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THESIS

STUDY ON THE SPIRAL CURVE IN HIGHWAYS AND INTERCHANGE RAMPS

THET ZAW WIN

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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Thet Zaw Win 2011: Study on the Spiral Curve in Highways and Interchange Ramps. Master of Engineering (Civil Engineering), Major Field: Civil Engineering, Department of Civil Engineering. Thesis Advisor: Associate Professor Chavalek Vanichavetin, Ph.D. 71 pages.

Applying corresponding spiral curve in the horizontal alignment of highways not only creates aesthetic impression but also conforms to a natural path for the driver and makes minimum encroachment into the adjoining lane, provides a rational superelevation transition, accomplishes uniformity in speed and finally results in better and safer geometric design than using the normal circular curve.

The primary objective of this research is to recommend the appropriate guideline for spiral curve loop ramp design to be adopted in Myanmar. To realize the objective, the guidelines of AASHTO (2001), Iowa Department of Transportation and Texas Department of Transportation were reviewed and compared.

The secondary objective is to speed up the usual complicated way of working out spiral curve by using the Excel spreadsheet which was developed and shown to simplify the calculation procedure. This research was intended to be widely used in agencies in Myanmar which have been reluctant to use spiral curve because of the cost of the design software. Another purpose of using Excel in this research was, since Excel is not an expensive software and is also user-friendly and easy to learn, anyone who would like to adopt this design spreadsheet can easily modify it to the expected status when it is needed so that it can be used nationwide in the future. To satisfy this aim, the design spreadsheet of spiral curve was developed including related parameters, superelevation and widening using Microsoft Excel with the data from the existing intersection in Myanmar as a case study.

The comparison of the results of this study with the guidelines indicated that most of the AASHTO (2001) guidelines can be applied in the loop ramp design and it is recommended to be adopted as a future practice for loop ramp design in Myanmar. Also, the development outcome was the proposed loop ramp design with the easy-to-use, low cost, time saving Excel design spreadsheet that could be used in the design practice of the horizontal equal transition spiral curve.

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LIST OF ABBREVIATIONS

A	=	Clothoid parameter (flatness of the spiral)
A_i	=	Front overhang of inner lane vehicle
α	=	Lane adjustment factor
C	=	Rate of change of lateral acceleration
C_l	=	Lateral clearance
C_s	=	Correction for deflection angle
CL	=	Control line
CS	=	Point of change from circular curve to spiral curve
D	=	Degree of curve at any point based on 100 foot arc
D_c	=	Degree of curve of the adjoining circular curve based on 100 foot arc
D_s	=	Degree of curve of the spiral at any point on the spiral based on 100 foot arc
Δ	=	Total central angle of the circular curve from TS to ST
Δ_c	=	Central angle of circular curve of length L extending from SC to CS
e	=	Superelevation
e_d	=	Design superelevation rate
e_{max}	=	Maximum superelevation
e_{NC}	=	Normal cross slope rate
E_s	=	External distance from the SCS PI to the center of the circular curve
f	=	Side friction factor
f_{max}	=	Maximum side friction factor
F_A	=	Width of front overhang of vehicle
F_B	=	Width of rear overhang of vehicle
g	=	Acceleration due to gravity
G	=	Relative gradient
γ	=	Angle of inclination of the roadway

LIST OF ABBREVATIONS (Continued)

k	=	Abscissa of the distance between the shifted PC and TS
K	=	Rate of change of degree of curvature per foot of spiral
l	=	Spiral arc from the TS to any point on the spiral ($l = l_s$ at the SC)
l_i	=	Wheelbase of design vehicle between consecutive axles (or sets of tandem axles) and articulation points
l_s	=	Total length of spiral curve from TS to SC (typically the superelevation runoff length)
$l_{s,max}$	=	Maximum length of spiral
$l_{s,min}$	=	Minimum length of spiral
l_r	=	Length of superelevation runoff
l_t	=	Length of tangent runout
L	=	Length of the adjoining circular curve
L_{wb}	=	Wheelbase of single unit, tractor
LC	=	Long chord
LT	=	Long tangent
N	=	Number of lanes
p	=	Offset from the initial tangent to the PC of the shifted circle
p_{max}	=	Maximum lateral offset between the tangent and circular curve
p_{min}	=	Minimum lateral offset between the tangent and circular curve
PC	=	Point of curvature for the adjoining circular curve
PT	=	Point of tangency for the adjoining circular curve
φ	=	Spiral deflection angle at the TS from initial tangent to any point on the spiral
R	=	Radius of the curve or turn
R_s	=	Radius of the spiral at any point
R_c	=	Radius of the adjoining circular curve
R_{min}	=	Minimum radius of curve
SC	=	Point of change from spiral curve to circular curve
SCS PI	=	Point of intersection of main tangents

LIST OF ABBREVATIONS (Continued)

ST	=	Point of change from spiral curve to tangent
ST_s	=	Short tangent
T_s	=	Tangent distance from TS to SCS PI or ST to SCS PI
TS	=	Point of change from tangent to spiral curve
θ	=	Central (or spiral) angle of arc l
θ_s	=	Central (or spiral) angle of arc l_s
u	=	Track width on tangent (out-to-out of tires)
U	=	Track width on curve
V	=	Design speed of the vehicle
V_d	=	Design velocity
w	=	Widening of traveled way on the curve
W	=	Weight of vehicle
W_c	=	Width of traveled way on curve
W_n	=	Width of traveled way on tangent
x and y	=	Coordinates of any point on the spiral from the TS
X_c	=	Tangent distance at the SC
Y_c	=	Tangent offset at the SC
Z	=	Extra width allowance

STUDY ON THE SPIRAL CURVE IN HIGHWAYS AND INTERCHANGE RAMPS

INTRODUCTION

Overview

Transport has always been one of the main characters in the spread of civilization. Land transport is considered as major mode of travel in transportation. It is also the principal freight mode and most people are relying on road networks. Thus, it is important that roads have to not only be in good condition but also need to be constructed with appropriate design in order to maintain the improving rate of the development of society.

In optimizing and maintaining the road systems, the basis is the geometric design. The geometric design refers to the design of visible dimensions of streets and highways and it should be such that it minimizes cost during construction, possesses safe operating condition and makes least disturbance to the environment.

The task of geometric design is to determine the horizontal alignment, vertical alignment and cross section of the roadway. All these are important in geometric design but this thesis will emphasize only on part of the curves in the horizontal alignment. In horizontal alignment, the basic curves used are circular and transition curves.

A transition or an easement curve is a curve of varying radius and varying curvature, introduced between the tangent length and a circular curve, or between two branches of a compound curve, or a reverse curve (Duggal, 1996).

There are three common types of transition curves, namely; Cubic spiral or clothoid or Euler spiral, Bernoulli's lemniscates and Cubic parabola or Froude's curve. Among them, Cubic spiral or clothoid or Euler spiral is chosen as ideal transition curve because there is no significance between these curves up to deflection angle of 9 degrees but in lemniscates and Cubic parabola, rate of change of radius and hence rate of change of centrifugal acceleration is not constant for large deflection angles.

Transition spirals for highways are curves which provide a gradual change in curvature from straight to a circular path or vice versa. Such easement curves have long been found necessary on high-speed railroads as well as in highway design. Nowadays, the use of transition spirals on high speed road facilities is a common practice because of the increase in operating speed of vehicles.

Generally, both circular and spiral curves are used together in geometric design. A circular curve has a radius that is constant, while a spiral curve has a radius that varies from infinity to the radius of the circular curve it is intended to meet. A driver cannot suddenly change the path of his or her vehicle from a straight line to a line of constant curvature. When steering a vehicle into a circular curve, the driver naturally steers the car in a spiral path by increasing the amount of curvature of the car's path. When the car attains the amount of curvature of the circular curve, the driver holds that position through the curve until the car reaches the spiral at the end of the curve. The driver then steers the vehicle back out to the tangent.

When travelling at low speeds or on curves with large radii, a driver can maneuver a vehicle from a line of straight travel into a circular curve without driving out of the lane. At high speeds or on curves with small radii, this maneuver becomes more difficult, causing considerable movement of the vehicle with, and possibly outside, the lane. In such cases, spirals are provided prior to and after the circular curve. This facilitates comfortable and safe travel throughout the curve.

American Society of State Highways and Transportation Officials (American Society of State Highways and Transportation Officials, 2001) stated that the use of transition curve provides a vehicle path that gradually increases or decreases the radial force as the vehicle enters or leaves a circular curve. The degree of a transition curve placed between a tangent and a circular curve varies from zero at the tangent end to the degree of the circular curve at the curve end. When placed between two circular curves, the degree varies from that of the first circular curve to that of the second circular curve.

A properly designed transition curve provides a natural, easy-to-follow path for drivers, such that the lateral force increases and decreases gradually as a vehicle enters and leaves a circular curve. Transition curves minimize encroachment on adjoining traffic lanes and tend to promote uniformity in speed. A spiral transition curve simulates the natural turning path of a vehicle (AASHTO, 2001).

AASHTO (2001) stated that the appearance of the highway or street is enhanced by the application of spiral transition curves. The use of spiral transitions avoids noticeable breaks in the alignment as perceived by driver at the beginning and end of circular curves. Figure 1 illustrates such breaks, which are made more prominent by the presence of superelevation runoff.

The use of spirals in design of curves also provides less turning area required for turning roadway at intersection or interchange ramp design while conforming to the turning path of the vehicles better than circular curve as well.

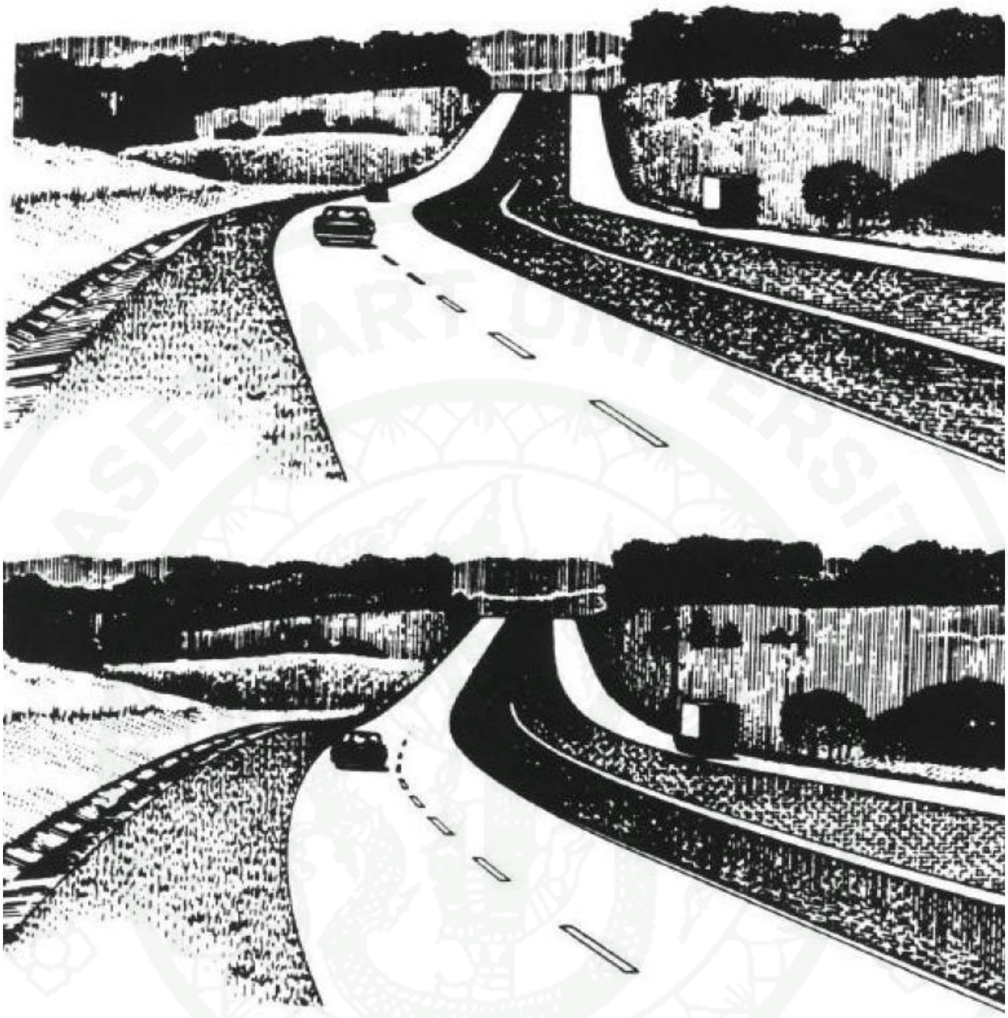

Figure 1 Transition Spirals vs. Simple Circular Curves

Source: Tunnard and Pushkarev (1963)

The transition curve length provides a suitable location for the superelevation runoff. The transition from the normal pavement cross slope on the tangent to the fully superelevated section on the curve can be accomplished along the length of the transition curve in a manner that closely fits the speed-radius relationship for vehicles traversing the transition. Where superelevation runoff is introduced without a transition curve, usually partly on the curve and partly on the tangent, the driver approaching the curve may have to steer opposite to the direction of the approaching curve when on the superelevated tangent portion in order to keep the vehicle within its lane (AASHTO 2001). Since the demand for decrease in travel time and at the same time the call for safe, efficient and economical movement of traffic, depending mostly on driver behavior and traffic performance, it is necessary not only to have proper relationship between design speed and curvature but also the joint relationship with superelevation and side friction.

A spiral transition curve also facilitates the transition in width where the traveled way is widened on a circular curve. Use of spiral transitions provides flexibility in accomplishing the widening of sharp curves (AASHTO 2001).

Statement of Problems

According to national statistics, approximately 25% of the 42,815 people killed in 2002 on US highways were involved in crashes on horizontal curves (TRB, 2008). Further studies suggested that the accident rate for horizontal curves was about three times that of straight sections (RTIRP, 1999). Thus, horizontal curves should be designed with care for safety.

Besides, once the layout of the geometric alignment has already been set, it is unlikely to realign the roadway later because it would be difficult, time consuming and costly. Therefore, it is advisable to use the correct kind of alignment curves in the design for safety and economic reasons.

When a transition curve is not provided on a road, a vehicle passes from a straight into a circular curve, the passengers and the vehicle experience a shock or jerk at the junction point because at this point the curvature changes abruptly from zero to a definite quantity, and centrifugal force comes into play. If this centrifugal force exceeds a certain limit, the vehicle may even overturn. To overcome these ill effects, a length of transition curve is introduced between the straight and the circular curve at both ends (Duggal, 1996).

In the horizontal alignment of highways, it is frequently necessary to use transition curves to connect tangents with sharp circular curves. The calculations required for the design of a transition (spiral) curve are somewhat lengthy, and are often facilitated by the use of tables that give the elements of the curve for selected values of length and minimum radius of the transition (Rao, 1995).

In Myanmar, the criterion for the loop ramp design using spiral curve is currently not available in Myanmar guidelines till now. Therefore, the guideline for the design of spiral curves is adopted mostly from the specified foreign codes which may be quite inappropriate for existing geometric and climate conditions. Most of these codes are usually aimed for high type facilities and it is not suitable for the economic status of the developing country such as Myanmar.

Also, in the past, application of spirals in highways and in ramp design of interchanges was challenging because it required a lot of practice on calculations. Because of the lack of high speed computers at that time, though spiral curves have more safety compared to circular curves, the design was not popular among highway agencies. Now, with the ability of high speed computers and also the introduction of modern engineering software, the design process of the transition spirals is a lot easier than before.

This is one of the reasons for developing the design spreadsheet in Excel. Even though there may be developed programs for this kind of work, these programs are still costly and unaffordable to the engineering firms including government agencies in developing countries such as Myanmar which are running with the limited constraint of financial budget.

