AC 2009-2401: GEOMETRIC DESIGN OF HIGHWAY VERTICAL AND HORIZONTAL CURVES USING EXCEL

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Geometric Design of Highway Vertical and Horizontal Curves
Using Excel

Abstract

This paper presents the work that was developed as a project in the first offering of the transportation engineering class at the new civil engineering program at Indiana University-Purdue University Fort Wayne. The project statement required the use of Excel in developing a program for highway geometric design; from simple curves to compound curves; both vertical and horizontal. In addition, the goal of this project was linked to ABET outcomes that address the ability of students to design a system, component, or process to meet desired needs within realistic constraints and, measure student's ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

The paper presents the process of developing the spreadsheet step-by-step, the command used, challenges, and skills and lessons learned by the author and other student in the class. As a result, a simple and efficient spreadsheet to design vertical curves and simple and compound horizontal curves including default values was developed.

The results of the survey suggested a major improvement of students' skills in Excel in general and in developing engineering design in particular. Major improvements were found in using functions and nested If statements. The least skills acquired were in using the Absolute and Sum commands and graphing in Excel. Most of the students either knew these commands before the class or they were familiar with them. Finally, this project enabled students to advance their knowledge of spreadsheets while learning important transportation engineering topics.

1) Introduction

This paper presents a term project that was assigned in the first offering of the Transportation Engineering class in the new Civil Engineering program at Indiana University-Purdue University Fort Wayne. The Civil Engineering program was approved in the summer of 2006 and students were accepted in the fall of 2006.

The goal of this project as listed in the course syllabus is to design basic horizontal and vertical alignment of the highway using Excel. The goal of this project was linked to two ABET outcomes (c) and (k). Outcome C addresses the ability of students to design a system, component, or process to meet desired needs within realistic constraints and outcome K focus on student ability to use the techniques, skills, and modern engineering tools necessary for engineering practice[1].

A major step in the development of the new Civil Engineering program is receiving ABET's accreditation. Accreditation is critical for the survival of the program both academically and professionally. Part of the processes is to assess the course outcome at the end of the class. The department requires all courses are assessed at the conclusion of each term to guarantee filling all the requirements that ABET as seen necessary to ensure the quality of education.

In order to achieve the goals of this project, a spreadsheet to design vertical and horizontal curves was to be developed. Both vertical and horizontal curves are changes in the alignment of a highway and needed in the layout of a new highway. Spreadsheets are becoming an important tool in organizing, computing, and analyzing data. Since spreadsheets made their appearance, the diversity of applications of spreadsheets is evident by its continual reappearance in scholarly journals[2]. Among the strong features of spreadsheets are their intuitive cell-based structure and the simple interface that is easy to use even for first time users[3]. Using this software in design will provide a simple tool that is easy to use and manipulate. Spreadsheets have been developed so they can be used to analyze multiple solutions for engineering problems efficiently and accurately, and to produce graphs that convey the solution[4]. For this project, Microsoft Excel (*Microsoft 2007*) was used as the tool for design. The reason of using Excel software for the project is because it is readily available in most companies. In order to achieve the goals of the project, the student is required to have a solid understanding of the engineering background of the design and command skill in using Excel.

The project statement required the design to have an input and output table that is simple, flexible, and easy to use. During the design of the project the manipulation of the equations of the curves was vital in keeping the spreadsheet flexible. This task enhanced the knowledge-base of the students about spreadsheets. Not only being able to manipulate the equations but also knowing how to input formulas into Excel made this task challenging. With the flexibility of the spreadsheet, most any curve design can be calculated with the proper input data.

The objective of this research is to present the use of the spreadsheet in highway geometric design with focus on vertical curves and simple and compound horizontal curves. In addition, a casual assessment of computer skills acquired from this project will be presented.

2) Vertical and Horizontal Curves

2.1) Vertical Curves

The vertical alignment of highways is a very important part of design. Each type of vertical curve has its own set of rules for the minimum length of the curve and they are as follows:

1. Sight distance
2. Rider comfort;
3. Drainage control; and,
4. General appearance.

2.2) Horizontal curves

Horizontal curves are usually segments of circles, which have radii that will provide a smooth flow of traffic along the curve[5]. There are three basic types of horizontal curves, simple, compound, and reverse (transition) curves.

