IDEA

Innovations Deserving Exploratory Analysis Programs

Transit IDEA Program

Track Geometry/Design Testing for Transit Applications

Final Report for Transit IDEA Project 41

Prepared by:
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Fairfax, Virginia

June 2007

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

**Innovations Deserving Exploratory Analysis (IDEA) Programs
Managed by the Transportation Research Board**

Track Geometry/Design Testing for Transit Applications

Final Report

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This project developed and tested a concept to determine actual track geometry alignment and cross level in sharp curves and turnouts in rail transit systems. The improved track geometry testing system would utilize the current track design or a "best fit" track design as a baseline for testing rail rapid transit and light rail transit track. This concept would provide transit systems the ability to accurately identify track geometry defects based on their track design, thereby reducing maintenance time and cost. Transit agencies could also benefit by utilizing the "best fit" track design data generated by the track geometry system as an alternative to improve their current track design.

Automated track geometry tests using original design criteria or calculated "best fit" designs would provide accurate results for evaluating track alignment deviations. Evaluating current track conditions and managing these conditions on rail rapid transit and light rail transit systems could be greatly improved if this concept is implemented. Time and costs currently incurred by transit systems in evaluating and managing their track could be significantly reduced by methods developed in this project. This would improve the efficiency of the track evaluation and of tamper maintenance, which would enable the transit agency to focus its time and efforts on actual track problems, contributing to improved track safety.

The comprehensive "best fit design", digital track design database, once obtained, has several features:

> 1) The design is always an achievable design. This occurs as basic criteria of the mathematical model development process use minimal track adjustments or "throw limits" to discover the design given actual track position as the starting point.
>
> 2) The analysis of current geometry from track tests will use valid track design parameters when reporting deviations from design.
>
> 3) The real-time reporting will be testing for deviations at the same location as the data acquisition vehicle so that visual verification can be accomplished with out delay.
>
> 4) The absolute determinations of the location of track geometry test results are independent of operator inputs, making detection and correction of operator inputs practical.
>
> 5) There is a practical method for managing the track geometry-testing program to insure everything is tested.
>
> 6) The byproducts of geometry testing include both finding geometry defects and the data input for fixing these geometry defects with automatic machinery.

The effort has been to develop and demonstrate automatic programs for curve design based on the manual and semi-automatic and automatic methods developed. We were fortunate to discover these methods, which have been applied to all 16 curves in a Geometry Test run and brief explanations are given in each case shown in this report.

We are confident as a result of this project that the specified benefits of having the track design database are achievable. Digitizing the complete track design of a transit system, foot by foot is practical. The concepts described are the essential elements for systematizing the complete track design effort. The construction of the track design database that achieves the above six features is fully automated when these procedures are imbedded in a track geometry data acquisition and reporting system that includes an historical database for sequential periodic geometry testing. Such systems exist and now contain years of geometry test data at both the Washington Metropolitan Area Transit Authority (WMATA) and the Massachusetts Bay Transit Administration (MBTA).

PROBLEM DEFINITION

The research project statement and objectives were to develop and test a concept to determine actual track geometry alignment in sharp curves and turnouts in rail transit systems. The track geometry system would utilize the current track design or a "best fit" track design as a baseline for testing rail rapid transit or light rail transit track. This report describes the software that has been developed to handle the automation of curve design.

BENEFITS FOR GEOMETRY TEST REPORTING

This concept provides rail transit systems the ability to accurately identify track geometry defects based on their track design, thereby reducing maintenance crew time and cost. Transit agencies would also have the ability to utilize "best fit" design data generated by the track geometry system to make lining and tamping corrections to the current track. Track classification standards in sharp level curves and turnouts cannot be defined using the industry's current geometry testing methods. Therefore, during an automated track geometry test, this type of track is not properly classified, and required track geometry maintenance may not be defined. When using conventional methods of track geometry testing, the track design criteria are not considered. Automated track geometry tests using original design criteria or calculated "best fit" designs would provide the desired results for evaluating track alignment and crosslevel deviations. Evaluating current track conditions and managing these conditions on heavy rail rapid transit and light rail transit systems could be greatly improved if this concept is implement. Time and costs currently incurred by transit systems in evaluating and managing their track would be significantly reduced.