Another reason is, if it is able to afford it, it will be for one workstation only and not nationwide. Many bottleneck computers in agencies around the country can use only software that requires low memory usage and processor speed. That is why the research is related to Excel spreadsheet which can be used on almost any computer in developing countries. Moreover, the future intention of this research is, since Excel is user-friendly and easy to learn, anyone who would like to upgrade this design spreadsheet can easily modify it to the expected status when it is needed. In addition, Bawnatgyi Overpass in Myanmar will be used as a case study in the thesis. The location map of the overpass is shown in figure 2.

Figure 2 Location Map of Case Study

Source: PWD (2009)

There is lack of design in the Bawnatgyi Overpass in Myanmar nowadays because at first, the exit ramps were designed to handle low speed traffic and now this access route is connected to the part of the proposed ASIAN Highway Route (AH1), thus, it is necessary to upgrade the existing conditions to maintain the required service level and safety for operations. Therefore, the proposed exit ramp design will also be described in this research. The location of Bawnatgyi Overpass is also shown in figure 3. More details of existing Bawnatgyi Overpass can be seen in figures of appendix section.

Figure 3 Location of Bawnatgyi Overpass

Source: PWD (2009)

Finally, for interchanges in the suburban area, there is a problem related to land acquisition because interchanges need a lot of land for construction process to maintain the level of service for the roadway facility. To solve this problem, clover leaf with spiral curve design, which has the least requirement for land, least cost and also can handle gradual increase or decrease in speed, is used.

OBJECTIVES

The objectives of this study are as follows:

1. To select the recommended design procedures of the spiral curve on loop ramp facility in Myanmar according mostly to the appropriate result from comparing three guidelines: American Association of State Highways and Transportation Officials (2001) guideline, Iowa Department of Transportation guideline and Texas Department of Transportation guideline.

2. To develop the design spreadsheet on low cost, user friendly platform such as Microsoft Excel and compute using the required design parameters, superelevation, widening and analyze the suitable spiral curve and then apply it to interchange loop ramp in Myanmar as a case study using the developed spreadsheet.

3. To recommend the appropriate guideline of loop ramp to be adopted in Myanmar.

Scope of Study

The scope of study will include

1. Using statements and functions in Microsoft Excel Spreadsheet to solve the calculations.

2. Mainly, the study will also be based upon American Association of State Highways and Transportation Officials (AASHTO, 2001), "A Policy of Geometric Design of Highways and Streets" Guideline, Iowa Department of Transportation Design Guideline and Texas Department of Transportation Guideline.

3. The elements of design will be studied, mainly: the length of spiral and the location of spiral by offsets including how to carry out the design process step by step.

4. Also, the criteria of the design parameters, superelevation and widening will be studied.

5. The behavior of the exit loop ramp of partial cloverleaf type service interchange will be emphasized in this study.

6. Evidently, it is to focus on detail design of spiral curve consisting of evaluating the components of spiral curve including the length of spiral and its offsets on highways and interchange loop ramp geometric design.

7. For case study, an overpass in Myanmar is selected to apply the developed spreadsheet to design the proper horizontal, spiral curve loop ramp geometric design. Therefore, the existing conditions of the overpass will be thoroughly considered.

8. For the combined curve, the scope is only on the spiral applied to circular curve where the central portion is shifted.

LITERATURE REVIEW

Not much literature has been found on the transition spirals and most of them emphasize the theories. It is found that transition spirals are used in many ways but the combined curve, consisting of two identical spirals and a central circular curve, is the case most commonly met in practice.

There are several issues needed to be considered to achieve the most suitable horizontal alignment design but this study will focus only on the combined curve which is the combination of the spiral curve and the circular curve, that is used in the loop ramp geometric design.

1. Design Speed

Design speed is the principal factor controlling the horizontal alignment design. Allan (1997) suggested that since the speed of vehicles using a particular road is a variable quantity, a design speed must be defined which is normally taken as the 85 percentile speed i.e., the speed that will not be exceeded by 85% of the vehicles using, or expected to use, the road.

AASHTO (2001) also mentioned that when the design speed of turning roadway is 45 mph or less, compound curvature can be used to perform the entire alignment of the turning roadway. But the exclusive use of compound curves can lead to increase the right-of-way impacts.

AASHTO (2001) described that ramp design speeds above 30 mph for loops involve large areas which are costly and require traveling considerable extra distance but it should be no less than 25 mph with radius of 150 ft. The values suggested by AASHTO are shown in the following table 1.

Table 1 Guide Values for Ramp Design Speed as Related to Highway Design Speed

Highway design speed (mph)	30	35	40	45	50	55	60	65
Ramp design speed(mph)								
Upper range (85%)	25	30	35	40	45	48	50	55
Middle range (70%)	20	25	30	33	35	40	45	45
Lower range (50%)	15	18	20	23	25	28	30	30

Source: AASHTO (2001)

Bonneson *et al.* (2003) also predicted that major road design speed of 60 mph should have speed of 45 mph in loop curve section. But these values are aimed for use in high type facilities and therefore, speed should be in accordance with the AASHTO (2001) guideline of 30 mph for loop ramp section.

2. Radius of the Curve

It will be obvious that from traffic considerations, the largest possible radius and the longest spiral are desirable but that some restriction will always arise from site restriction or causes. The first problems to tackle, therefore, are the determination of suitable minima for the central radius and the length of the spiral for given traffic speeds.

The curvature is defined by stating the length of radius. In design practice, the radius is chosen on the design speed, allowable superelevation, and friction factor then is rounded up to the nearest feet (to be conservative). The formula for the minimum radius for a given design speed is:

$$R_{min} = \frac{{V_d}^2}{15(e_{max} + f_{max})} \quad (1)$$

where

R_{min} = minimum radius of curve, ft;

V_d = design velocity, mph;

e_{max} = maximum superelevation, percent;

f_{max} = maximum side friction factor, percent.

From the aforementioned formula, the greater the maximum superelevation and the greater the maximum allowable lateral friction coefficients that are adopted, the smaller the minimum radius will be for any given design speed. The minimum radius can be obtained using this formula and compared with AASHTO (2001) recommendation of minimum radii for curves, which is shown in table 2.

Table 2 Minimum Radii for Curves

Design turning speed (mph)	10	15	20	25	30	35	40	45
Side friction factor, f	0.38	0.32	0.27	0.23	0.20	0.18	0.16	0.15
Assumed minimum superelevation	0.00	0.00	0.02	0.04	0.06	0.08	0.09	0.10
Calculated min radius (ft)	18	47	92	154	231	314	426	540
Suggested min radius (ft)	25	50	90	150	230	310	430	540

Source: AASHTO (2001)

2.1 Maximum radius for use of a spiral

Bonneson (2000) recommended that the maximum radius for use of a spiral should be based on a minimum lateral acceleration rate of 1.3 m/s^2 [4.25ft/s^2]. The recommended radius related to design speed suggested by AASHTO (2001) is shown in table 3.

Table 3 Maximum Radius for Use of a Spiral Curve Transition

Metric		US Customary	
Design Speed (km/hr)	Maximum radius (m)	Design Speed (mph)	Maximum radius (ft)
20	24	15	114
30	54	20	203
40	95	25	317
50	148	30	456
60	213	35	620
70	290	40	810
80	379	45	1025
90	480	50	1265
100	592	55	4531
110	716	60	1822
120	852	65	2138
130	1000	70	2479

Source: AASHTO (2001)

3. Elements of the Spiral

Generally, the Euler spiral, which is also known as the clothoid, is used in the design of spiral transition curves. The radius varies from infinity at the tangent end of the spiral to the radius of the circular arc at the end that adjoins the circular arc. By definition, the radius of curvature at any point on an Euler spiral varies inversely with the distance measured along the spiral. In the case of a spiral transition that connects two circular curves having different radii, there is an initial radius rather than the infinite value (AASHTO, 2001).

3.1 Length of spiral

There is no detail in exact value given for choosing the length of the spiral. AASHTO, Iowa DOT and Texas DOT only recommend the minimum, maximum and desirable lengths of the spiral. The components and layout of spiral curve is shown in figure 4.

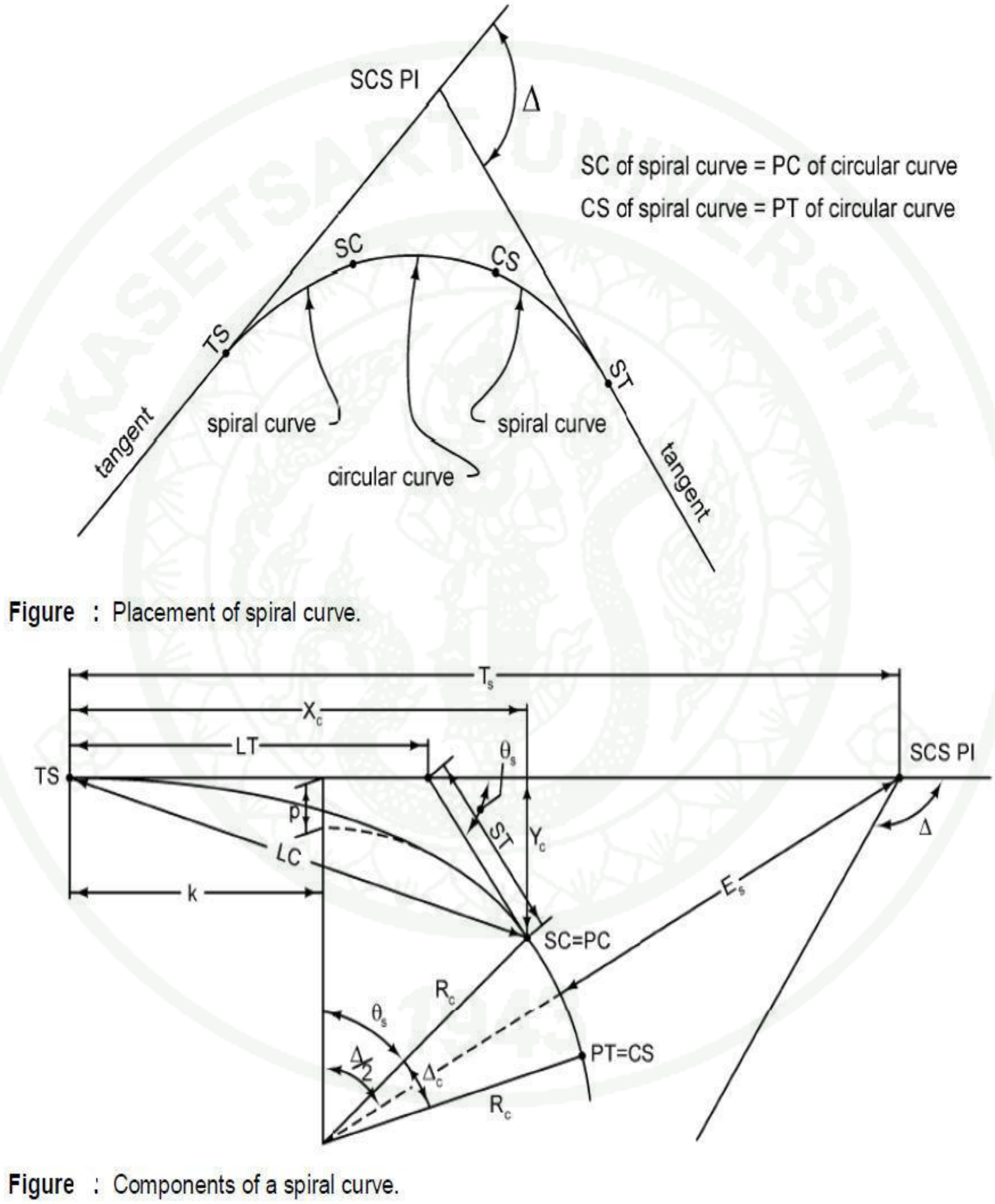

Figure 4 Placement and Components of the Spiral Curve

Source: Iowa Department of Transportation (2010)

3.1.1 Minimum length of spiral transition curve

The criteria based on driver comfort are intended to provide a spiral length that allows for a comfortable increase in lateral acceleration as a vehicle enters a curve. The criteria based on lateral shift are intended to ensure that a spiral curve is sufficiently long to provide a shift in a vehicle's lateral position within its lane that is consistent with that produced by the vehicle's natural spiral path. It is recommended that these two criteria be used together to determine the minimum length of spiral (AASHTO 2001).

Minimum length of spiral transition curve is the larger of values of I and II.

I. (based on driver comfort) (Shortt, 1909)

$$l_{s,min} = \frac{3.15V^3}{R_c C} \tag{2}$$

II. (based on lateral shift)

$$l_{s,min} = \sqrt{24(p_{min})R_c} \tag{3}$$

where

$l_{s,min}$ = minimum length of spiral, ft;

V = design speed, mph;

R_c = radius of adjoining circular curve, ft;

C = rate of change in lateral acceleration, ft/s^3;

p_{min} = minimum lateral offset between the tangent and circular curve, ft.

The recommended minimum value of C by AASHTO (2001) is 4 ft/s^3. The use of lower values will give larger more comfortable spirals. A value of

0.66 ft also is recommended for p_{min} by AASHTO (2001). This value is consistent with the minimum lateral shift that occurs as a result of natural steering behavior.

3.1.2 Maximum length of spiral transition curve

According to (AASHTO, 2001), the maximum length of spiral should be

$$l_{s,max} = \sqrt{24(p_{max})R_c} \tag{4}$$

where

$l_{s,\,max}$ = maximum length of spiral, ft;
p_{max} = maximum lateral offset between tangent and circular curve, ft;
R_c = radius of adjoining circular curve, ft.

A value of 3.3 ft is recommended for p_{max} with maximum lateral shift at highways.

3.1.3 Desirable length of spiral

Bonneson (2000) found that spiral length is an important design control. AASHTO (2001) stated that the desirable length of spiral transition curves correspond to 2.0 s of travel time at the design speed of highway.

In most practical geometric designs, all the recommendations and standards cannot be met simultaneously. The length of the spiral that each vehicle requires varies. The minimum length of the spiral can be calculated using the law of mechanics, but this approach generally yields lengths much shorter than the superelevation runoff lengths. It is therefore convenient to use the superelevation runoff length as the length of spiral, since the lengths are conservative and the superelevation gradually increases as the radius decreases (i.e. as the curvature of the spiral transition gets sharper) (WYDOT, 2001).

4. Superelevation

LandXML (2006) described that there are two methods of determining the need for superelevation. They are

4.1 Method of maximum friction

In this method, we find the values of radius above which we don't need superelevation needs to be provided. That is given by the following equation.

$$\frac{WV^2}{gR} = fW \tag{5}$$

$$R = \frac{V^2}{fg} \tag{6}$$

If the radius provided is less than the above value that has to be compensated by

$$\frac{V^2}{gR} = \frac{(\tan\gamma + f)}{(1 - f\tan\gamma)} \tag{7}$$

where

V = design speed, mph;

W = weight of vehicle, lb;

g = acceleration due to gravity, ft/sec^2;

R = radius of curve, ft;

f = side friction factor, percent;

γ = angle of inclination of the roadway, degree.

4.2 Method of superelevation

In this method, it is assumed that there is no friction factor contributing and hence making sure that swaying due to the curvature is contained by the cant.

$$R = \frac{V^2}{g \tan \gamma} \qquad (8)$$

In general, method of friction is accepted by most leading agencies. From equation (7), “1-ftan γ =1-ef”and the product “ef” in this formula is always small. So “1-ef” term is nearly equal to 1.0 and is normally omitted, resulting in a formula shown in equation (9).

If the greater the value of the superelevation and allowable lateral coefficient are used, the smaller it will result with the value of minimum radius. According to AASHTO (2001) and NHCRP Report 439, the maximum superelevation rate recommended is 10%.

Superelevation and side friction factor for highway curves, when the foot is the unit of measure, are given (AASHTO, 1996) by

For minimum safe radius,

$$e + f = \frac{V^2}{15R} \qquad (9)$$

where

e = superelevation, ft/ft;

f = side friction factor, percent;

V = design speed, mph;

R = radius of curve, ft.