The main design equations for the shaping a horizontal curve include but are not limited to equations for the radius, tangents, chords, and relationships of angles and lengths. These equations are as follows:

As in all engineering projects, safety should be of upmost concern. Horizontal curves present a different problem than vertical curves, which is objects can reduce the line of sight of the driver in a vehicle. Therefore, it is imperative that the environment near the curve not impede the sight of the driver of the vehicle. The distance between the road and the line of sight is referred to as the middle ordinate. The middle ordinate can be found by:

3) Spreadsheets as a Design Tool

Spreadsheets are becoming very powerful tools in solving engineering problems. They are also becoming an important tool in practice. The spreadsheet that was chosen to use as a tool to help developing the design is Microsoft Excel 2007.

During the development, some assumptions were made for the ease of calculation. Some default values were also added. The perception reaction time of each individual is different; therefore the AASHTO standard of 2.5 seconds is used. Also, the AASHTO standard of acceleration of 11.2 ft/s^2 was used. These values were used in governing the value of the stopping sight distance (SSD). Velocity is also a vital component in determining the SSD. A value of 55 mph will be used in determining the SSD, unless otherwise stated by the user. If a value is not available to the engineer a minus symbol should be inserted.

3.1) Input table

The layout of the information is a very important aspect of the program. With readability being simple, the data can be quickly gathered. The development of a user input table was a beneficial

way of implementing the engineer's field data. Also, by utilizing a user input table, this allows the engineer to see what information is available for the use of design. This will also help the engineer to see what information needs to be gathered for the design of a curve, acting as a checklist. The input table in the design is show in Figure 1.

INPUT			
Simple Curve enter **1**, Compund Curve enter **2**	CT=	1	
Simple Curve Data			
Multiple of the Stationing (ex. 25, 50, 100)	n =	100	ft
u = Speed [mph]	u =	-	mph
PC = Point of Curvature	PC =	4+65	
Length of Curve 1 (max 68 STA)	L_1 =	183	ft
Radius of First Curve	R_1 =	500	ft
User Deflection Angle	D_1 =	-	degrees
Degree Angle of Simple Curve 1	θ_1 =	34	degrees
Second Curve Data, For Compund Curve			
PCC = Point of Compound Curve	PCC =	6+00	
Length of Curve 2 (max 68 STA)	L_2 =	-	ft
Radius of Second Curve	R_2 =	350	ft
Degree Angle of Simple Curve 2	θ_2 =	26	degrees
User Deflection Angle	D_2 =	-	degrees

Unavailable Data

Figure 1: Horizontal Curve Input Table

The user input table was crucial in developing a flexible program. One of the key elements of the input table is the horizontal curve type (CT) that is to be designed. A user input of one (1) signifies a simple curve while a two (2) signifies a compound curve. If a one (1) is inputted then the program does not calculate the values of a compound curve and a "N/A" is displayed. Also, different length stations can be used in the design of the curve. There can be a maximum of 68 stations for the horizontal curves and 80 stations for vertical curves. If the number of stations is too high, then an error message will appear at the bottom of the sheet.

3.2) Output table

As shown in Figure 2, the design output table was also implemented to efficiently show the results of the output design data. With the data values from the output table gathered together, one can imagine the form of the curve.

Simple Curve Output Data			
Point of Curvature	PC =	4+65	
Radius	$R_1 =$	500.00	ft
Length (max 68 STA)	$L_1 =$	183.00	ft
Tangent Length	$t_1 =$	152.87	ft
External Distance	$E_1 =$	22.85	ft
Middle Ordinate	$M_1 =$	21.85	ft
Degree of Curvature	$\theta_1 =$	34.00	degrees
Deflection Angle	$D_1 =$	11.459	degrees
Angle to determine first full STA	$\delta_{11} =$	6.503	degrees
Angle to determine last STA	$\delta_{12} =$	0.000	degrees

Figure 2: Output Table for Simple Horizontal Curve

3.3) Excel commands used in the design

Using nested If statements were a very important issue in the design of the project. Without taking advantage of nested If statements, the project would have become extremely difficult so, they were used to implement the calculations of the stationing of the curves. A sample of the use of a nested If statement in the design of a compound curve can be found in Figure 3.