OTHER BENEFITS

Along with the desired values of track geometry parameters being established, the locations of these values are also established and standardized, just as they are in standard track charts. The curve design identification points become the equivalent of automatic location detectors (ALDs) for all track work and future track maintenance and test reports.

The standard form for a track design database is equivalent to a Digitized Track Chart (DTC). This DTC becomes a convenient place to store other fixed data for use in track evaluation such as designated Track Speed and Ride Quality.

The DTC is ideal for input data to models such as NUCARS that are used to evaluate the performance of new rail transit revenue vehicles prior to purchase.

The methodology for validating a curve design that was utilized in this project is the same technique as is used to maintain the track both manually and with automatic machines. The throws for restoring current track geometry to the desired track geometry are calculated using data from each geometry test.

DATABASE DESIGN, MODELING, AND AUTOMATION

Establishing The Database

Data has been provided for this project by MBTA and WMATA including detailed construction details on curves selected for inclusion in this project. The curve parameters provided include locations of the curve points as well as the spiral-curve details. Conversion among several coordinate systems is required to complete the comparison of the absolute locations in the construction design and the locations discerned from the mathematical models using detailed track geometry data. There is direct comparison of the length of track between the curve points specified on the design charts and the length measured from the geometry system.

The fact that so much detailed design data is available ensures that the curve points generated from track geometry test data will be validated as "matching" the design documents. The database is being structured to include the design coordinates of the curve points. The conversion algorithms are defined and can be automated.

The database structure is an extension of the "one-foot-files" fundamental to the track geometry measurements database. The extended data is the foot-by-foot description of the "actual" track design for direct comparison with each foot of track geometry measurements from repeated track geometry data acquisition runs.

Establishing The Curve Points List

The establishment of curve points from track geometry data is inherently a difficult and relatively unreliable process. It has been hoped that with the expanded capability of the state-of-the-art gyro and inertial sensors we can significantly improve the process. Some progress has been made. An improved procedure was designed and implemented. The procedure involves both automated curve point generation and manual editing of curve point lists.

The first step is to utilize the acquired data on alignment and crosslevel each foot to detect changes in rates per foot using selected thresholds. Changes over (or under) the threshold persisting for several feet are monitored and the locations of the beginning of the change are recorded as curve transitions. Each transition is recorded in the "Curve Point List" for the test run. These curve points are plotted, for each curve together with the values of the mathematical model of the curve, the absolute alignment, the mean alignment and the absolute crosslevel.

Achieving Curve Design Data

The procedures discovered were applied to selected data from track geometry tests for MBTA and data sets were established for all the curves on the Green Line. Each data set contains a list of curves for the test run, the curve points from the test run, the measurements at stations every 31 feet for each curve, the mathematical model at each station of the "ideal curve" drawn through the curve points, the half-throws to transfer the curve measurements to the positions determined by the model, and parameters describing the validity of the model.

The model validity testing procedure is automatically executed each time there is a change in the model, and the model is changed every time there is a change in the ordinate or position of a curve point. An ideal curve model is valid for a given curve if the sum of model ordinates equals the sum of measured ordinates, (the difference of the sums is zero), the maximum half-throw is practical and the final throw is zero. Iterative solutions of the model are used to test divergence or converge to a valid "fit" of the model to the measurement data.

Choosing The Mathematical Model

A simple "stick" model of the curve has been inserted in the system as the model of each curve from the curve points. The solution of the model results and testing of validity of the model is presented on a graph for each curve in the database. The applications performed in this project illustrate the need for a data management procedure for the curve points so that obvious errors in the curve point generator can be "fixed" manually. Initially the curve point list for the curve will contain a "best estimate" of the type and number of curve points. A preliminary procedure for adding, deleting and modifying curve points was implemented. This basic curve-modeling tool provides the basis for experimenting with and improving the capability to create models of valid curve designs automatically.

Manual Curve Designing

The manual procedures for modifying the lists of curves and curve points allows all the curves in each data run to be selected consistent with available track charts. Each curve will have the proper type and number of curve points. Given this basis, which allows a track design engineer to visually position the curve points initially, the mouse is used for adjusting curve points while simultaneously noting the effects of the changes on the validity of the resultant model. The changes are accomplished by using the computer displays, mouse-keys, and control-keys to "move" the curve point. This manual effort is very interesting as one is led to discern how certain combinations of these manual movements can be automated. An extensive effort along these lines has let do the development of a preliminary set of semi-automatic tools.