For maximum degree of curve,

$$D = \frac{85660(e + f)}{V^2} \tag{10}$$

where

D = degree of curve at any point based on a 100 ft arc, ft;

V = design speed, mph.

4.3 Length of superelevation runoff

AASHTO (2001) predicted that the length of spiral should be set equal to the length of runoff and suggested that in transition design with a spiral curve, the superelevation runoff be accomplished over the length of the spiral. The superelevation attainment of the two-lane roadway is shown in figure 5.

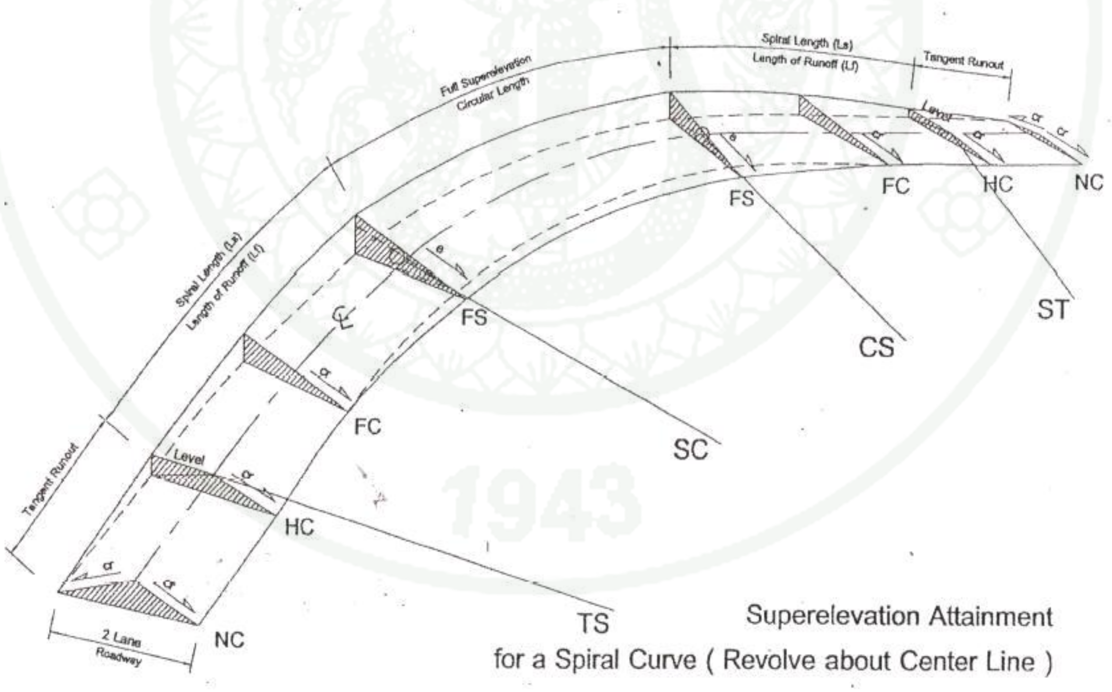

Figure 5 Superelevation Attainment of the Spiral Curve

Source: DOH, Thailand (2008)

In figure 5, the change in cross slope begins by introducing a tangent runout section just in advance of the spiral curve. Full attainment of superelevation is then accomplished over the length of the spiral. In such a design, the whole of the circular curve has full superelevation.

AASHTO (2001) recommended that the length of superelevation runoff should be set equal to length of spiral. The following formula is used as minimum superelevation runoff value for the spiral curve design.

$$l_r = \frac{12 \times e\alpha}{G} \tag{11}$$

where

l_r = length of superelevation runoff, ft;

e = superelevation rate, percent;

α = lane adjustment factor;

G = relative gradient, percent.

4.4 Length of tangent runout

AASHTO (2001) recommended the tangent runout length for a spiral curve transition design should be based on the same approach used for the tangent-to-curve transition design. Here, in following formula, l_s is used instead of l_r for the spiral curve design.

$$l_t = \frac{e_{NC}}{e_d} l_s \tag{12}$$

where

l_t = length of tangent runout, ft;

l_s = length of spiral, ft;

e_{NC} = normal cross slope rate, percent;

e_d = design superelevation rate, percent.

Table 4 Tangent Runout Length for Spiral Curve Transition Design

US Customary					
Design Speed (mph)	Tangent runout length (ft)				
	Superelevation rate				
	2	4	6	8	10
15	44	-	-	-	-
20	59	30	-	-	-
25	74	37	25	-	-
30	88	44	29	-	-
35	103	52	34	26	-
40	117	59	39	29	-
45	132	66	44	33	-
50	147	74	49	37	-
55	161	81	54	40	-
60	176	88	59	44	-
65	191	96	64	48	38
70	205	103	68	51	41
75	220	110	73	55	44
80	235	118	78	59	47
Note:	1.	Based on 2.0 % normal cross slope			
	2.	Superelevation rates above 10 % and cells with “-” coincide with a pavement edge grade that exceeds the maximum relative gradient by 1.5 times or more. These limits apply to roads where one lane is rotated; lower limits apply when more lanes are rotated.			

Source: AASHTO (2001)

4.5 Methods of Attaining Superelevation

AASHTO (2001) stated that four methods are used to transition the pavement to a superelevated cross section. These methods include:

A. Revolving a traveled way with normal cross slope about the centerline profile,

B. Revolving a traveled way with normal cross slopes about the inside-edge profile,

C. Revolving a traveled way with normal cross slopes about the outside-edge profile, and

D. Revolving a straight cross-slope traveled way about the outside-edge profile.

Figure 6 provides diagrammatic profiles for details of four methods.

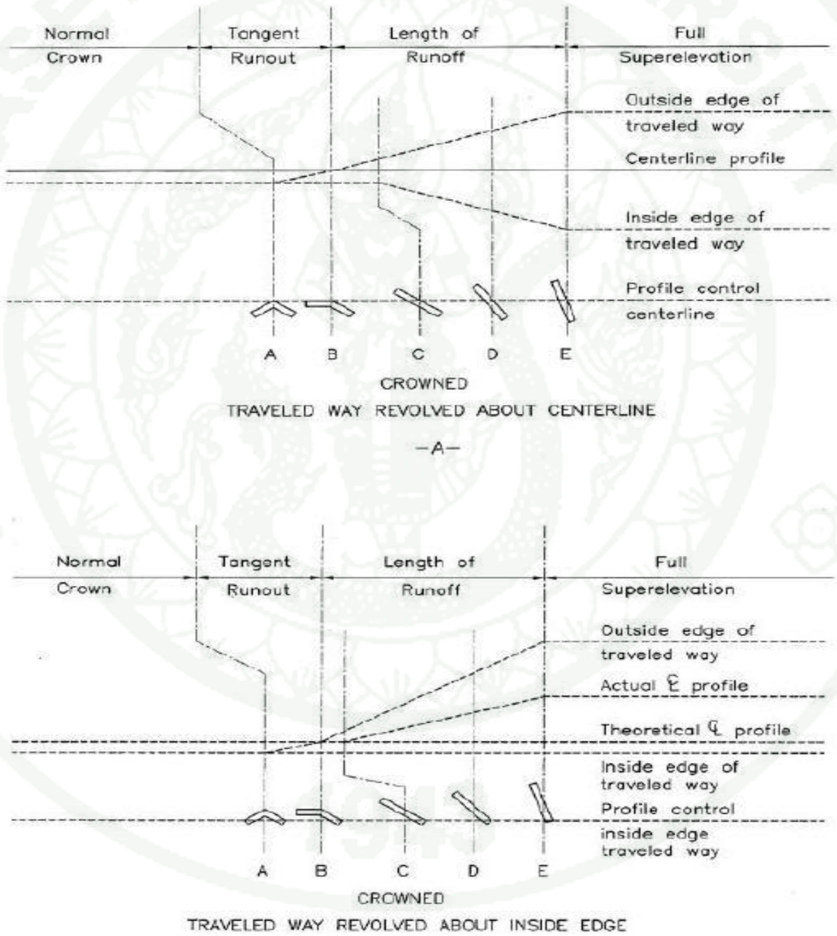

Figure 6 (A) Profiles Showing Method of Attaining Superelevation for a Curve to the Right

Source: AASHTO (2001)

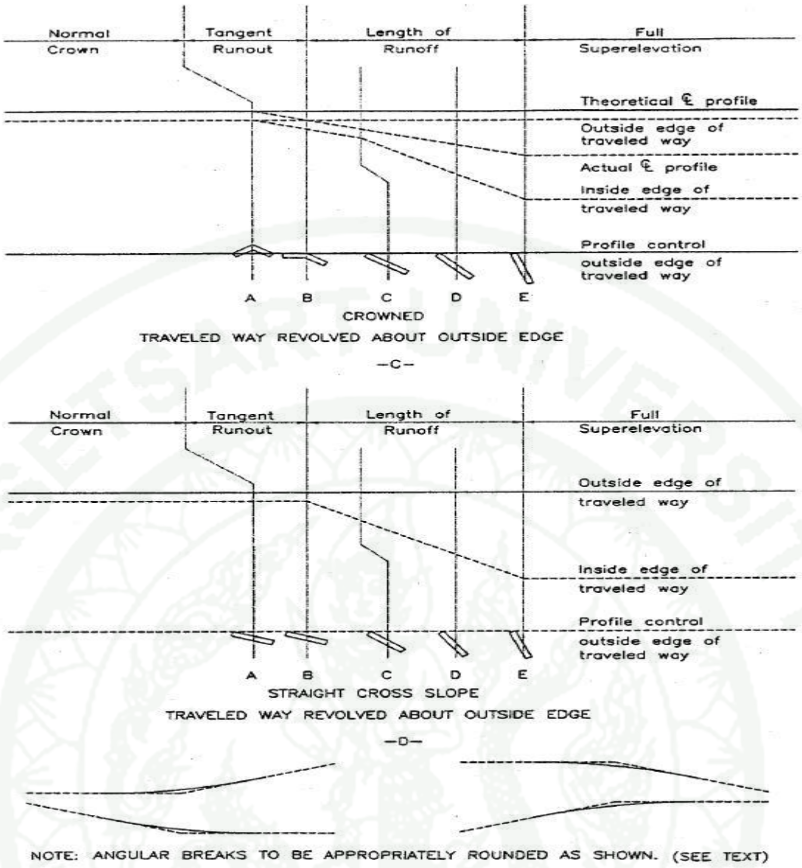

Figure 6 (B) Profiles Showing Method of Attaining Superelevation for a Curve to the Right

Source: AASHTO (2001)

In an overall sense, the method of rotation about the centre line shown in figure 6 (A) A is usually most adaptable. On the other hand, the method shown in figure 6 (A) B is preferable where the lower edge profile is a major control, as for drianage. With uniform profile conditions, its use results in the greatest distortion of the upper edge profile. Where the overall performance is to be emphasized, the methods of figure 6 (B) C and 6 (B) D have advantages in that the upper-edge profile ─ the edge most noticeable to drivers ─ retains the smoothness of the control profile. Thus, the shape and direction of the centreline profile may determine the preferred method for attaining superelevation.

The superelevation transition diagrams for compound curves and reverse spiral curves are also shown in the following figure.

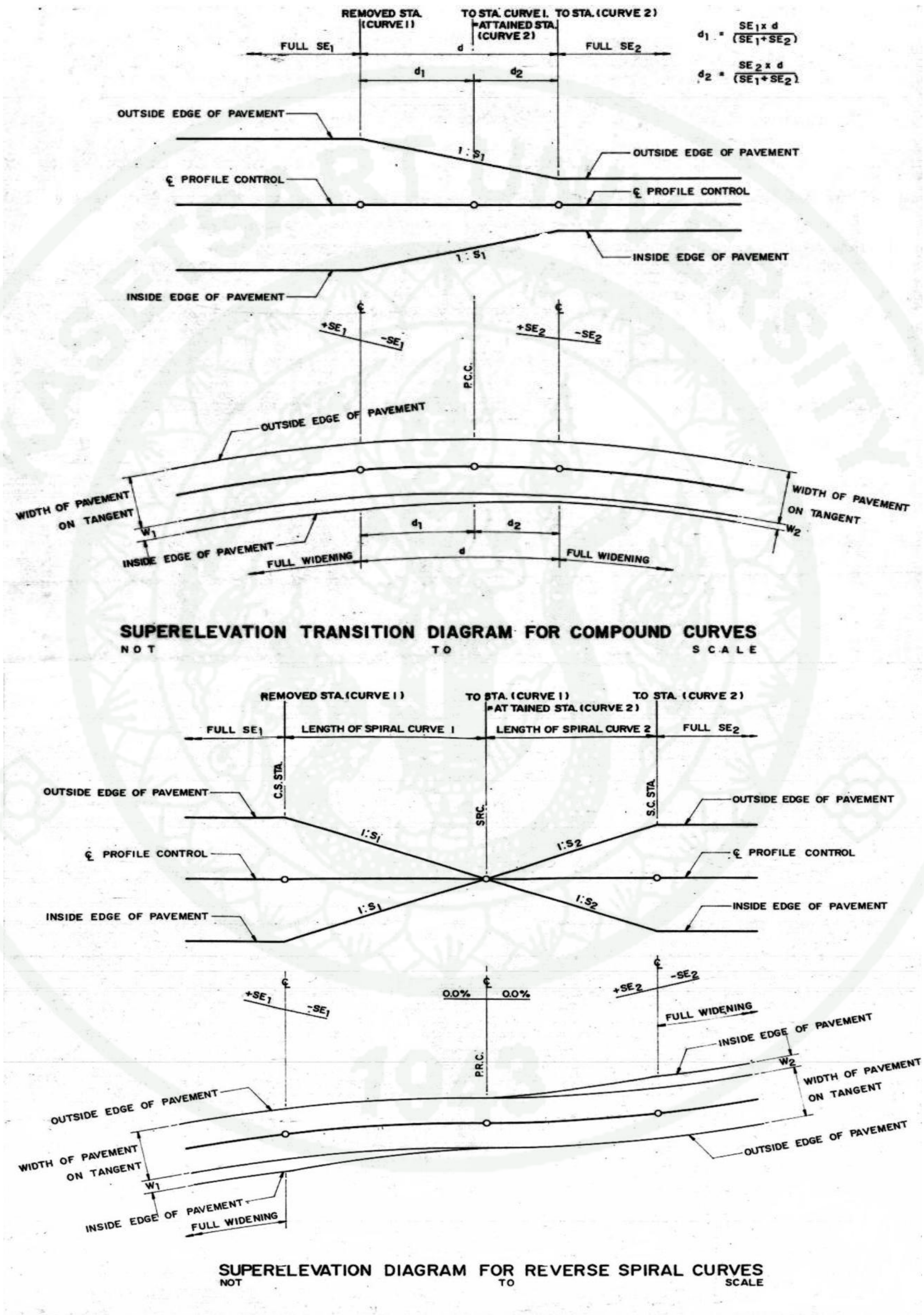

Figure 7 Superelevation Diagrams for Compound and Spiral Curves

Source: DOH, Thailand (1994)

Bonneson *et al.* (2003) predicted that the use of maximum superelevation of 8% allowed for smaller curve radii and the use of a smaller maximum rate tends to yield radii that need significant right-of-way to be constructed and that require the road users to travel considerable extra distance. He also recommended the 8% rate for sharpest curve on the loop ramp. Bonneson *et al.* (2003) also described in the Texas Manual about the recommended radius of curve of design speed for ramps. These values are shown in Table 5.

Table 5 Minimum Radius by Curve Design Speed for Ramps

Curve Design Speed (mph)	Minimum Radius by Curve Design Speed (ft)	
	Maximum Superelevation 6%	Maximum Superelevation 8%
25	185	170
30	275	250
35	380	350
40	510	465
45	660	600
50	835	760
55	1065	965
60	1340	1205
65	1660	1485
70	2050	1820

Source: Bonneson *et al.* (2003)

5. Side friction factor

The side friction factor (f) represents the vehicle need for side friction, also called the side friction demand; it also represents the lateral acceleration, C (where C =f g) that acts on the vehicle. It can also be calculated from the following equation:

$$f = \frac{V^2}{15R} - e \tag{13}$$

where

f = side friction factor, percent;

V = design speed, mph;

R = radius of curve, ft;

e = superelevation rate, percent.