	I	J	K	L	M	N
				G12	f_x	
2			For Simple Curve or Curve 1 of Compound Curve			
3			Deflection Angle			
4	Station	Distance from PC [ft]	Decimal Degrees	D° M' S"	Chord Length [ft]	Cumulative Chord Length [ft]
5	4+65	0	0	0° 0' 0"	0.00	0.00
6	5+00	35	3.251	3° 15' 5"	56.72	56.72
7	6+00	135	12.541	12° 32' 28"	161.42	217.14
8	6+48	183	17.000	17° 0' 0"	77.75	292.37

The formula for the stationing using a nested If statement is
=**IF**(I8="","",**IF**(I8=C$27,"",**IF**(I8+$C$11<C$27,I8+$C$11,C$27)))
where C27 is the PT and C11 is the increment of station.

Figure 3: Nested If Statement Used in the Design of Compound Curve

Stations are used to give reference to a point on a project so engineers can communicate with each other effectively. This proved to be extremely difficult so a flowchart exercise was performed to show how the formulas would execute. An example of the difficulty is that the stationing stops at the end of the curve; instead the last station of the design was calculated repeatedly. To fix this problem a nested If statement was employed to omit the repeated final station. Figure 4 shows the flow chart of the stationing.
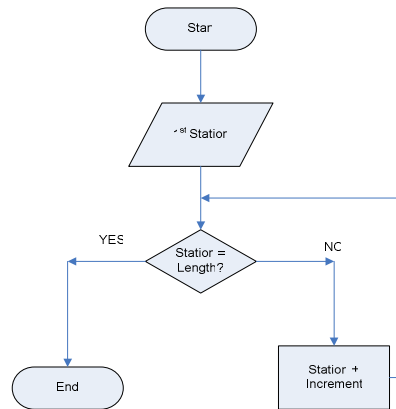

Figure 4: Flow Chart for Stationing

Many other functions were applied in the spreadsheet that helped with the flexibility of the program. For instance, the ceiling command was used to round the first station to the first full station of the increment designated by the user. A sample of the Ceiling command used in the design of compound curve is shown in Figure 5.

Station	Distance from PC [ft]	Deflection Angle Decimal Degrees	D° M' S"	Chord Length [ft]	Cumulative Chord Length [ft]
4+65	0	0	0° 0' 0"	0.00	0.00
5+00	35	3.251	3° 15' 5"	56.72	56.72
6+00	135	12.541	12° 32' 28"	161.42	217.14
6+48	183	17.000	17° 0' 0"	77.75	292.37

The formula of the first full station using the ceiling command.
=IF(**CEILING**(I$6,$C$11)=I$6,$I$6+$C$11,**CEILING**(I$6,$C$11))
where C11 is the increment of stations.

Figure 5: Ceiling Command Used in the Design of Compound Curve

Figure 6 shows a sample of the data charts that were organized to allocated curve design input and output data at each station including chord length, deflection angle, and distance from point of curvature (PC). The other important information was placed below the input table. This information does not change due to variation in position along the curve.

CHART 1					
For Simple Curve or Curve 1 of Compound Curve					
		Deflection Angle			
Station	Distance from PC [FT]	Decimal Degrees	D° M' S"	Chord Length [ft]	Cumulative Chord Length [ft]
4+65	0	0	0° 0' 0"	0.00	0.00
5+00	35	3.251	3° 15' 5"	56.72	56.72
6+00	135	12.541	12° 32' 28"	161.42	217.14
6+48	183	17.000	17° 0' 0"	77.75	292.37

Figure 6: Table of Design Data at Each Station

In the curve charts, the use of an If statement enables the program to leave blank spaces to keep the table neat and clean; by doing so, the table is easier to read. An example of such formula is shown in Figure 7.

Figure 7: Formula to Create Blank Cells

The length of a vertical curve can be calculated by multiplying the algebraic difference (A) to the rate of curvature (K).