Semi-Automatic Designing

The basic semi-automatic design tool that was shown to be essential was a tool that would iterate toward a valid solution in the neighborhood of a solution discovered by manual manipulation. The application of a semiautomatic tool becomes a major time-saver when the manual solution range is visualized but the required manipulations are too sensitive to be optimized by mouse positioning. Various parameters for specifying automated movement of the curve point are selected on the computer display and the final results are found to the specified precision. This tool operates on a single curve point at one time.

This effort provides a number of semi-automated procedures to achieve solutions with manual assistance. It also provides the groundwork for imagining a wide variety of ways to fully automate the solution process accelerating the continuing effort to solve more different types of curves in practice. These are summarized, including:

1. A process for automatically selecting the curve geometry data every foot from a track geometry test run.
2. A process for automatically discerning the curve points with reasonable accuracy from the curve geometry data.
3. A process for manually upgrading the quality of the curve point data based upon visual inspection of the results of automatic acquisition.
4. A system of recording and managing the results all manual and automatic curve point upgrades.
5. Iterative procedures for adjusting curve points to maximize the "fit" of the "ideal" curve to the available geometry data.

Given these "tools", the business of marrying the actual curve design described in the construction documents with the foot-by-foot design that can be compared with the geometry measurements data can be accomplished with reasonable cost and high precision. Under such circumstances, the track geometry test can in truth report "deviation from design" and the deviations can be verified to determine track maintenance priorities accurately.

The framework has been established for the continuing expansion of this technology as more elaborate applications can be undertaken over time: These will include:

1. A more refined mathematical model containing increased precision (foot increments instead of 31 foot increments) and state of the art spiral designs.
2. Mathematical aids for transforming construction curve point designs into modeling curve point locations and ordinates.
3. Discovery of more advanced iterative algorithms that automate the functionality of more complex manual adjustments that converge the models to match the actual curve designs.

The ultimate goal of the project is to confirm and permanently record the track design for any railroad within a reasonable budget and to perform track geometry tests that factually report deviation from design.

AUTOMATED CURVE DESIGN AND APPLICATIONS

Automatic Curve Design Geometry Test

A geometry test run containing sixteen curves was used as a sample from which the curve design data was extracted. This data sample was analyzed and each curve was solved using the procedures described below.

The analysis process for full automation required several extensions of the software, which are demonstrated. The first extension is the enhancement of the Curve Design Chart to include both the "Deviation from Design (DD)" and the "Deviation from Mean (DM)" curves relating to the differences between the measurement and the model (DD) and the differences between the measurements and the mean (DM), This yields a chart with seven graphs.

Figure 1 -- Curve Design Chart Description

Figure 1 shows the chart configured for the analysis of Absolute Alignment Measurements. The chart includes the graphs for:
1. Absolute Alignment
2. Mean Alignment
3. Absolute Crosslevel
4. Alignment Model
5. Half Throws (Lining Machine Data)
6. Deviation From Design
7. Deviation From Mean
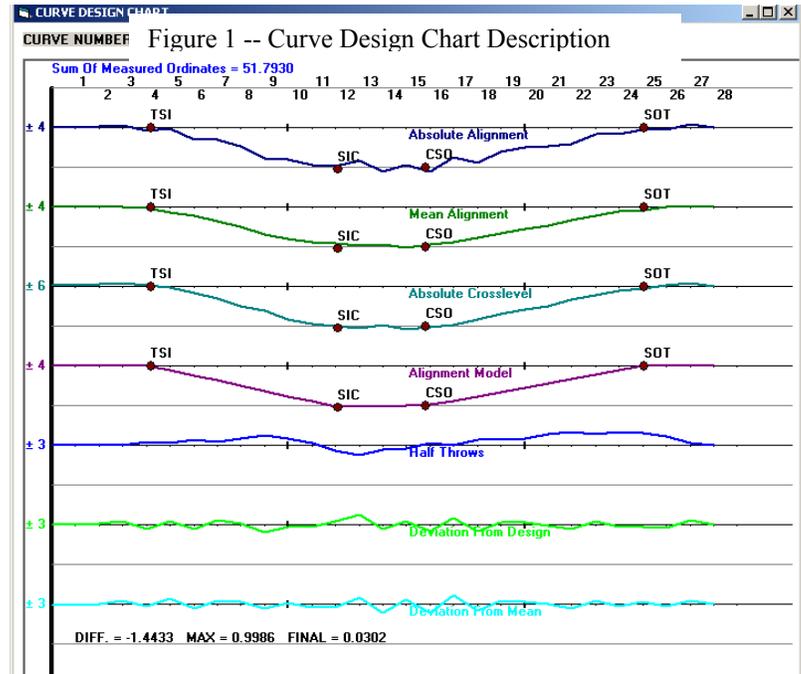
The corresponding analysis for Crosslevel Measurements will use the same technology and the chart outputs will be:
8. Absolute Crosslevel
9. Mean Crosslevel
10. Absolute Alignment
11. Crosslevel Model
12. Half Lifts (Tamping Machine Data)
13. Deviation From Design
14. Deviation From Mean