The maximum side friction factor is the point at which the vehicles tend to skip. Therefore, the design value of f is chosen somewhat below this maximum value so that there is a margin of safety.

Furthermore, Moyer *et al.* (1940) concluded that 30 mph speed on curves that avoid driver discomfort resulted in side friction factor of 0.18. But from other test, Barnett (1936) recommended to use the maximum side friction factor of 0.16 for speeds up to 60 mph. AASHTO organized all the recommended values of each personnel and is shown in figure 8.

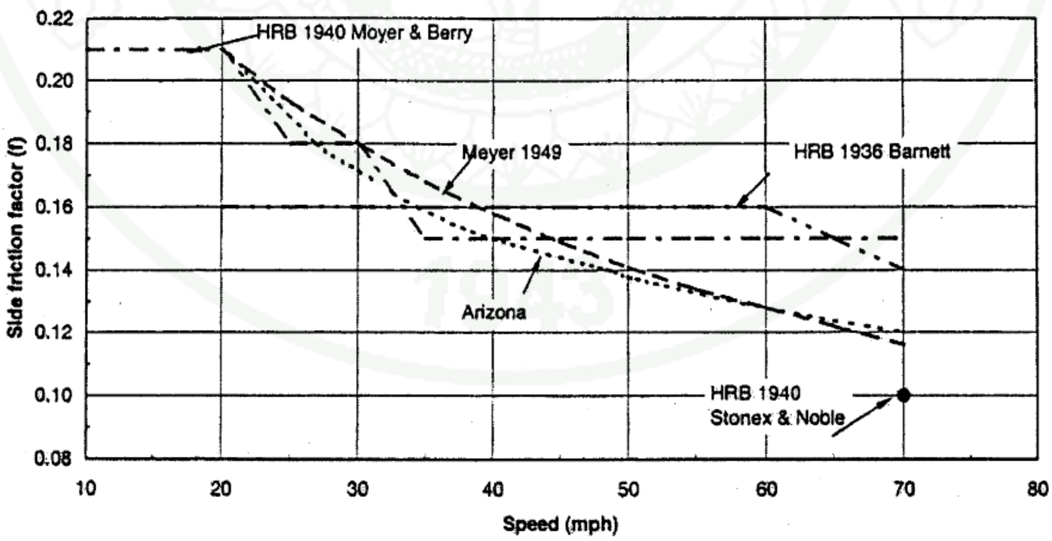

Figure 8 Side Friction Factor for Rural Highways and Urban Streets

Source: AASHTO (2001)

6. Method of widening

The extra width for central widening have been determined, two cases considered here are: (I) when the survey centre line is a spiral and (II) when the survey centre line is a circular cure.

Hickerson (1964) stated that for case I, the inner edge is a modified spiral, and widening takes place only on the inside with perhaps a slight adjustment, by eye, at the SC. However it would be feasible to divide the widening so that half takes place on the inner and half on the outer edge. For case II, the inner edge is a compound circular curve, and widening occurs only on the side. Details are shown in figure 9.

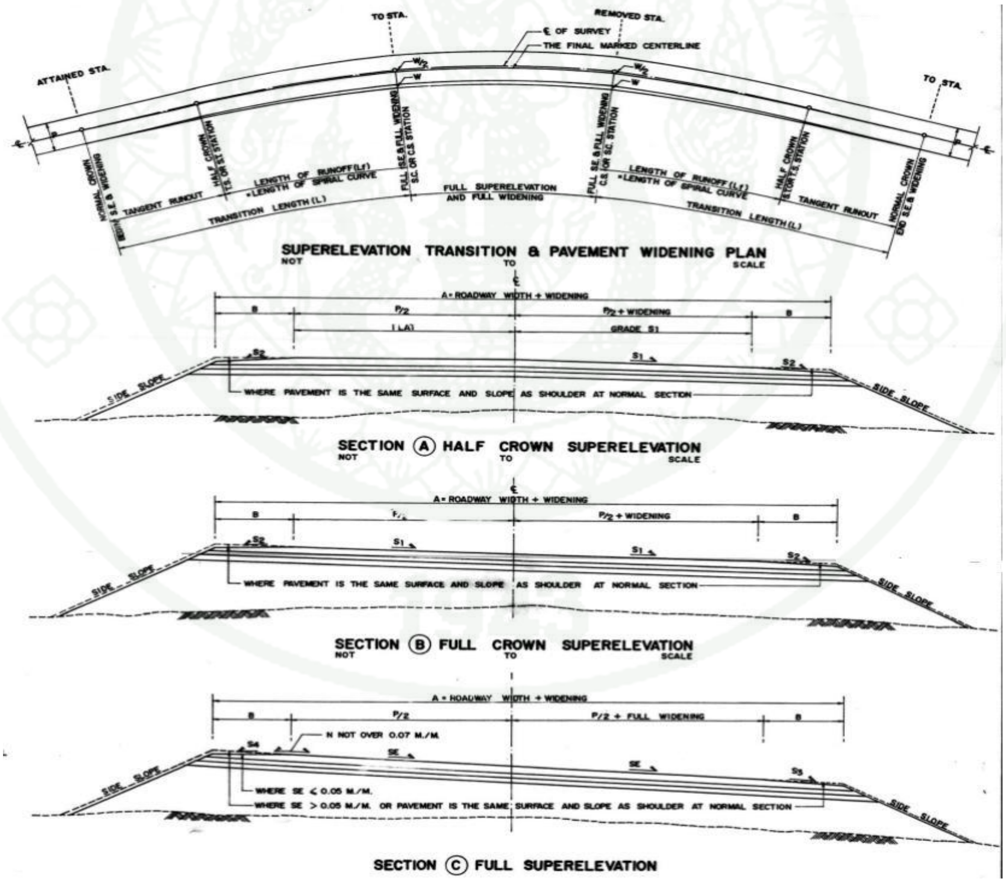

Figure 9 Widening of Pavement for Spiral Curve

Source: DOH, Thailand (1994)

AASHTO (2001) predicted that the amount of widening needed increases with the size of the design vehicle (for single-unit vehicles or vehicles with the same number of trailers or semitrailers) and decreases with increasing radius of curvature. This width elements of the design vehicle used in determining the appropriate roadway widening on curves include the track width of the design vehicles that may meet or pass on the curve, U; the lateral clearance per vehicle, C_l; the width of front overhang of the vehicle occupying the inner lane or lanes, F_A; the width of rear overhang, F_B; and a width allowance for the difficulty of driving on curves, Z.

The track width (U) for a vehicle following a curve or making a turn is the sum of the track width on tangent (u) and the amount of offtracking. The offtracking depends on the radius of the curve or turn, the number and location of articulation points, and the lengths of the wheelbases between axles. For turning roadways, the radius is the path of outer front wheel (AASHTO 1996).

$$U = u + R - \sqrt{R^2 - \sum {l_i}^2} \tag{14}$$

where

U = track width on curve, ft;

u = track width on tangent (out-to-out of tires), ft;

R = radius of curve or turn, ft;

l_i = wheelbase of design vehicle between consecutive axles (or sets of tandem axles) and articulation points, ft.

The width of the front overhang (F_A) is the radial distance between the outer edge of the tire path of the outer front wheel and the path of the outer front edge of the vehicle body. For curves and turning roadways, F_A depends on the radius of the curve, the extent of the front overhang of the design vehicle, and the wheelbase of the unit itself.

$$F_A = \sqrt{R^2 + A(2L_{wb} + A)} - R \tag{15}$$

where

F_A = the width of front overhang of vehicle, ft;

R = radius of curve or turn, ft;

A = front overhang of inner lane vehicle, ft;

L_{wb} = wheelbase of single unit, tractor, ft.

The width of the rear overhang (F_B) is the radial distance between the outer edge of the tire path of the inner rear wheel and the inside edge of the vehicle body.

The extra width allowance (Z) is an additional radial width of pavement to allow for the difficulty of maneuvering on a curve and the variation in driver operation. This additional width is an empirical value that varies with the speed of the traffic and the radius of the curve. The additional width allowance is expressed as:

$$Z = \frac{V}{\sqrt{R}} \qquad (16)$$

where

Z = extra width allowance, ft;

V = design speed of the highway, mph;

R = radius of curve or turn, ft.

The amount of widening of the traveled way on a horizontal curve is the difference between the width needed on the curve and the width used on a tangent.

$$w = W_c - W_n \qquad (17)$$

where

w = widening of traveled way on the curve, ft;

W_c = width of traveled way on curve, ft;

W_n = width of traveled way on tangent, ft.

The traveled way width needed on a curve (W_c) has several components related to operation on curves, including: the track width of each vehicle meeting or passing, U; the lateral clearance for each vehicle, C_l; width of front overhang of the vehicle occupying the inner lane or lanes, F_A; and a width allowance for the difficulty of driving on curves, Z. To determine width, W_c, it is necessary to select the appropriate design vehicle. The design vehicle should usually be a truck because offtracking is much greater for trucks than for passenger cars. The width W_c can be calculated by the equation:

$$W_c = N(U + C_l) + (N - 1)F_A + Z \quad (18)$$

where

W_c = width of traveled way on curve, ft;

N = number of lanes;

U = track width of design vehicle (out-to-out tires), ft;

C_l = lateral clearance, ft;

F_A = width of front overhang of inner-lane vehicle, ft;

Z = extra width allowance, ft.

Design widths of ramp traveled ways for various conditions are shown in Table 6. In table 6, traffic condition A has a small amount of trucks or only an occasional large truck, truck condition B has a moderate volume of trucks (5 to 10 % of the total traffic), and traffic condition C has more and larger trucks.

For the case study, traffic condition A in Table 6 is chosen as design condition. The ramp will be designed to meet the requirements of Case II condition in case of emergency break down of vehicles. The vertical sloping curbs are also considered to use for safety of vehicles.

Table 6 Design Widths of Pavements for Turning Roadways

	Pavement width (ft)								
	Case I			Case II			Case III		
Radius on inner edge of pavement	One-lane, one-way operation─ no provision for passing a stalled vehicle			One-lane, one-way operation─ with provision for passing a stalled vehicle			Two-lane operation─ either one-way or two-way		
	Design traffic conditions								
R (ft)	A	B	C	A	B	C	A	B	C
50	18	18	23	20	26	30	31	36	45
75	16	17	20	19	23	27	29	33	38
100	15	16	18	18	22	25	28	31	35
150	14	15	17	18	21	23	26	29	32
200	13	15	16	17	20	22	26	28	30
300	13	15	15	17	20	22	25	28	29
400	13	15	15	17	19	21	25	27	28
500	12	15	15	17	19	21	25	27	28
Tangent	12	14	14	17	18	20	24	26	26
Width modification regarding edge treatment									
No stabilized shoulder	None			None			None		
Sloping curb	None			None			None		
Vertical curb:									
one side	Add 1 ft			None			Add 1 ft		
two sides	Add 2 ft			Add 1 ft			Add 2 ft		
Stabilized shoulder, one or both sides	Lane width for condition B & C on tangent may be reduced to 12 ft where shoulder is 4 ft or wider			Deduct shoulder width; minimum pavement width as under Case I			Deduct 2 ft where shoulder is 4 ft or wider		
Note:	A= Predominantly P vehicles, but some consideration for SU trucks								
	B= Sufficiently SU vehicles to govern design, but some consideration for semitrailer combination trucks.								
	C= Sufficient bus and combination-trucks to govern the design.								

Source: AASHTO (2001)

7. Behavior of Cloverleaf Interchange

The cloverleaf loop ramp was chosen as a proposed design. Unlike other types, the cloverleaf design needs two level structures only, i.e., it is partially separated structure. The advantage of this facility is all the left turns are handled by the loop ramps and only one bridge (overpass) is needed. As a result, there are less construction costs than the other structures. The examples of loop exit ramp of the highway interchange are shown below in the figures 10 and 11.

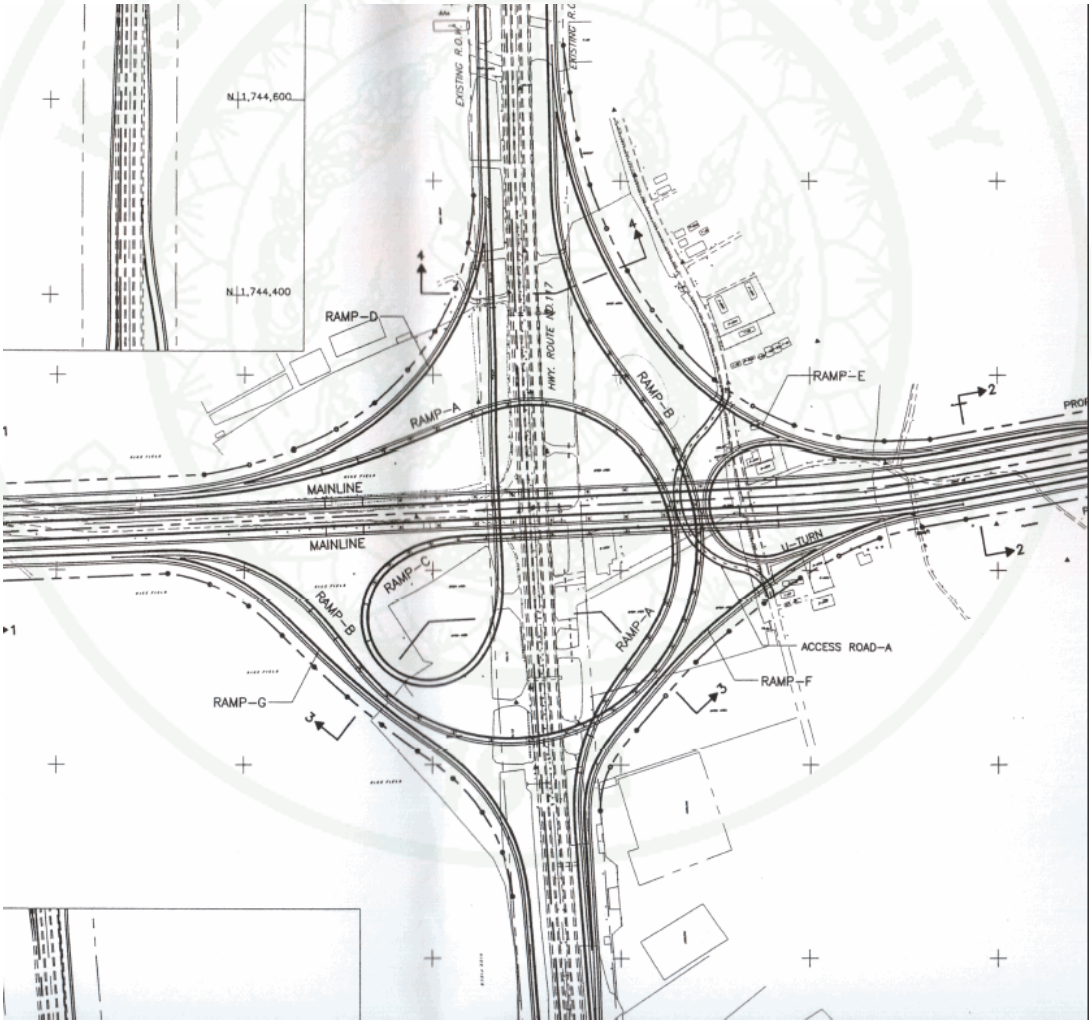

Figure 10 Overview of Highway Interchange

Source: DOH (2008)