$$L = K * A \tag{11}$$

Since the algebraic difference of the grades can be negative, the absolute value function was applied in determining the length as shown in Figure 8.
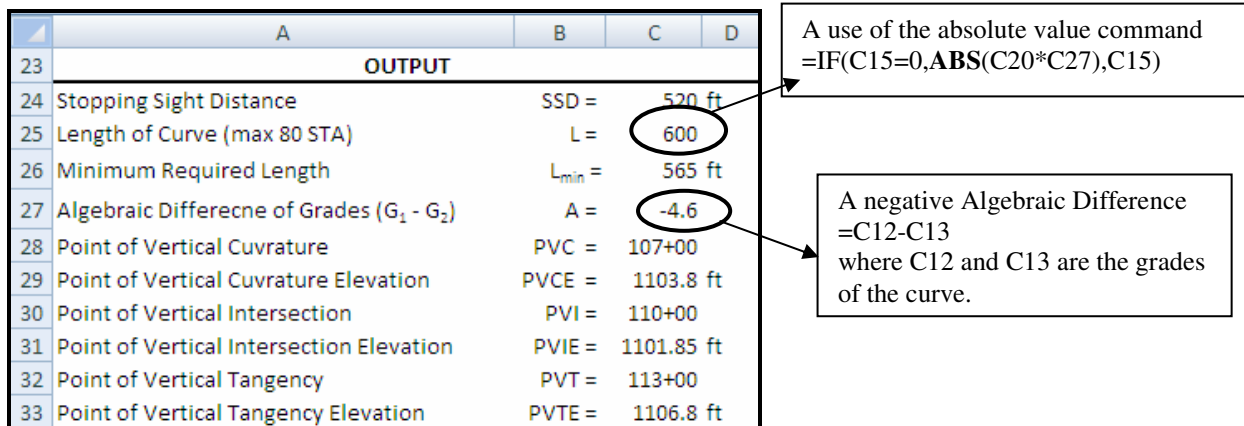
	A	B	C	D
23	OUTPUT			
24	Stopping Sight Distance	SSD =	520 ft	
25	Length of Curve (max 80 STA)	L =	600	
26	Minimum Required Length	L_{min} =	565 ft	
27	Algebraic Differecne of Grades (G_1 - G_2)	A =	-4.6	
28	Point of Vertical Cuvrature	PVC =	107+00	
29	Point of Vertical Cuvrature Elevation	PVCE =	1103.8 ft	
30	Point of Vertical Intersection	PVI =	110+00	
31	Point of Vertical Intersection Elevation	PVIE =	1101.85 ft	
32	Point of Vertical Tangency	PVT =	113+00	
33	Point of Vertical Tangency Elevation	PVTE =	1106.8 ft	

A use of the absolute value command =IF(C15=0,**ABS**(C20*C27),C15)

A negative Algebraic Difference =C12-C13 where C12 and C13 are the grades of the curve.

Figure 8: Absolute Value and Algebraic Difference

The difficulty of giving all the measurements of the desired curve is that there is no set information that will always be available. Sometimes one might be given length, radius, and degree of curvature while other times one might receive tangent length, PC, and PT. Trying to make the program flexible enough to be able to accommodate such diversity was a challenge. Manipulating the formulas for the curve, without creating circular references, was another project in itself. The equations associated with vertical curves were straightforward because there was an assumption that the curves did not have a change in grade. Any freeway with multiple grades is considered to be segments that need to be analyzed individually[5].

4) **Casual Assessment of Spreadsheet Skills**

There were only 4 students in the class including the author. Therefore, a statistically reliable data could not be achieved. However, in the order to learn the process of conducting a survey, it was decided to conduct a casual assessment to evaluate the students' knowledge of Excel before and after the project. A simple survey was designed and students were requested by the author to volunteer to fill out the survey. All students agreed to fill out the survey and the results of the survey are based on 4 surveys including the author. There were twelve (12) questions in the survey about the skills or command used in the project. Students were asked to evaluate their skills of these commands on a sale from 0 to 4; where 0 being poor and 4 being excellent. The author entered the input results in a spreadsheet, found the average, and graphed the results.

As shown in Figure 8, students improved their skills in Excel commands significantly. A major improvement was found in using functions and nested If statement. The least skills acquired

were in using the Absolute and Sum commands and graphing in Excel. Most of the students either knew these commands before the class or they were familiar with them.