The Crosslevel results are not considered in this study except by direct analogy.

Automation of the Stage One procedures was achieved by introducing routines that called the manual and semiautomatic functions. The procedures were designed to take advantage of the characteristics of the solution process discovered in Stage One for moving the curve points to "better" positions on each pass from first to last curve point. Then these were performed repeatedly until the solution no longer improves.

The procedures developed in Stage One worked with limited success. This was initially attributed to the fact that the model was not the advanced model with sophisticated spiral designs. It was discovered, however, that the existing "stick-model" could be improved by simply adding more curve points and rules for automating this process were created in Stage Two. Interestingly, the solutions were found that

otherwise were elusive or impossible, especially on long curves. It was discovered that the curve body design was not constant over long curves. This is now obvious to the investigation that no curve body has absolutely uniform curvature. Therefore very minor adjustments of the curvature in the curve body had to be provided for. Curve points are therefore added automatically during data acquisition on each long curve body.   Provision is made for adding curve points manually wherever desired.

The success we had in finding solutions increased to the point that it seemed that the difficult problems are solvable if the initialization of curve points is close enough to correct. There seems to be no requirement to refine the model beyond the available accuracy of the stick-model. The changes in the spirals to eliminate the "jerk" are below the level of detection of track geometry defects.   There is a need for tampers to have this capability, however, and it might be added to the curve designing process for that purpose.

Using the extended tools, we were able to observe what would happen if we deliberately used the mean value curve as the desired model. The discovery was that the mean was never a solution to the equations, in other words the mean was never an achievable position for maintaining the track. This being the case, it seems that any geometry test that reports "deviation from the mean" seems logically invalid. This may not mean that the track is unsafe if it passes the "deviation from mean" testing criteria but if the track passes or fails this type of test, it is inconclusive as to whether it requires maintenance.

CURVE DESIGN SOFTWARE

The development of this software has been focused on automating what has been a difficult engineering task of digitizing the curve points of railroad track to provide a foot-by-foot detailed database of track design. This design data, once established, is to be compared with the corresponding foot-by-foot geometry test data with sufficient precision to input to the automatic tamping machines. False geometry exceptions caused by false track "design" models are eliminated once and for all by the complete design database.

The development effort is in its initial stages and cannot be expected to accomplish all its goals in present form. The first goal is to provide a method for manual interaction with the mathematical equations that determine what effects "throwing the track" has on the line of a curve between the two tangent points. We do this with a chart plotting three graphs: a) a desired model of curve alignment and b) an actual measured alignment and c) the "throws" necessary to make the transformation. The positions of the transition points between tangent, spiral and uniform curvature are also plotted. The mouse is used to drag the curve points, recalculate the model and to improve the solution and reduce the throws. Unless the throws are within specified limits, the track will be thrown too far, i.e. off the ballast bed or too close to tunnel walls, etc. The length of rail to achieve a specified design must be the same before and after the shift. The final throw must be zero.