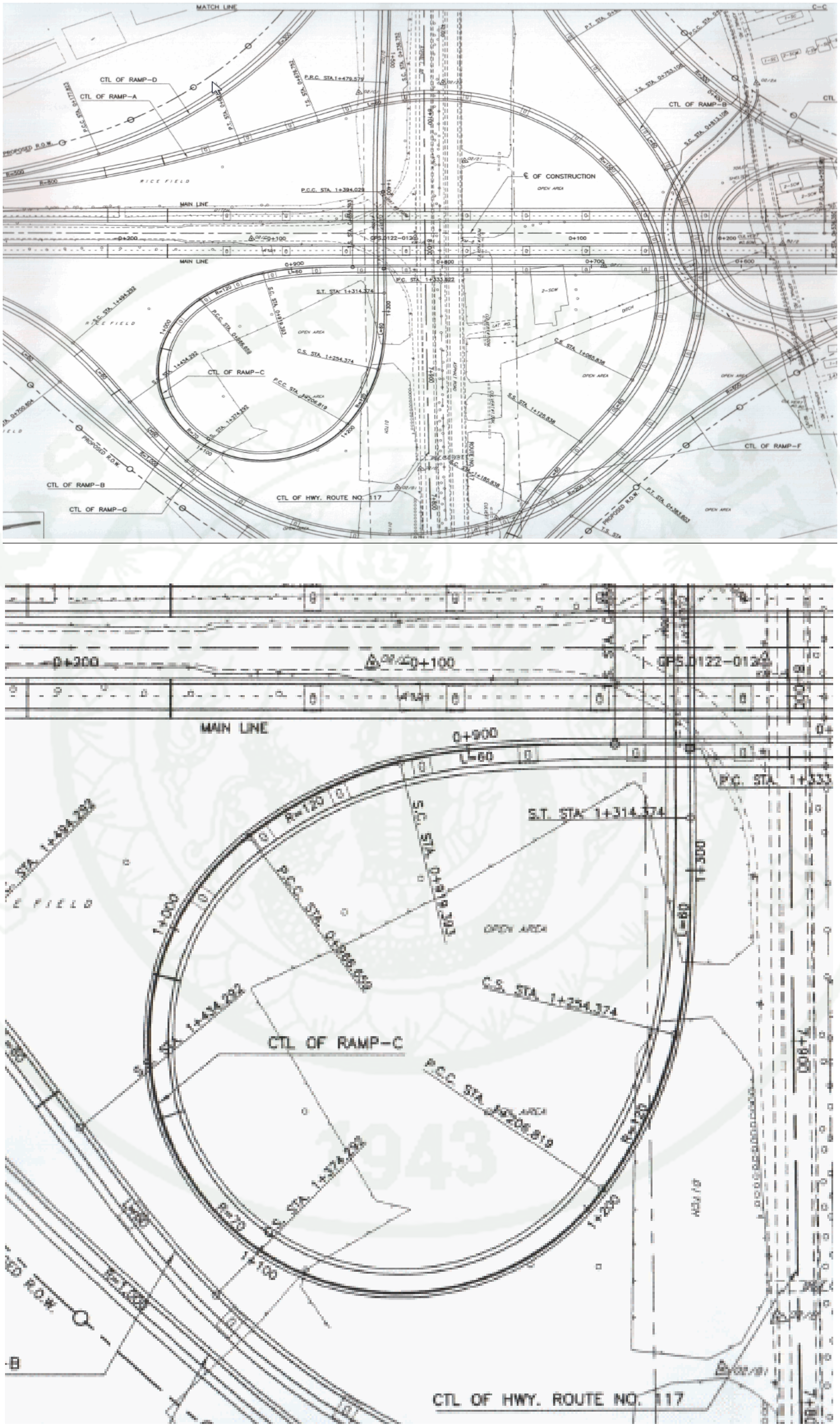

Figure 11 Details of Exit Loop Ramp Portion at Highway Interchange

Source: DOT, Thailand (2008)

MATERIALS AND METHODS

Materials

In this study, the laptop computer with Intel Core 2 Duo 2.53 GHz processor and 4 GB RAM was used to develop and test the developed spreadsheet. Mircosoft Excel 2007 was used in developing the design spreadsheet tool.

Methods

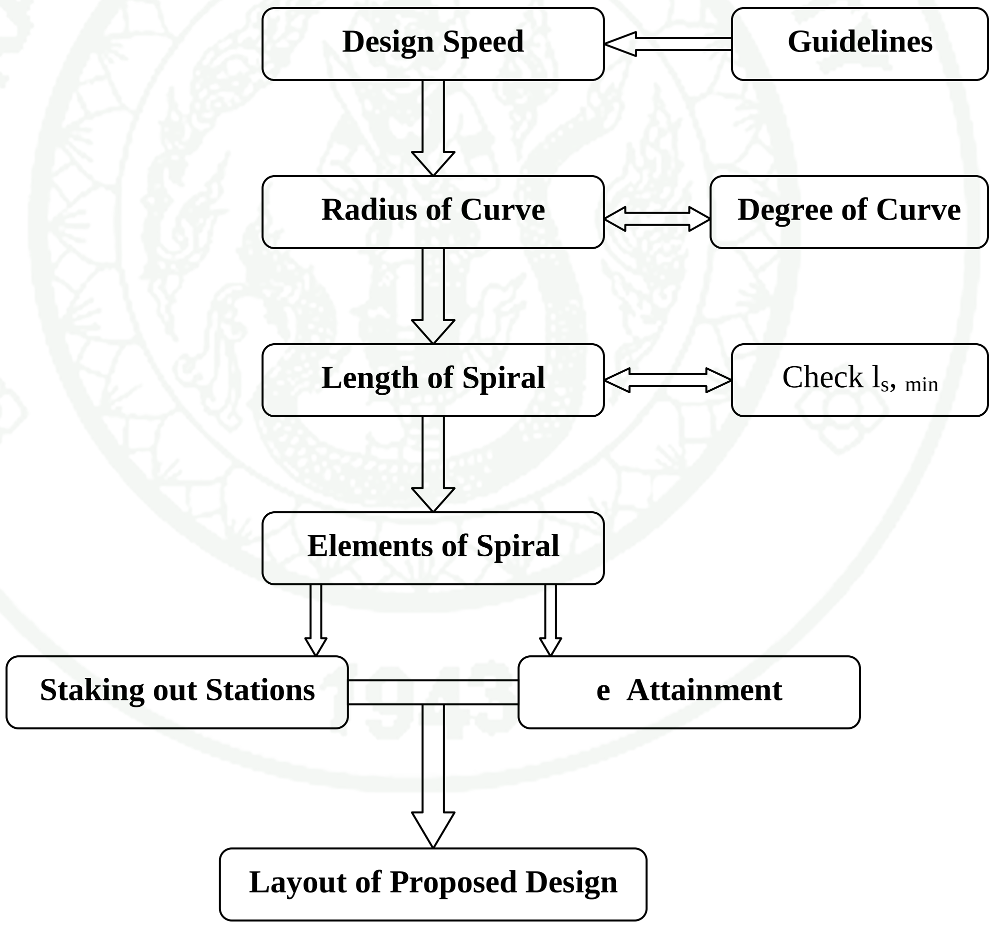

Figure 12 Flowchart Showing the Design Procedure Using Excel

The procedures of proposed design were as follows:

1. First, the design speed for the loop ramp facility was chosen using the recommended guidelines.

2. Then, the recommended values of the degree of curve was calculated using equation (10) and the recommended radius of adjoining circular curve was also calculated using equation (19). From the recommendation values, the design values were chosen.

3. Once the design values of degree of curve and radius of curve were calcuated, the length of spiral was calculated by using relative equations compared with allowable minimum value from the larger value of equation (2) and (3), and maximum value from equation (4) using Excel spreadsheet.

4. Then the total central angle of the curve was chosen and the elements of the spiral were evaluated.

5. After all the elements of the curve have been computed, the location of each chain station is staked out (positioned) using two methods in Excel Spreadsheet. The first method was Rankine deflection method, which is based upon polar coordinate system, and the second method was locating the stations with x and y coordinates, which is based upon rectangular coordinate system.

6. After that, superelevation and widening for the roadway section was calculated and then, the details of loop ramp was drawn by using Excel with reference to x and y cooridnates.

7. Finally, the proposed loop ramp design of Myanmar with recommended practice was achieved.

1. Speed

Ramp design speeds generally (but not always) represent increments rounded to nearest 5 mph increment of 85, 70 or 50 percent of the highway design speed. The design speed of the expressway in Myanmar is 60 mph and therefore, from the calculation compared by (Fitzpatrick *et al.*, 2007) in Table 7, the recommended value of 30 mph is adopted as a loop ramp design speed.

Table 7 Ramp Design Speed between Calculated and Given Value in Texas Manual

Highway Design Speed mph	30	35	40	45	50	55	60	65	70	75	80
Calculated range											
Upper (85%)	26	30	34	38	43	47	51	55	60	64	68
Mid (70%)	21	25	28	32	35	39	42	46	49	53	56
Lower (50%)	15	18	20	23	25	28	30	33	35	38	40
Rounded range											
Upper (85%)	25	30	35	40	45	48	50	55	60	65	70
Mid (70%)	20	25	30	33	35	40	45	45	50	55	60
Lower (50%)	15	18	20	23	25	28	30	30	35	40	45
Difference range											
Upper (85%)	-1	0	1	2	3	1	-1	0	1	1	2
Mid (70%)	-1	1	2	2	0	2	3	-1	1	3	4
Lower (50%)	0	1	0	1	0	1	0	-3	0	3	5

Source: Fitzpatrick *et al*. (2007)

On severely restricted sites, curves may have to be designed from purely geometric considerations, but in the main, design is based on traffic requirements for safety and comfort, possibly modified by aesthetic considerations or site restrictions. In most practical cases, the overall intersection angle is predetermined by the general layout, and the problem finally resolves into determining a suitable radius for the circular arc and length for the spiral, from the traffic viewpoint.

In highway, the sharpness of curvature is commonly expressed in one of two ways: radius and degree of curve according to arc definition.

2. Degree of Curve (Arc Definition)

In the US customary system, D is defined as the angle subtended by a 100 ft arc. The relation between the radius and the degree of curve is shown in the following formula.

$$D = \frac{360 \times 100}{2\pi R} \qquad (19)$$

where

D = Degree of curve, degree;

R = Radius of curve, ft.

From the equation, if one of these values is known, it can be easily converted to another.

3. Length of the curve (L)

As the arc length corresponding to a given radius varies in direct proportion to the central angle subtended by the arc, the length of the arc for any central angle Δ_c can be defined as

$$L = \left(\frac{\Delta_c{}^\circ}{360^\circ}\right) 2\pi R \qquad (20)$$

$$L = 100\,\frac{\Delta_c}{D} \qquad (21)$$

where,

L = length of curve, ft;

R = radius of curve, ft;

Δ_c = central angle of curve, degree;

D = degree of curve, degree.

4. Geometry of the spiral

The relative elements of the spiral can be calculated by the following formulas. The rate of change of curvature of a spiral in degree per station is

$$K = \frac{100D}{l_s} \tag{22}$$

where

K = rate of change of curvature of a spiral per station, degree;

l_s = length of spiral, ft.

The central angle of a spiral is a function of the average degree of curvature of the spiral and is given by

$$\theta_s = \frac{l_s D_c}{200} \tag{23}$$

$$l_s = 2R_c\theta_s \tag{24}$$

$$\theta_s(\text{decimal degrees}) = \frac{180}{\pi} \times \theta_s(\text{radians}) \tag{25}$$

$$X_c = \left(\frac{l_s}{100}\right) \times (100 - 0.0030462(\theta_s)^2) \tag{26}$$

$$Y_c = \left(\frac{l_s}{100}\right) \times (0.58178\theta_s - 0.00001265(\theta_s)^3) \tag{27}$$

$$p = Y_c - R_c \times (1.0 - \cos\theta_s) \tag{28}$$

$$A = \frac{20000 \times \theta_s}{{l_s}^2} \tag{29}$$

$$LC = l_s - 0.00034A^2 \times \left(\frac{l_s}{100}\right)^5 \tag{30}$$

$$LT = X_c - (Y_c \times \cot\theta_s) \tag{31}$$

$$ST_s = \frac{Y_c}{\sin\theta_s} \tag{32}$$

$$E_s = (R_c + p) \times \tan\frac{\Delta}{2} + k \tag{33}$$

$$\Delta_c = \Delta - 2 \times \theta_s \tag{34}$$

$$k = \frac{1}{2} l_s - 0.000127A^2 \times \left(\frac{l_s}{100}\right)^5 \tag{35}$$

$$\theta = \left(\frac{l}{l_s}\right)^2 \theta_s \tag{36}$$

$$\emptyset = \frac{1}{3}\theta - C_s \tag{37}$$

$$\emptyset = \frac{1}{3}\left(\frac{l}{l_s}\right)^2 \theta_s - C_s \tag{38}$$

$$C_s = 0.0031{\theta_s}^3 + 0.0023{\theta_s}^5(10)^{-5} \tag{39}$$

The notations related to the above formulas are as follows:

SCS PI = Point of intersection of main tangents.

TS = Point of change from tangent to spiral curve.

SC = Point of change from spiral curve to circular curve.

CS = Point of change from circular curve to spiral curve.

ST = Point of change from spiral curve to tangent.

LC = Long chord.

LT = Long tangent.

ST_s = Short tangent.

PC = Point of curvature for the adjoining circular curve.

PT = Point of tangency for the adjoining circular curve.

T_s = Tangent distance from TS to SCS PI or ST to SCS PI.

E_s = External distance from the SCS PI to the center of the circular curve.

R_c = Radius of the adjoining circular curve.

D_c = Degree of curve of the adjoining circular curve, based on a 100 foot arc.

D = Degree of curve of the spiral at any point, based on a 100 foot arc

l = Spiral arc from the TS to any point on the spiral ($l = l_s$ at the SC).

l_s = Total length of spiral curve from TS to SC (typically the superelevation runoff length)

L = Length of the adjoining circular curve.

θ_s = Central (or spiral) angle of arc l_s.

Δ = Total central angle of the circular curve from TS to ST.

Δ_c = Central angle of circular curve of length L extending from SC to CS.

p = Offset from the initial tangent.

k = Abscissa of the distance between the shifted PC and TS.

Y_c = Tangent offset at the SC.

X_c = Tangent distance at the SC.

x and y = Coordinates of any point on the spiral from the TS.

A = Clothoid parameter (flatness of the spiral).

C_s = Correction for deflection angle, degree.

5. Superelevation

To obtain the most pleasing and functional results, each superelevation transition section should be considered indiviually. In practice, any pavement reference line used for the axis of rotation may be best suited for the problem at hand. The method of applying superelevation for the proposed design is illustrated in figure 11.