There was a good improvement in the use of Excel in general; however, a major improvement was in using Excel in design. Most of the students were using Excel in generating tables and graphs. However, this project was the first experience for students to using exclusively for a design project. The most benefit from the project is being familiar with the new version of Excel 2007.
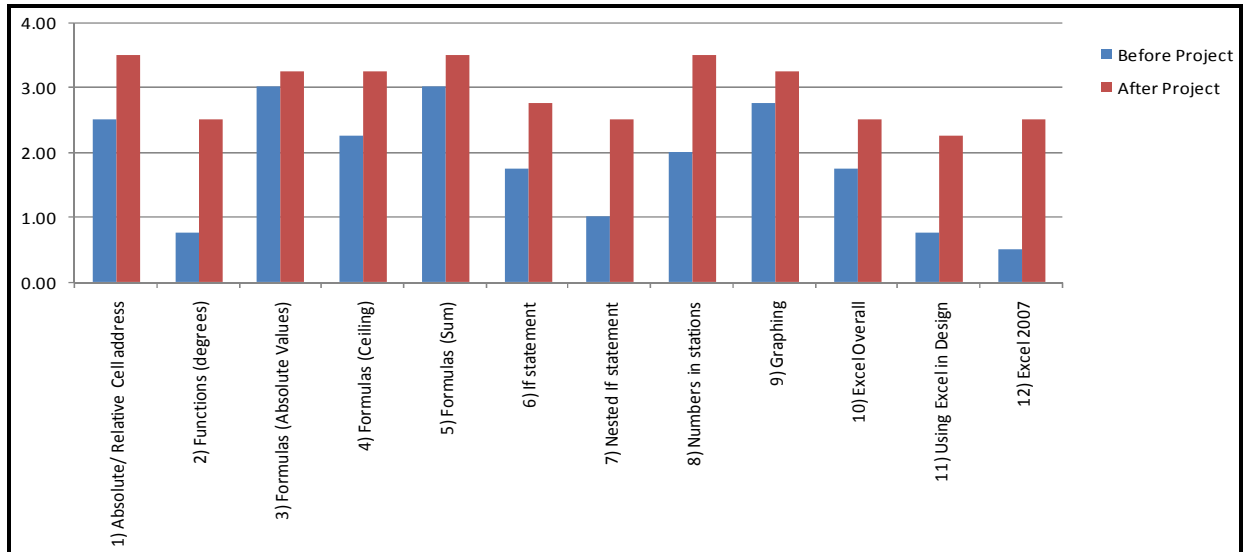

Figure 9: Assessment of Students' Excel Skills

As a result, this project contributed strongly to the parts (c) and (k) of ABET criteria. This class project started out as an in-class project, but the professor suggested taking extra time to expand the capabilities of the program and participate in a conference. Using this project as a learning tool, not only taught technical skills about the alignment of highways, but it also showed the powerful tool spreadsheets are becoming.

5) Conclusions and Recommendations

The use of spreadsheets can make design work easier; not only from a technical standpoint, but also makes the data easier to read and extract information quickly. Spreadsheets have the flexibility to perform an array of operations to data. They are also good for computing many values quickly and accurately. Engineering problems can be long and tedious and spreadsheets can make the task easier. Using spreadsheets in design will provide an available package easy to do engineering work and manipulate the spreadsheet design to accommodate special needs by each firm. The only difficulty was in adapting to the new design of Excel 2007. It was a challenge to be familiar of the commands and to navigate your way in the newly designed software.

The goal of the project was achieved by designing a simple and efficient spreadsheet to design vertical curves and simple and compound horizontal curves. Several new commands and

functions were learned in the process of developing the project. Most importantly, students are now familiar with the new version of Excel 2007.

The results of the casual assessment indicate that there was a major improvement of the Excel skills in general and in developing engineering design in particular. Developing and conducting the casual assessment for the skills learned in the class was very exciting. Going through the process made the author recognized not only the importance of the accreditations but also the major effort needed for assessment. The process is not simple; however, it shows the quality of education of the new program and it illustrates the new program is on the right path of getting accreditation.

It is highly recommended that spreadsheets are introduced earlier in design. In addition, students in general need to use the new version of Excel. It is not an easy move, but one has to do it. Microsoft has developed an interactive "Excel 2003 to Excel 2007 command reference guide" to help new user navigate the new software. The template is located at: http://office.microsoft.com/en-us/excel/default.aspx goes to "Quick Start" and click on "Find commands in Excel 2007."

Finally, this project is done individually by each student in class with validation and help from the instructor. This exercise enabled students to advance their knowledge of spreadsheets while learning important transportation engineering topics. The project helped achieve the outcome objective of the class as stated in the syllabus: 1) design basic horizontal alignment of the highway; 2) design basic vertical alignment of the highway; 3) use Excel as tools for geometric design of highways. There was a strong consensus among the students that the skills learned in this project were invaluable in preparing us for professional life. As a measure of success of this project in preparing us for professional life, one of my colleagues, who works part time as a drafter at a local company, presented his program to his superiors. For the use of the program in their company, they paid him consulting wages for his time and the development of the program.

7) **Bibliography**

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