The engineering process for managing this is called "string-lining" and involves some adjustment of data on a spreadsheet such as that described in the 1996 AREA Handbook. Each row of the spreadsheet describes the curvature of the track at "stations" 31 feet apart measured along the curve. The differences between the measured and the desired curvature are used to calculate the "half-throws" at that station. The standard engineering practice is to adjust the rail so that at each station has moved to restore a desired uniform pattern or curve design. Once correctly specified, the design does not change.

Automatic curve alignment equipment is used to shift the track to positions that might be different from the original track design. Since the desired pattern is basically a trapezoid, we introduced methods for adjusting the lines rather than the points. These adjustments can be achieved on the graph by moving the transition points, redrawing the lines, and recalculating the throws. The manual design user can use the mouse to drag the curve transition points individually or in groups to achieve the desired solution.

We allow use of some of the accepted curve design practice. One practice is to transition into and out of a curve with the same rate of change of curvature. The second is to maintain a constant rate of curvature between the transitions. The positions of the curve points are in a proper design when the same amount of

rail and acceptable maximum throws are achieved. The final throw always has to be zero at the end of a curve.   These rules of practice are a matter of designer choice and are not always relevant.

The manual interface with the curve design process as implemented is a basic first step in many curve design applications. The model is moved to "fit" the irregular existing curve data. The first discovery is that the unique desired solution is visibly correct on the chart. The exact position of the curve points is so critical that the increment of adjustment required is too small to do manually. But it is possible to see in which direction very small adjustment of the curve point is required. We have automated the fine adjustment process for any chosen point or group of points.

It is possible to observe by the manual manipulation process that we can adjust the points in sequence with minimum influence on the previous points. The characteristic propagates along the curve making step-by-step partial solution of the curve practical. So we introduced partial solutions into the algorithm.

We observed that the partial solutions can be extended station by station and tend to follow a "crease" in the solution surface that cannot be discovered any other way. The solution surface is so critical that very high precision in the calculations is necessary for ascertaining where the next partial solution "station" is located. This "ranging" of the partial solutions over specified station limits then becomes another part of the solution algorithm. This discovery has been the only avenue for finding solutions to long curves.

Based upon these discoveries we prepared a solution search function, which can be specified for the range of stations around each curve point. We then proceeded to establish suitable sequences of these functions for identifiable curve types and are now in the process of establishing a useful family of identifiable curve types. With this introduction, we have a context for understanding the software tools that allow this research to continue.

The further development of the system to automate these manual procedures was implemented in Stage 2. The procedure implemented functionality that replicates solutions schemes discovered by manual experimentation.   Each solution scheme involves:

1. Selecting the curve
2. Selecting the sequence for adjustment of curve points
3. Selecting the range of stations involved in the solution
4. Selecting the criteria for direction of curve point adjustment
5. Selection the objective for ending the curve point movement
6. Determination of the repetitions of steps 2. -- 5.

CURVE DESIGN SOFTWARE OPERATION

The Curve Design software developed under the first Stage of the project includes a complete subsystem under the General Analysis System developed by Trak-Tech Corporation. The General Analysis System converts raw sensor data from an inertial based non-contacting geometry test into values of the geometry parameters per foot of track, including alignment and crosslevel. The Curve Design subsystem uses alignment and crosslevel, detects the location of curve points, and maintains a set of lists for analysis of curves. These lists include the Curve List, Curve Point List, Measurement Data List, and Model Data List. Each of the lists is maintained in text form to allow maintenance with common editing subroutines.

Curve List and Curve Point List

Curves and Curve Points are accessible from dropdown lists on the following form. The Curve List is visible together with each of the associated lists. The curves are numbered sequentially for the test run, usually all or part of a Line of track.
The Curve Points are numbered sequentially for the entire run and are indexed via the Curve List. The Track Code usually identifies each of multiple tracks on a line. Each point in the Curve Point List is a transition between tangent, spiral, and curved track conditions. These transition points include the following and are specified as Point Type on the above form:

Transition Types:

CBT -- CURVE BODY TO TANGENT
SOT -- SPIRAL-OUT TO TANGENT
TSI -- TANGENT TO SPIRAL-IN
CSI -- CURVE BODY TO SPIRAL-IN
SOI -- SPIRAL-OUT TO SPIRAL-IN
TCB -- TANGENT TO CURVE BODY
SIC -- SPIRAL-IN TO CURVE BODY
SOC -- SPIRAL-OUT TO CURVE BODY
SOO -- SPIRAL-OUT TO SPIRAL-OUT
SIO -- SPIRAL-IN TO SPIRAL-OUT
SII -- SPIRAL-IN TO SPIRAL-IN
CSO -- CURVE BODY TO SPIRAL-OUT
CSC -- CURVE BODY TO CURVE BODY

Each entry in the Curve Point List includes its Ordinate and its Location. Each of these parameters is to be modified as a part of the curve design process, and the original value of the parameter is maintained as a baseline reference.

Curve design involves the establishment of Stations every 31 feet along the track and the measurement of track curvature and crosslevel at each station. The locations of the start and end of each curve are measured in terms of feet from a standard marker, in this case the start of the run.

Curve Measurements

The measurements that are input from the geometry test and the results computed from the model are displayed on the following screen. The Station List includes the actual geometry measurement for each station on the curve. Currently included are the Absolute Alignment, Mean Alignment and Absolute Crosslevel. Each of these data elements influences the determination of Curve Points. Their simultaneous display on the Curve Design Chart provides insight on where the Curve Points are located, and is used in the manual and automated curve design procedures.

The screen also includes a section that displays the results of calculations for the current placing of the curve points. The results include total length of the curve and each part of the curve, including the spirals, and curve body. The theoretical speed limits are also displayed here.

Curve Model

The Model List contains the calculated results for each station on the curve and a copy of the overall curve lengths at current Curve Point positions.

Designing Curve Models

The Curve Design desktop software provides a number of "tools for manipulating the positions of the curve points in order to obtain a satisfactory "solution". The user interface is shown below. The OPTIONS frame displays the option buttons and checkboxes used to control the adjustment of curve points. The STATUS frame controls the execution modes. The FUNCTION frame selects the function to be performed.

The Design tab on the right together with the chart below displaying the simultaneous plots of the data in text boxes on the other tabs is the curve designers desktop. We will refer to this form as we discuss curve designing in the following.

Figure 2 -- Software Operation Curve Design
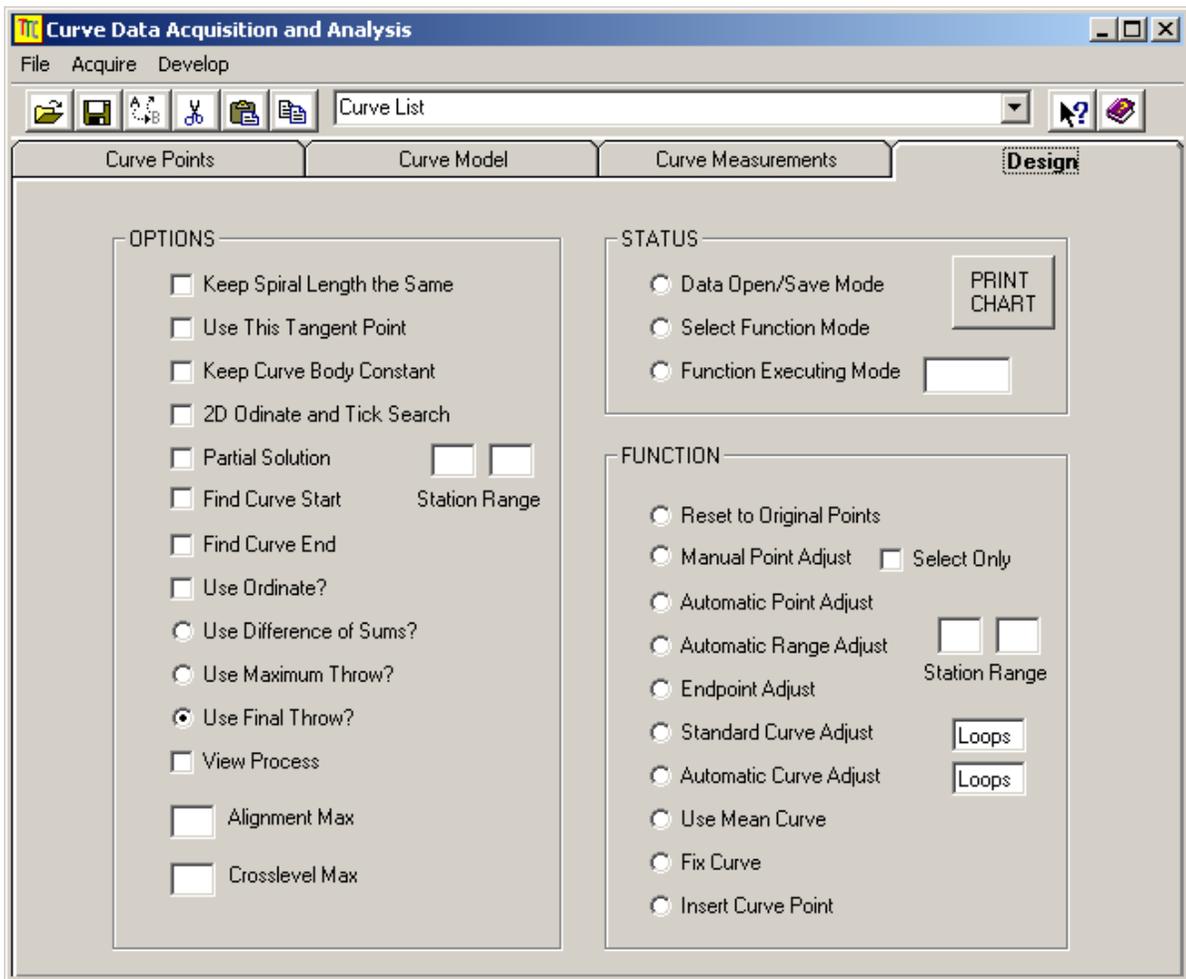
Displaying The Solution

