESIGN

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

Designers should take note that these recommended values are the upper limits for design and construction values need to be added to the design values. The IRI values from design and construction are not strictly additive in nature, i.e.

$$\text{IRI (design)} + \text{IRI (construction)} \neq \text{IRI (total)}$$

The exact effect of construction induced roughness is not known at this time. However, one can safely conclude that total IRI is somewhat greater than the sum of the IRI from design and construction.

The IRI of newly constructed highways in Louisiana generally ranges between 80 inches/mile and 200 inches/mile with a propensity of the value estimated to be approximately 110 inches/mile. If this value (110) is used as the construction IRI and is added to the IRI value due 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.

12 SUMMARY AND CONCLUSIONS

The objective of this research was to develop a decision support system to aid the highway designer in designing an intersection. The project started with a series of simulation experiments to understand how various profiles are affected by the properties of curves that make up the profile. The simulation experiments were performed on six types of intersections at grade. 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 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.

Curve parameters providing lower IRI values are different for each intersection. However, to obtain a low roughness, a short tangent is required for the six types of intersections. The results of the experiments are summarized below:

1. A tangent length of around 30 feet and a parabola length of around 20 percent of the T-intersection result in a lower IRI value. The IRI values are more sensitive to the change in the parabola length than to variation in the tangent length.

2. Profile SUD is a combination of two T-Intersections facing each other. In spite of this fact, the curve parameters that result in a lower IRI value are different for profile SUD and T-Intersection. For profile SUD, a parabola of short length gives a lower IRI value.

3. Observation of experimental results on profile SDU revealed that the IRI value is directly proportional to the elevation difference between the secondary roadway and the main highway. The IRI value is less sensitive to variation in the tangent length than to variation in the parabola length. A tangent length of about 30 feet and a parabola length of about 25 percent of one side of the intersection length produces a lower IRI value.

4. For profile XUU, the IRI value is also directly proportional to the elevation difference. The IRI value is more sensitive to variation in the parabola length than to variation in the tangent length. The parabola length of around 23 percent of one half of the intersection length results in a lower IRI value.

5. In SVV experiments, the IRI value is again directly proportional to the elevation difference. Two tangent lengths of approximately 30 and 40 feet give a lower value of IRI. The IRI value is very sensitive to variation in the length of the two parabolas. When the length of the second parabola is less than 10 feet, a low IRI value can be obtained.

6. Observation of the results for profile SCC show that the IRI value is inversely proportional to the elevation difference of the secondary roadway and the main highway. The IRI value for this intersection is very sensitive to variation in the sag length.

From the results of the six sets of simulation experiments, six heuristic procedures are implemented in a computer program called SIDRA. The heuristic procedures generate feasible profiles with low levels of roughness based on the following input data: (1) elevations of the secondary roadway and the main highway, (2) the length between the secondary roadway and the main highway, and (3) the cross slope and the width of the main highway. SIDRA is written in QuickBASIC language and the current version contains approximately 11,000 lines of code, with 8 modules and 90 subprograms.

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.

To develop a confidence level for SIDRA generated profiles, for each intersection type, a group of profiles was randomly generated. A series of t-tests was conducted to compare the results obtained for randomly generated profiles with the one produced by SIDRA. The results of the t-test show that SIDRA generates profiles have significantly lower IRI than feasible profiles produced randomly (Table 64).

Finally a regression model (see Section1.2.3) was developed to examine the relationship between IRI and SI. The coefficient of determination indicated a strong relationship between SI and IRI. Table 66 summerizes a set of values that can be used in the design process.

13 RECOMMENDATIONS

The design of an intersection should provide for the comfort of riders. It is therefore recommended that the roughness be evaluated at the design stage. As it is costly to modify an existing intersection after construction, it is prudent that the roughness evaluation be performed at the design stage. The specific recommendations are as follows:

1. International Roughness Index (IRI) should be used as a performance measure to estimate the roughness of intersection profiles.

2. SIDRA should be used to evaluate the design decisions before the final design is prepared.

3. The roughness of the existing intersections can be computed using SIDRA. The existing intersections with high levels of roughness should be evaluated to produce an alternative design for potential improvements.