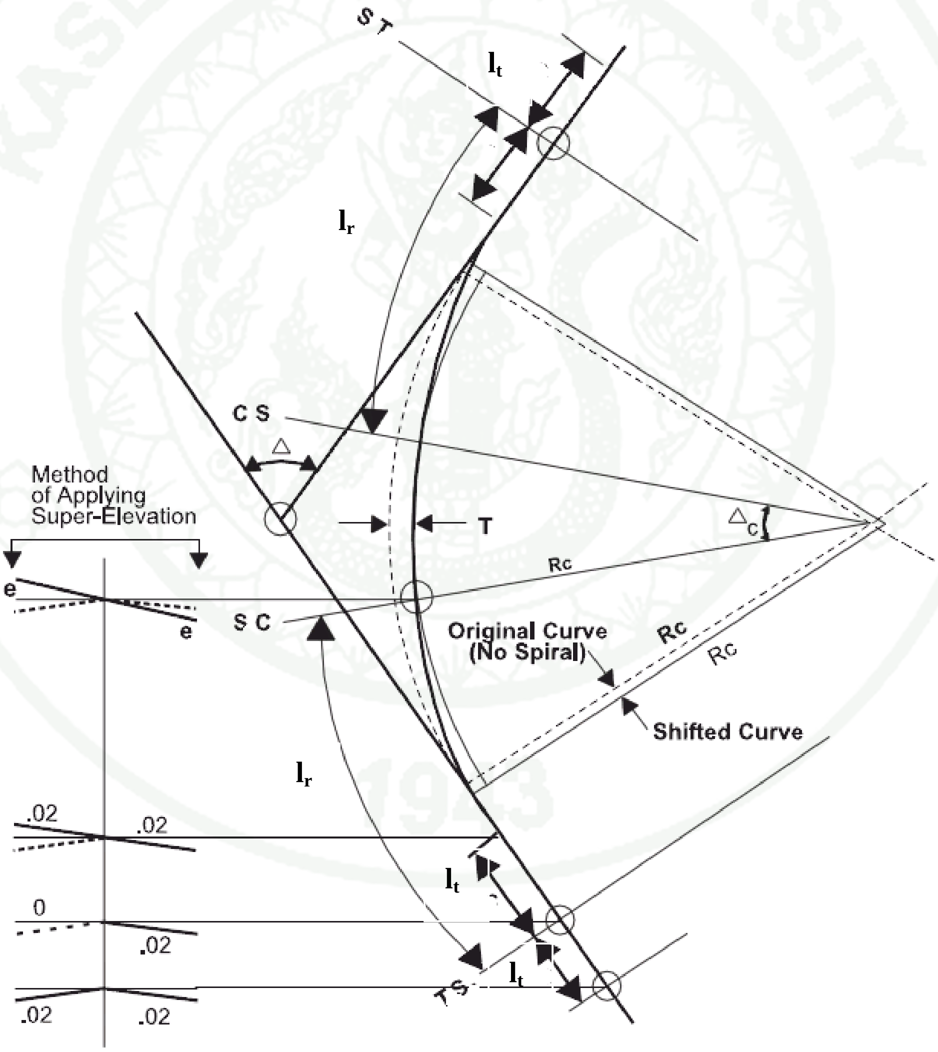

Figure 13 Location of l_r and l_t on a Shifted Circular Curve with Spiral Transitions

Source: WYDOT (2001)

Length of tangent runout, l_t is applied prior to reaching the spiral and ends at the TS (tangent to spiral). Length of superelevation runoff, l_r starts at the TS and ends at the SC (spiral to curve). On the other side of the curve, l_r starts at the CS (curve to spiral) and ends at the ST (spiral to tangent). Then, l_t begins at the ST and extends beyond the spiral.

6. Staking out Process

A common method of locating a curve in the field uses deflection angles (Rankine's method of deflection) which is the method of using theodolite and the tape. In this method, the theodolite is set up at a point ,say SC, and then each station is staked out by using cumulated deflection angles and chord lengths. It is now popular with the total station to position the curve using polar coordinates. In this study, method of deflection and x-y coordinate system are used for staking out curve which is intended to be used without the need of total station.

7. Proposed Design of Case Study

In the case study of figure 14 shown in the next page, the main road is the expressway, which connects the two major cities: Yangon and Mandalay. The crossing road is the access route to Highway route number 1, which is part of Asian Highway route 1 (AH1).

At the case study site, the main problem of this facility was the diverging exit lane. The angle between the exit lane and the access road was nearly 90 degrees. In order to make a turn to the access road, the diverging traffic had to wait at the junction point. With the volume of traffic increasing over these years, this conflict increased the travel time of road users and decreased the level of service of the facility. The existing traffic pattern can be seen in figure 14.

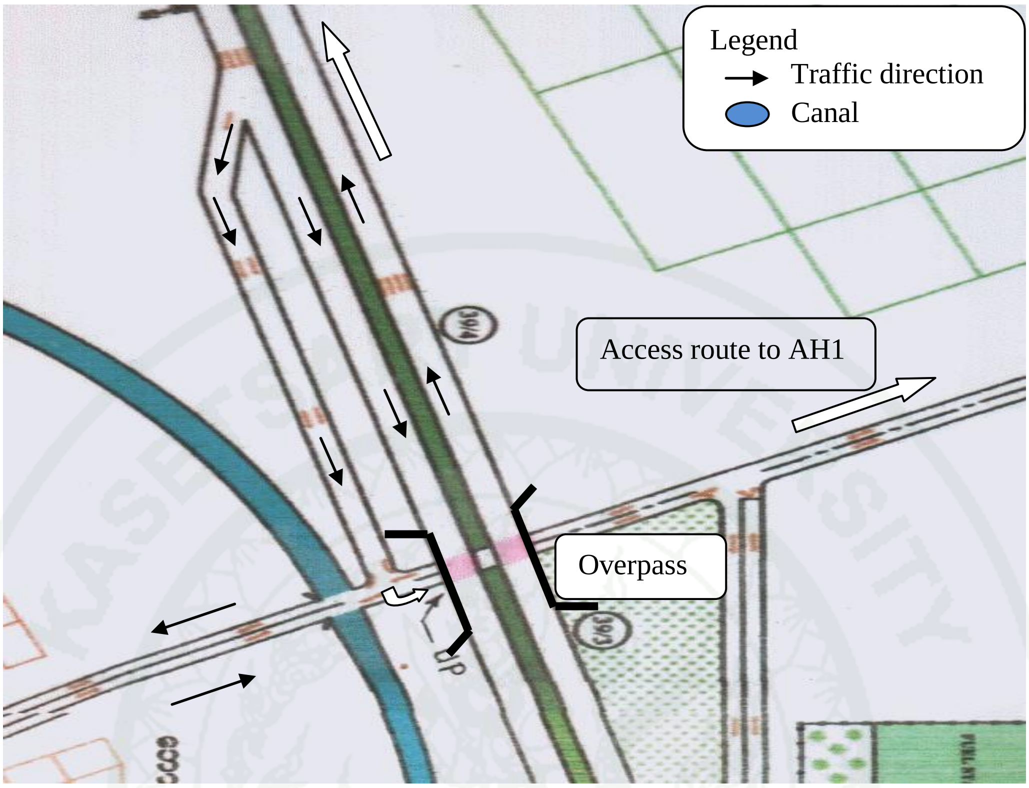

Figure 14 Existing Traffic Pattern of Overpass

Source: PWD (2009)

This problem was minimized by proposing to use a partial cloverleaf loop ramp which is not a high type facility. In the proposed facility, the traffic that diverged from the expressway did not need to wait at the conflict point as in the existing facility. Instead, the traffic could move along the loop structure with nearly constant speed and then easily converged to the access route. This new desgin improved the conditions of the existing facility. The old exit lane is intended for use as a local road and is also retained for emergency cases. The new traffic design pattern with the proposed loop ramp is shown in figure 15. The cross section of the proposed loop ramp is also shown in figure 16.

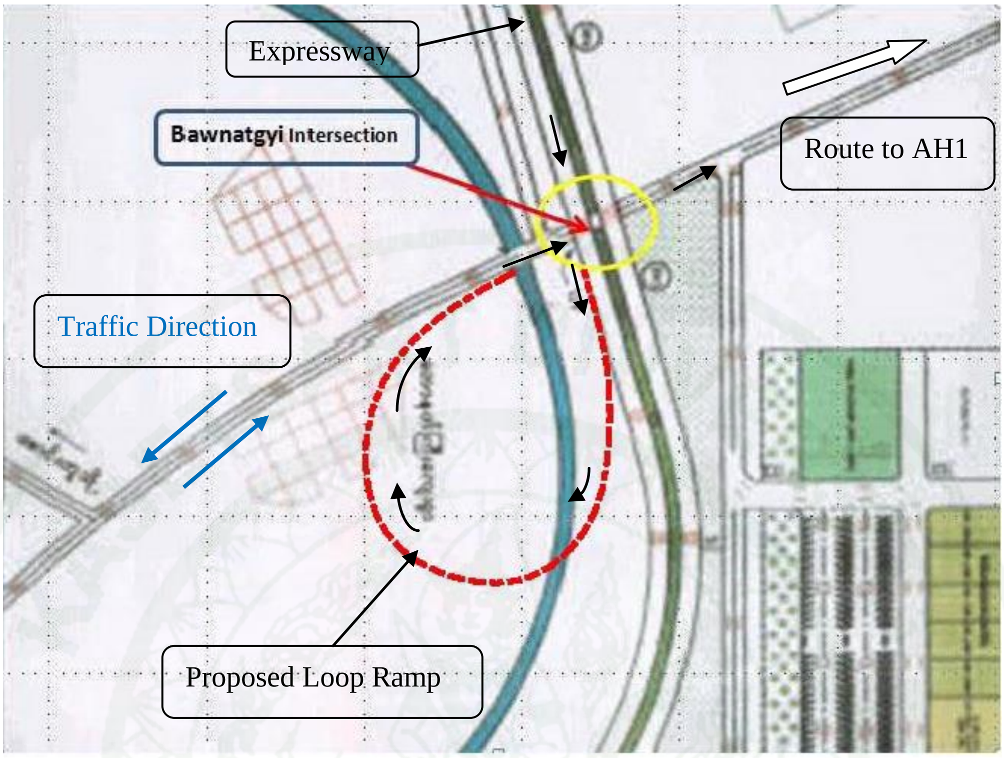

Figure 15 The Proposed Traffic Pattern

Source: PWD (2009)

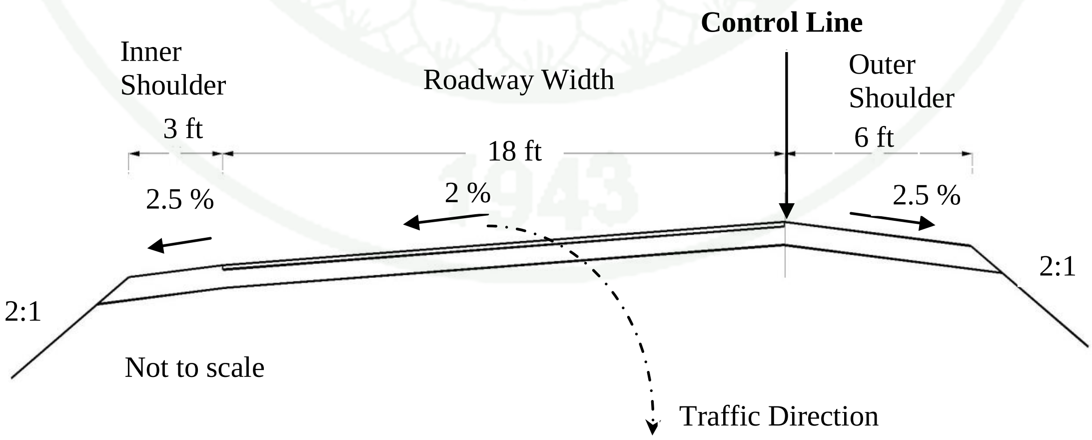

Figure 16 Cross Section of the Proposed Loop Ramp

RESULTS AND DISCUSSION

In this study, Microsoft Excel 2007 spreadsheet was chosen as a tool to develop the horizontal alignment design. The related equations for the elements of circular curve, compound curve and spiral curve were already input by using functions and formulas in associated cells. The corresponding equations were taken from "The Design Manual of Iowa State Department of Transportation" and "Route Location and Design, fifth edition," written by Hickerson (1964). In the following spreadsheet design tool, the data of existing roadway of the intersection in Myanmar was used as input design values and the outcomes were calculated.

Design Values and Assumptions

Many assumptions and their corresponding default values were used in this research spreadsheet for ease of calculation. In this spreadsheet design, it was assumed that when spiral is applied to circular curve, the central portion was shifted related to its original position. In order to use the spreadsheet, the user should have some knowledge in the horizontal alignment design requirements and understanding of the basic Excel spreadsheet usage.

Table 8 Horizontal Geometric Design Values of Proposed Ramp

Item	Design (Chosen) Value	Reference	Values recommended by reference
Design Speed of loop ramp (mph)	30	AASHTO (2001)	30
Superelevation	0.08	Bonneson *et al.* (2003)	0.08
Side friction factor	0.15	Barnett (1936)	0.16

Development of Input and Output Spreadsheets

In order to compile the data quickly, the data for most requirement of the curve needed to be input was implemented with a layout that was simple and easily readable. The main input table of the spreadsheet is shown in figure 17. The input requirement display shown in figure 17 would be the calculation of compound curve using spiral transition if "c" is chosen: i.e., compound circular curve is to be used as design preference. The user could choose between "s" and "c" for the design between the simple or compound curve types to be connected with the spiral, which is for the future development.

Calculation of Transition Spiral		
Input Data		
Type of circular curve (Simple=s or Compound=c)	s	
Operating Speed	30	mph
Superelevation	0.08	ft/ft
Side friction factor	0.15	
Max Degree of curve recommended	21.89089	degree
Min Radius of curve recommended	261.74	ft
Degree of adjoining circular curve, D1 (choose)	21.8	degree
Radius of adjoining circular curve, R_1	262.9	ft

Figure 17 Input Spreadsheet Showing Calculations with Circular Curve and Spiral Transitions

From now on, the figures shown in this study would be based on simple circular with transition spiral design to fulfill the requirement of the junction design. In figure 17, the dark gray coloured cells represented values needed to be defined by user and light gray colored cells were calculated outcomes.

The resulted design values from table 8 were used in figure 17 as input values for the spreadsheet tool. The maximum degree of curve recommended by the spreadsheet was 21.8909. The design value was chosen as 21.8 because the smaller the degree of curve, the larger the radius of adjoining circular curve which in turn promoted improvement in operating speed and safety. Both in figures 17 and 18, the blank lines between data input were programmed for future compound curve inputs.

The relative values required for the junction desgin is shown in figure 18. The stations of TS, SC, CS, ST and PI were computed once the values of l_s and deflection angles were input.

Point of Intersection (PI) (if known)	00+00.00	ft
Point of change from tangent to spiral (TS) (If known)	00+00.00	ft
Horizontal Chain Interval (multiple of)	50	ft
Point of Intersection(PI) (resulted)	-00+56.14	ft
Point of change from tangent to spiral (TS) (resulted)	00+00.00	ft
Point of change from spiral to curve (SC_1)	04+60.00	ft
Point of change from curve to spiral (CS)	12+52.29	ft
Point of change from spiral to tangent (ST)	17+12.29	ft
Length of spiral (l_s)	460	ft
Deflection angle of curve	273	degree
Deflection Angle	273	degree

Figure 18 Input Spreadsheet of Circular Curve Elements

In figure 19, the design elements of the corresponding curves were calculated using the input data. Here, the negative values resulted at PI shown that the SCS PI was on the opposite side in contrast to the values found in open highways. This was the difference found in designing a loop ramp which was different from normal practice of open highways.

Tangent distance from TS to SCS PI or ST to SCS PI (T_s)	-56.14	ft
External dist. from the PI to the circular curve center (E_s)	-670.05	ft
Length of adjoining circular curve (L)	729.29	ft
Central (or spiral) angle of arc l_s (θ_s)	50.14	degree
Total central angle of the circular curve (Δ_c)	172.72	degree
Long chord of spiral(LC_s)	444.30	ft
Long Tangent of spiral (LT)	318.87	ft
Short Tangent of spiral (ST_s)	165.24	ft
Offset from the initial tangent (p)	32.44	ft
Abscissa of the distance between shifted PC and TS(k)	224.13	ft
Tangent offset at SC (Y_c)	126.84	ft
Tangent distance at SC (X_c)	424.77	ft

Figure 19 Output Spreadsheet of Elements of the Curve

For convenience in calculation, this spreadsheet was designed to handle a total of 114 stations for the entire design curve. The cells of extra stations not used in design were marked as “N/A” for clear understanding of the user. These commands were written by using nested IF statements together with other mathematical and logical functions in Excel to get the smooth outcome of the design. Figure 20 shows a sample of writing the nested IF statements to get the flexibility of the station data.