This Chart shows the typical display of graphs being modified as the user moves the curve points. Curve points can be moved manually, semi automatically or automatically. The "solution" is found when the chart of the half-throws indicates that the adjustment is practical.

Figure 3 -- Display of a Solution
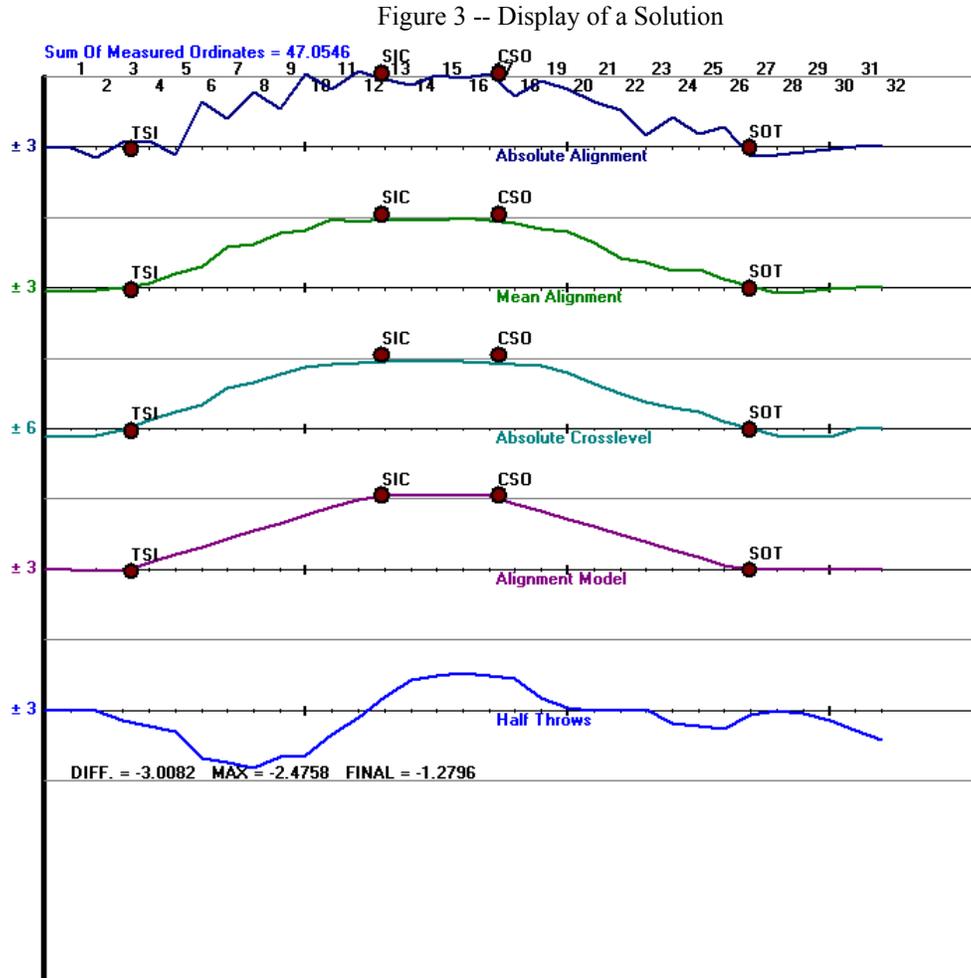
Finding a Solution Manually