4. It is recommended that the highway designers utilizing SIDRA, document their design decisions before and after using SIDRA. Future improvements on SIDRA can be implemented based on the recommendations of those who use it on a regular basis.

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APPENDIX A

There are many devices available to physically measure the road roughness. This section discusses the advantages and disadvantages of some roughness measuring techniques. The discussion is further extended to the use of IRI program developed in the International Road Roughness Experiment (IRRE).

Roughness Measurement Devices

Roughness measuring devices can be classified in two categories: Response Type Road Roughness Measuring Systems (RTRRMS) and profilometers. Roughness measurements by RTRRMS are accomplished by using a vehicle equipped with a roadmeter device to produce a numeric value proportional to the vehicle response to road roughness, when the road is traversed at constant speed (2). Most of the RTRRMS systems share commonality in configuration and operation, and are in such a widespread use that they are expected to play a large role in roughness measurement in the near future. The main advantages of the RTRRMS's are their relatively low cost, simplicity of operation, and high measuring speed. Their disadvantages are the difficulty of correlating the measurements made by similar and dissimilar systems, and their susceptibility to change which affect their time stability. Periodic calibration minimizes the effect of these changes.

The roughness measurement obtained from RTRRMS is the result of many factors, two of which are road roughness and test speed. Other factors like shock absorber and tire nonuniformities affect the responsiveness of the vehicle and are difficult to control. There is a growing recognition that some variation will persist between RTRRMS in spite of efforts to limit the variability of these factors (7). Therefore, all RTRRMS systems should be independently calibrated.

All RTRRMS used in IRRE consisted of vehicles equipped with special instrumentations. Although different designs were employed, theoretically all instruments were measuring the same type of vehicle response: an accumulation of the relative movement of the suspension between the axle and body of the vehicle (2). The measurements obtained with these instruments were in the form of discrete counts, where one count corresponds to a certain amount of cumulative deflection of the vehicle suspension. When the vehicle is a passenger car the instrument is mounted on the body directly above the center of the rear axle. Some instruments were mounted on the frame of a single wheeled trailer, to one side of the wheel and directly above the axle. Four types of RTRRMS's participated in the IRRE: Opala Mayster systems, Caravan station wagon with two roadmeters, Bump integrator trailer, and Soiltest BPR roughometer. All four RTRRMS produced highly correlated measures when operated at the same test speed.

In the profilometric method, the longitudinal elevation profile of the road is measured and then analyzed to obtain roughness. Two methods, static and high speed profilometers, were used in the IRRE. A detailed discussion of this method is presented in (2).

International Roughness Index

The need to measure roughness has brought a plethora of instruments to the market (6). This has created a great deal of difficulty in the correlation and transferability of measurements among various instruments and their calibration to a common scale. This difficulty is exacerbated by a large number of factors that cause variations between readings in a similar instrument, and at times in the same instrument.

The need to correlate and calibrate, led to the International Road Roughness Experiment which were held in Brasilia, Brazil in 1982 (2). Roughness of 49 test sites was measured using a variety of test equipment and measurement conditions. Eleven types of equipment were used in the experiment for two categories of instruments: profilometers and Response Type Road Roughness Measuring Systems (RTRRMS) discussed earlier.

Analysis of the collected data showed that all RTRRMS produce highly correlated measures when operated at the same test speed and that all can be calibrated to a single roughness scale without compromising accuracy. Analysis of the profile data demonstrated that the different profilometric methods can give some of the common roughness indices when analysis is performed on the measured profile. Several of the profile-based roughness indices showed excellent correlation with the measures from the RTRRMS (2). As a result of these findings, a single index, called the international roughness index (IRI), was proposed.

The IRI is based on the simulation of the roughness response of a car traveling at 50 miles/hr. It is the Reference Average Rectified Slope which expresses a ratio of the accumulated suspension motion of a vehicle to the distance traveled during the test in units of inches/mile. The IRI has emerged as a scale that can be used both for calibration and for comparative purposes. The IRI is measurable by all roughness measuring instruments included in the IRRE and is also compatible with nearly all equipment used worldwide. The IRI is also strongly related to the subjective opinions of the public (9). Moreover, due to changes in reporting requirements for the Highway Performance Monitoring Systems (HPMS) all states are now required to report roughness in the form of IRI (10).