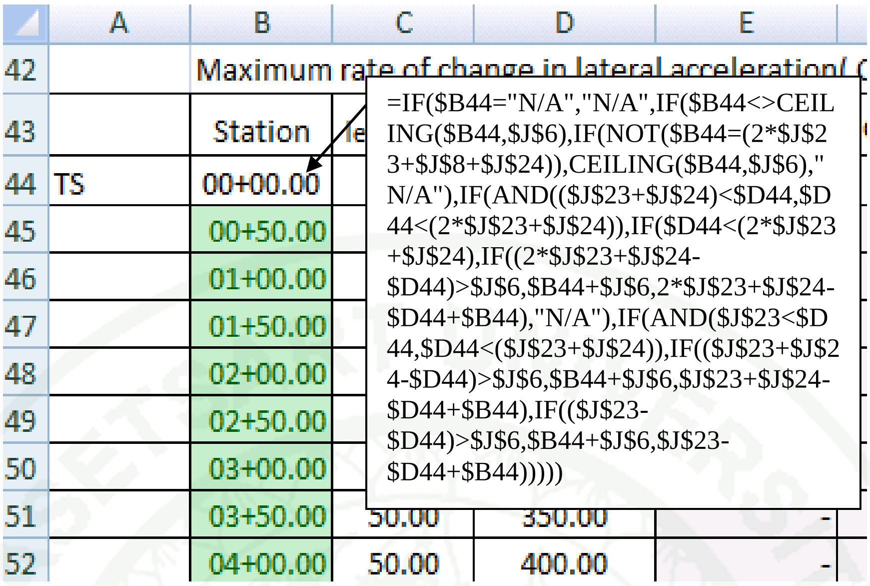

Figure 20 Sample of Using Nested IF Statements for Station Layout

Staking out Process

Table 9 is the calculated output of the spreadsheet that shows how each chain position of the spiral portion from TS to SC was positioned using Rankine's method of deflection. Also the values of stations from SC to CS and stations from CS to ST were calculated in the similar manner in the spreadsheet.

Table 9 Output Spreadsheet of "Tangent to Spiral (TS)" to "Spiral to Tangent (ST)"

	Station	Individ length	Cum length	Individ θ	Cum θ (degree)	φ (degree)
TS	**00+00.00**	0.00	**0.00**		**0.00000**	0
	00+50.00	50.00	**50.00**	-	**0.59239**	0.1974638
	01+00.00	50.00	**100.00**	-	**2.36957**	0.7898551
	01+50.00	50.00	**150.00**	-	**5.33152**	1.7771739
	02+00.00	50.00	**200.00**	-	**9.47826**	3.1594203
	02+50.00	50.00	**250.00**	-	**14.80978**	4.9365942

Table 9 (Continued)

	Station	Individ length	**Cum length**	Individ θ	**Cum θ**	φ
	03+00.00	50.00	**300.00**	-	**21.32609**	6.9981254
	03+50.00	50.00	**350.00**	-	**29.02717**	9.5651544
	04+00.00	50.00	**400.00**	-	**37.91304**	12.527111
	04+50.00	50.00	**450.00**	-	**47.98370**	15.883995
SC	**04+60.00**	10.00	**460.00**	-	**50.14000**	16.602763
	05+00.00	40.00	**500.00**	8.720000	**8.72000**	4.36
	05+50.00	50.00	**550.00**	10.900000	**19.62000**	9.81
	06+00.00	50.00	**600.00**	10.900000	**30.52000**	15.26
	06+50.00	50.00	**650.00**	10.900000	**41.42000**	20.71
	07+00.00	50.00	**700.00**	10.900000	**52.32000**	26.16
	07+50.00	50.00	**750.00**	10.900000	**63.22000**	31.61
	08+00.00	50.00	**800.00**	10.900000	**74.12000**	37.06
	08+50.00	50.00	**850.00**	10.900000	**85.02000**	42.51
	09+00.00	50.00	**900.00**	10.900000	**95.92000**	47.96
	09+50.00	50.00	**950.00**	10.900000	**106.82000**	53.41
	10+00.00	50.00	**1000.00**	10.900000	**117.72000**	58.86
	10+50.00	50.00	**1050.00**	10.900000	**128.62000**	64.31
	11+00.00	50.00	**1100.00**	10.900000	**139.52000**	69.76
	11+50.00	50.00	**1150.00**	10.900000	**150.42000**	75.21
	12+00.00	50.00	**1200.00**	10.900000	**161.32000**	80.66
	12+50.00	50.00	**1250.00**	10.900000	**172.22000**	86.11
CS	**12+52.29**	2.29	**1252.29**	0.500000	**172.72000**	86.35961
	13+00.00	47.71	**1300.00**	-	**0.53937**	5.0205997
	13+50.00	50.00	**1350.00**	-	**2.26228**	9.8962961
	14+00.00	50.00	**1400.00**	-	**5.16998**	14.377065
	14+50.00	50.00	**1450.00**	-	**9.26245**	18.462906
	15+00.00	50.00	**1500.00**	-	**14.53971**	22.15382

Table 9 (Continued)

	Station	Individ length	Cum length	Individ θ	Cum θ	φ
	15+50.00	50.00	**1550.00**	-	**21.00175**	25.339236
	16+00.00	50.00	**1600.00**	-	**28.64858**	28.240295
	16+50.00	50.00	**1650.00**	-	**37.48018**	30.746426
	17+00.00	50.00	**1700.00**	-	**47.49657**	32.857629
ST	**17+12.29**	12.29	**1712.29**	-	**50.14000**	33.316096
	N/A	N/A	**N/A**	N/A	**N/A**	N/A
	N/A	N/A	**N/A**	N/A	**N/A**	N/A
	N/A	N/A	**N/A**	N/A	**N/A**	N/A

In the following table 10, the positions of the stations are calculated in x and y coordinate values for easy checking and staking out process.

Table 10 Details of Staking out Curve by Using x and y Coordinates

	Station	Cum length	Individ θ	Cum x	Cum y
TS	00+00.00	0.00		0.00	0.00
	00+50.00	50.00	-	50.00	0.17
	01+00.00	100.00	-	99.98	1.38
	01+50.00	150.00	-	149.87	4.65
	02+00.00	200.00	-	199.45	11.01
	02+50.00	250.00	-	248.33	21.44
	03+00.00	300.00	-	295.87	36.85
	03+50.00	350.00	-	341.12	58.03
	04+00.00	400.00	-	382.84	85.51
	04+50.00	450.00	-	419.45	119.47
SC	04+60.00	460.00	-	426	127.02

Table 10 (Continued)

	Station	Cum length	Individ θ	Cum x	Cum y
	05+00.00	500.00	**8.720000**	449.21	159.56
	05+50.00	550.00	**10.900000**	470.87	204.56
	06+00.00	600.00	**10.900000**	483.61	252.84
	06+50.00	650.00	**10.900000**	486.99	302.67
	07+00.00	700.00	**10.900000**	480.90	352.23
	07+50.00	750.00	**10.900000**	465.54	399.76
	08+00.00	800.00	**10.900000**	441.48	443.51
	08+50.00	850.00	**10.900000**	409.57	481.94
	09+00.00	900.00	**10.900000**	370.99	513.62
	09+50.00	950.00	**10.900000**	327.11	537.44
	10+00.00	1000.00	**10.900000**	279.48	552.54
	10+50.00	1050.00	**10.900000**	229.89	558.36
	11+00.00	1100.00	**10.900000**	180.07	554.70
	11+50.00	1150.00	**10.900000**	131.87	541.67
	12+00.00	1200.00	**10.900000**	86.97	519.77
	12+50.00	1250.00	**10.900000**	47.06	498.78
CS	12+52.29	1252.29	**0.500000**	45.38	488.23
	13+00.00	1300.00	-	11.65	454.66
	13+50.00	1350.00	-	-17.38	414.09
	14+00.00	1400.00	-	-40.03	369.64
	14+50.00	1450.00	-	-56.78	322.63
	15+00.00	1500.00	-	-68.34	274.07
	15+50.00	1550.00	-	-75.60	224.69
	16+00.00	1600.00	-	-79.53	174.92
	16+50.00	1650.00	-	-81.14	125.02
	17+00.00	1700.00	-	-81.47	75.09
ST	17+12.29	1712.29	-	-81.48	62.81

Superelevation and Widening Spreadsheet

Figure 21 shows the calculated superelevation and widening positions for the proposed design curve. The tangent runout and superelevation runoff sections obtained here were computed within the spiral length according to AASHTO (2001) guidelines. The maximum relative gradient for the design speed was 0.66% and the multilane adjustment factor "α" was considered as 1.25 due to the standard width of loop for case II which was 18 ft (from Table 6) with vertical curbs including widening of 4 ft. The length of tangent runout calculated was 115 ft.

Super elevation positions	Station	Crown Slope (ft/ft)		Widening w (ft)	Total width from outer to inner edge (ft)	$Cr*(W_n+w)$ Elevation from CL(ft)	
		LT	RT	(RT.)	RT	LT	RT
FC (in)	-01+15.00	0	-0.020	4	18.000	0	-0.360
FC (in)	00+00.00	0	-0.020	4	18.000	0	-0.360
FC (in)	01+15.00	0	-0.020	4	18.000	0	-0.360
FS (in)	04+60.00	0	-0.080	4	18.000	0	-1.440
FS (out)	12+52.29	0	-0.080	4	18.000	0	-1.440
FC (out)	15+97.29	0	-0.020	4	18.000	0	-0.360
FC (out)	17+12.29	0	-0.020	4	18.000	0	-0.360
FC (out)	18+27.29	0	-0.020	4	18.000	0	-0.360

Figure 21 Output Spreadsheet Showing Superelevation and Widening

In figure 21, the superelevation attainment was assumed to be the same as that of the existing roadway to be practical, which was different from the theoretical attainments of superelevation. The control line (CL) of superelevation attainment defined here was the outer edge of the roadway. The outer edge of left side was already in 2 percent grade because it resembled the cross slope grade of the existing expressway. In this design, the widening was introduced by dividing equally to both sides of the pavement with constant value throughout the length of ramp.

Figure 22 shows the final one quadrant loop design of the junction obtained from the calculations. The location of each station was marked with reference to x and y coordinate values to easily stake out the proposed ramp design without the requirement of the Total Station. From the figure, the amount of land needed for the proposed ramp could be clearly checked and adjusted easily according to the requirement if the land acquistion was an important matter in the project.

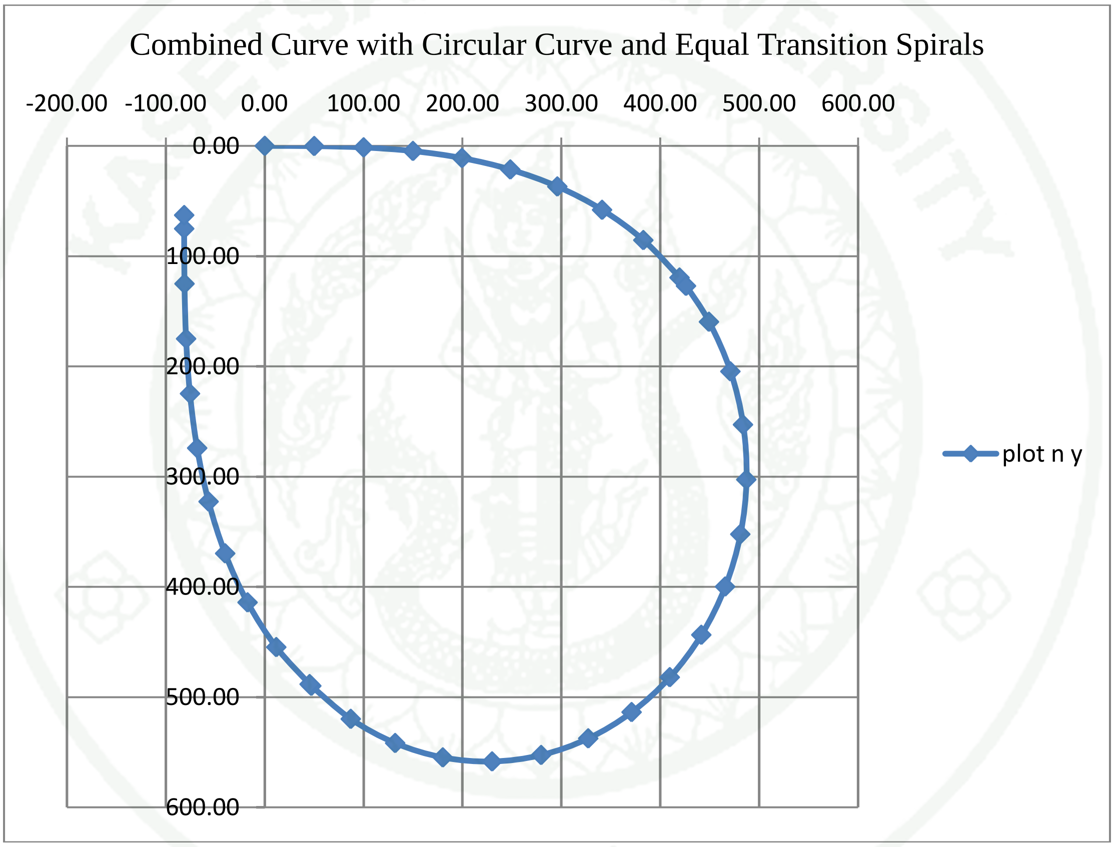

Figure 22 The Proposed Combined Loop Ramp

The detail positions and calculations of stations of figure 22 can be seen in appendix section.

CONCLUSION AND RECOMMENDATIONS

Conclusion

It was obvious that using equal spiral curve together with central circular curve instead of using simple circular curve alone in the proposed highway interchange ramp design not only shortened the circular portion of the curve but also offset the circular curve laterally. Besides, the calculations showed the reduction in the total distance of roadway needed and also minimized the right of way requirement which in turn reduced the total cost of the project and also made least disturbance to the environment. Moreover, the vehicles that traversed the ramp have achieved the required design speed of the facility without encroaching into another lane and thus improving safety of the vehicles. The superelevation transition was applied more gradually than the ordinary circular curves in this design so that there was no jerk between transition points. It also increased the aesthetic appearance of the roadway. As a result, low cost, operational partial clover leaf ramp design with spiral transtions is achieved.

Furthermore, the resulted proposed design and guideline practice for the horizontal loop ramp is shown in the following table.

Table 11 Proposed Guideline for the Horizontal Loop Ramp

Elements	**Suggested Value**	**Reference**
Ramp design speed (mph)	30	Fitzpatrick *et al*. (2007) Texas Design Manual
Superelevation (ft/ft)	0.08	Bonneson *et al*.(2003) Texas Design Manual
Side friction factor	0.15	Barnett (1936)

Table 11 (Continued)

Elements	Suggested Value	Reference
Degree of Curve (degree)	21.8	AASHTO (2001)
Radius of horizontal curvature (ft)	262.9	Bonneson *et al.* (2003)
		Texas Design Manual
Cross slope	2%	AASHTO (2001)
Lane width(ft)	18	AASHTO (2001)

In addition to the proposed design, this study also presented the tool in spiral curve design using Microsoft Excel in determining the tangent to curve transition sections of ramps and open roadways. Since the design spreadsheet tool was developed on Excel platform, it fulfilled the objective requirements of low cost and being user friendly. It was found that by using Excel spreadsheet with the proper input data, the horizontal alignment design of loop ramp was computed more quickly and accurately than the usual calculation procedure. Moreover, the iterative calculations required during design process were done efficiently and effecitvely. Because of the flexibility of the spreadsheet tool, most of the design requirements were analyzed in a short time and resulted in an accurate outcome. Therefore, the required design parameters were checked and revised quickly and the final decision of the design was done within a short time. As a result, despite some limitations, the development of transition spiral design using research tool is a valuable contribution to designers in agencies in developing countries such as Myanmar that make use of things they have for everyday use and also assists future research in enhancing low cost, fully functional design spreadsheet which can be used nationwide.

Recommendations

The procedures developed in this research are applicable to as future practice for design of horizontal loop ramp in Myanmar. If these processes are combined with vertical and cross section design, it will be a complete reference practice to be adopted in Myanmar. The spreadsheet developed in the study focused only on combined curve. To satisfy other useful curves such as compound curve, the spreadsheet should be studied and developed step by step in the future. The values obtained here were only based on horizontal geometric design practice.

In order to get the complete satisfactory design, the horizontal alignment should be unified with the vertical profile and cross section rotation associated with superelevation. This can be accomplished through the use of a cross sectional analysis. Under the aforementioned analysis procedure, the alignment is plotted onto the cross section to the lines and grades dictated by the geometry. The impacts on the existing topography, private property, environmental areas, etc. should be significant for successive cross sections, then modification to the vertical and horizontal geometry should be considered to minimize the impacts, thereby optimizing a balanced geometric design.

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APPENDICES

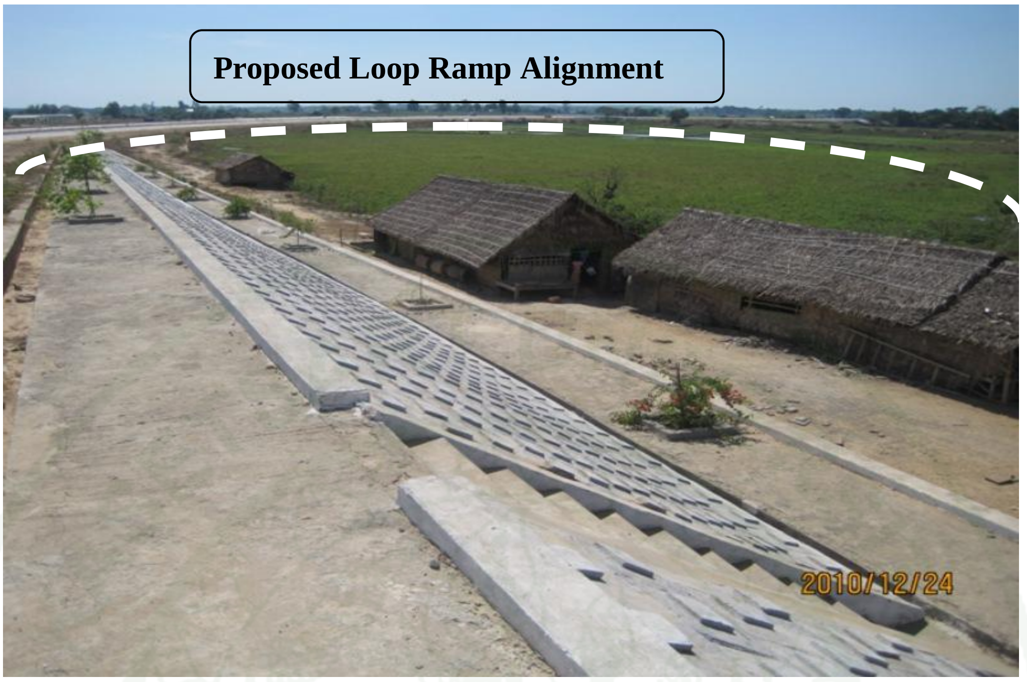
Appendix A

Location of Existing Overpass

Appendix Figure A1 Location of Highway Route Number One and the Expressway

Source: PWD (2009)

Appendix Figure A2 Existing Turning Roadway

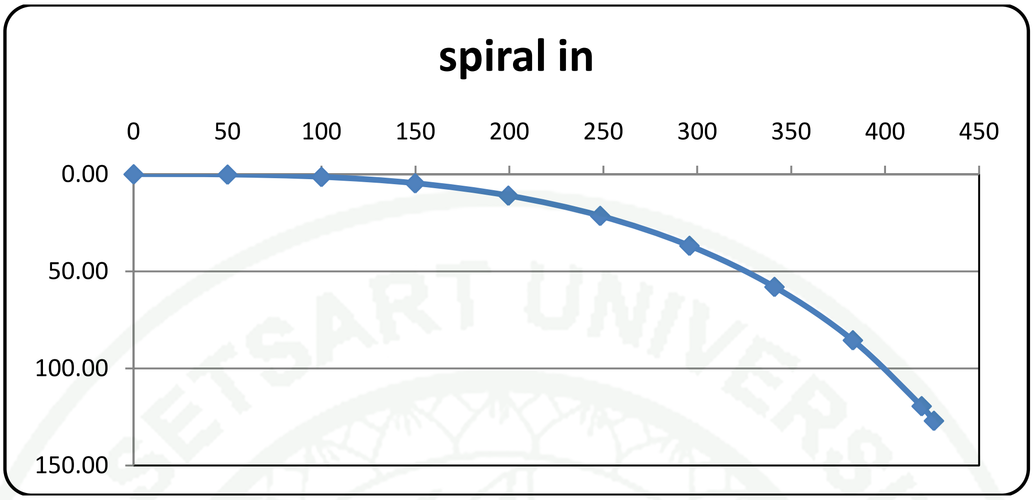


Appendix Figure A3 Location Site of Proposed Loop Ramp

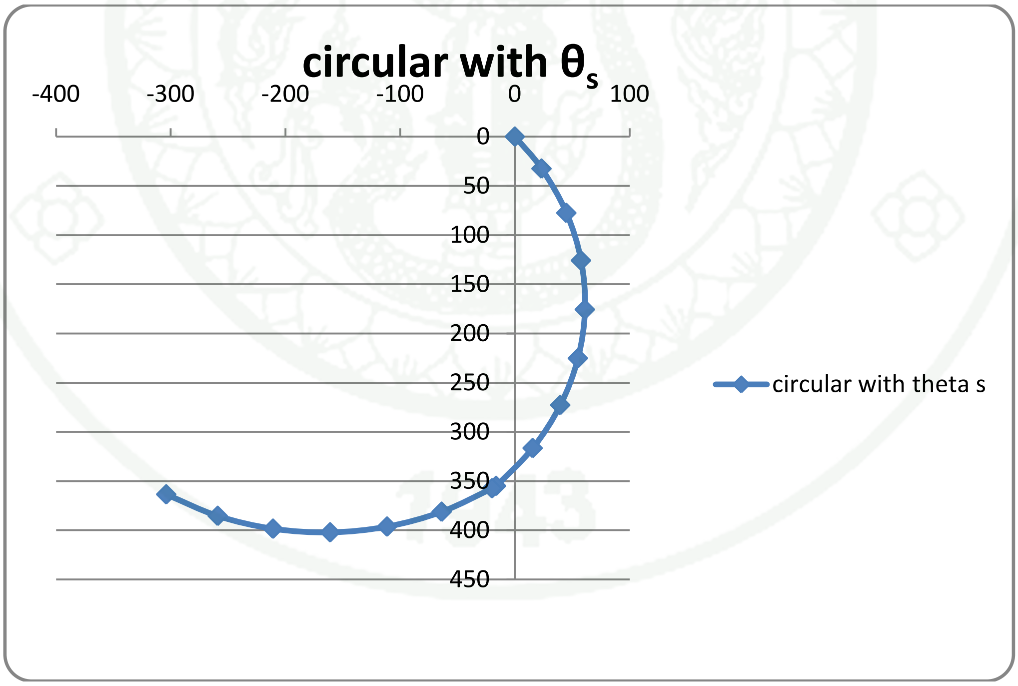
Appendix Figure A4 Existing Access Route

Appendix B

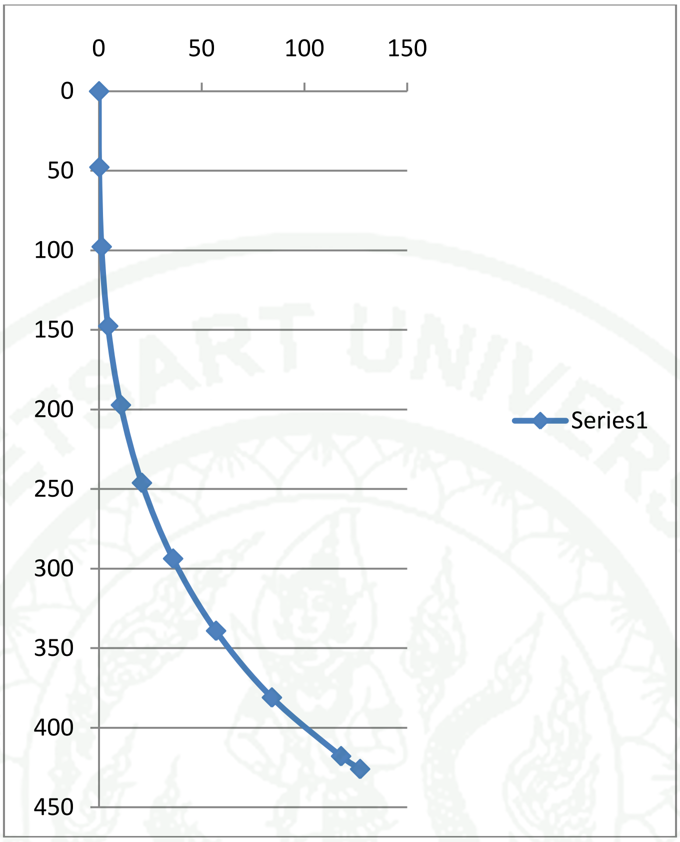
Detail Calculations



Appendix Figure B1 Individual Spiral Portion of “TS to SC”



Appendix Figure B2 Individual Circular Portion of “SC to CS” with θ_s



Appendix Figure B3 Individual Spiral out Portion from CS to ST

Appendix Table B1 Detail Calculations of SC to CS

	Station	Individ length	Cum length	Individ θ	Individ phi	Cum phi	Arc excess	Individ Chord length	Subtended chord ld from SC	length from SC
SC	**04+60.00**	0.00	**0.00**	-	**0.00000**	0.0000	**0**	0	**00.00**	0
	05+00.00	40.00	**40.00**	8.72	**4.36000**	4.3600	**0.04**	39.96	**39.96**	39.97
	05+50.00	50.00	**90.00**	10.90	**5.45000**	9.8100	**0.07544435**	49.92	**89.88**	89.59
	06+00.00	50.00	**140.00**	10.90	**5.45000**	15.2600	**0.07544435**	49.92	**139.8**	138.39
	06+50.00	50.00	**190.00**	10.90	**5.45000**	20.7100	**0.07544435**	49.92	**189.72**	185.94
	07+00.00	50.00	**240.00**	10.90	**5.45000**	26.1600	**0.07544435**	49.92	**239.64**	231.81
	07+50.00	50.00	**290.00**	10.90	**5.45000**	31.6100	**0.07544435**	49.92	**289.56**	275.59
	08+00.00	50.00	**340.00**	10.90	**5.45000**	37.0600	**0.07544435**	49.92	**339.48**	316.87
	08+50.00	50.00	**390.00**	10.90	**5.45000**	42.5100	**0.07544435**	49.92	**389.40**	355.29
	09+00.00	50.00	**440.00**	10.90	**5.45000**	47.9600	**0.07544435**	49.92	**439.32**	390.50
	09+50.00	50.00	**490.00**	10.90	**5.45000**	53.4100	**0.07544435**	49.92	**489.24**	422.18
	10+00.00	50.00	**540.00**	10.90	**5.45000**	58.8600	**0.07544435**	49.92	**539.16**	450.04
	10+50.00	50.00	**590.00**	10.90	**5.45000**	64.3100	**0.07544435**	49.92	**589.08**	473.83
	11+00.00	50.00	**640.00**	10.90	**5.45000**	69.7600	**0.07544435**	49.92	**639.00**	493.33
	11+50.00	50.00	**690.00**	10.90	**5.45000**	75.2100	**0.07544435**	49.92	**688.92**	508.38
	12+00.00	50.00	**740.00**	10.90	**5.45000**	80.6600	**0.07544435**	49.92	**738.84**	518.83
	12+50.00	50.00	**790.00**	10.90	**5.45000**	86.1100	**0.07544435**	49.92	**788.76**	524.59
CS	**12+52.29**	2.29	**792.29**	0.50	**0.24961**	86.3596	**7.2481E-06**	2.29	**791.05**	524.74
	N/A	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A
	N/A	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A
	N/A	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A	**N/A**	N/A

Appendix Table B2 Detail Calculations of TS to ST

	Station	Chord length	individ θ_x	indivd θ_y	x(x)byθ_s	x(y)byθ_s	y(x)byθ_s	y(y)byθ_s	True x	True y
TS	**00+00.00**	-	**0**	0.00	-	-	-	-	**0.00**	0.00
	00+50.00	-	**50.00**	0.17	-	-	-	-	**50.00**	0.17
	01+00.00	-	**99.98**	1.38	-	-	-	-	**99.98**	1.38
	01+50.00	-	**149.87**	4.65	-	-	-	-	**149.87**	4.65
	02+00.00	-	**199.45**	11.01	-	-	-	-	**199.45**	11.01

Appendix Table B2 (Continued)

	Station	Chord length	individ θ_x	individ θ_y	x(x)byθ_s	x(y)byθ_s	y(x)byθ_s	y(y)byθ_s	True x	True y
	02+50.00	-	248.33	21.44	-	-	-	-	248.33	21.44
	03+00.00	-	295.87	36.85	-	-	-	-	295.87	36.85
	03+50.00	-	341.12	58.03	-	-	-	-	341.12	58.03
	04+00.00	-	382.84	85.51	-	-	-	-	382.84	85.51
	04+50.00	-	419.45	119.47	-	-	-	-	419.45	119.47
SC	04+60.00	-	426	127.02	-	-	-	-	426	127.02
	05+00.00	39.97	39.85	3.04	25.54	30.59	2.33	1.95	23.21	32.54
	05+50.00	89.59	88.28	15.26	56.58	67.76	11.71	9.78	44.87	77.54
	06+00.00	138.39	133.51	36.42	85.57	102.48	27.96	23.34	57.61	125.82
	06+50.00	185.94	173.92	65.76	111.47	133.50	50.48	42.15	60.99	175.65
	07+00.00	231.81	208.06	102.20	133.35	159.71	78.45	65.50	54.90	225.21
	07+50.00	275.59	234.70	144.45	150.42	180.16	110.88	92.58	39.54	272.74
	08+00.00	316.87	252.86	190.96	162.06	194.10	146.58	122.39	15.48	316.49
	08+50.00	355.29	261.91	240.08	167.86	201.05	184.29	153.87	-16.43	354.92
	09+00.00	390.5	261.50	244.36	167.60	200.73	222.61	185.87	-55.01	386.60
	09+50.00	422.18	251.66	293.31	161.29	193.18	260.64	217.24	-98.89	410.42
	10+00.00	450.04	232.73	339.54	149.16	178.65	295.68	246.87	-146.52	452.52
	10+50.00	473.83	205.41	381.34	131.65	157.68	327.76	273.66	-196.11	431.34
	11+00.00	493.33	170.67	417.23	109.38	131.01	355.31	296.67	-245.93	427.68
	11+50.00	508.38	129.78	445.89	83.18	99.62	377.31	315.03	-294.13	414.65
	12+00.00	518.83	84.20	466.31	53.96	64.63	392.99	328.12	-339.03	392.75
	12+50.00	524.59	35.59	477.74	22.81	27.32	401.75	335.44	-378.94	362.76
CS	12+52.29	524.74	33.32	478.04	21.36	25.58	401.98	335.65	-380.62	361.21
	13+00.00	-	47.71	0.15	-	-	-	-	33.72	33.57
	13+50.00	-	97.69	1.29	-	-	-	-	62.75	74.14
	14+00.00	-	147.59	4.44	-	-	-	-	85.40	118.59
	14+50.00	-	197.19	10.63	-	-	-	-	102.15	165.60
	15+00.00	-	246.12	20.86	-	-	-	-	113.71	214.16
	15+50.00	-	293.73	36.03	-	-	-	-	120.97	263.54
	16+00.00	-	339.12	56.93	-	-	-	-	124.9	313.31
	16+50.00	-	381.03	84.11	-	-	-	-	126.51	363.21
	17+00.00	-	417.91	117.77	-	-	-	-	126.84	413,14
ST	17+12.29	-	426	172.02	-	-	-	-	126.85	425.42

CURRICULUM VITAE

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