Starting with the following desktop we can reset the points to their values pre-estimated from the measurement data. This will yield a chart that is not a solution. Then by selecting the manual mode one can position the cursor over each curve point and drag it to a new location as was done to obtain the first chart.

At the same time, the options to keep the spirals the same and to keep the curve body constant were selected. The "Use This Tangent Point" option chooses which tangent point is on the spiral to be matched.

Finding a curve start or end is a semiautomatic method for moving tangent points. The TSI or SOT point is set at zero ordinate and then shifted in the "X" direction to the lowest value for the selected search parameter. The Adjust Endpoint function executes the process.

The search parameters are Difference of Sums, Maximum Throw or Final Throw. The shifted parameter is the Y or Ordinate value or the X or Location value. It should be noted that these X and Y parameters are high precision in order to extend the observable range of their change as far as possible in the solution space.

For the Curve body points the search can be performed in both the X and Y directions simultaneously with the 2D Search option.

The Partial Solution Option provides a way of searching a specified partition of the solution surface. This become essential on long curves because intermediate points need to be fixed for the solution to progress. Otherwise points on the solution surface are moved off. Manual solving is terminated by a right click on the chart.

Finding a Solution Semi-Automatically.

It is possible to include searching a solution or partial solution from any chosen curve point with the selected options as described above. The point can be chosen in the Manual Select Only mode so there is no disturbance of previous results.

There are two semi-automatic functions, called Automatic Point Adjust and Automatic Range Adjust. The latter is a repeated application of the former over a specified range of stations using an automatically adjusting partial solution. Each repetition adjusts the partial solution range to be from the first station to the next final station for the range of final stations.

Finding a Solution Automatically.

Two mechanisms are introduced to automate the curve design process. These are software procedures called the Standard Curve Adjust (SCA) and the Automated Curve Adjust (ACA), which are logically sequenced applications of the semiautomatic design procedures. A typical curve design session will find a solution if the original curve points are in positions that appear to be visually correct. The curve points may need to be adjusted or inserted manually if the data acquisition run either dislocated them or failed to detect them. .

CURVE DESIGN SOFTWARE APPLICATION

The research effort for Transit-41 has been to establish methodology so that the development of a track design database is practical using track geometry data of existing track parameters. The objective is to achieve full automation in doing this, and such an objective is not unreasonable, but not within the time and effort of Transit-41. Instead, we have prepared software, a "workbench", on which we can "hammer out" a track design within the framework of practical endeavor including manual decision-making. One can also rationalize the manual decision may never be completely automated, but still, once made, these decisions can become a permanent part of the database and subject to constant review and revision as "designs" are repeatedly updated on the same track.

The material brought to the workbench from which the track design database is to be fabricated include the database of repeated track geometry tests sufficiently correlated so that each foot of track can be compared with previous tests of that track at regular intervals. The more frequent the intervals, the more certain of the "track design" parameters stored by track foot convenient for comparison with the current track test even while it is being performed foot by foot.

The tools in the drawer of the workbench used to "shape" the design vary from simple manual methods to computer controlled cutting and shaping machines. The purpose of this section of the report on Transit-41

is to a take a sample of the material and to perform the necessary shaping to the authors concept of the "best fit" using each of the available tools as examples. As the work progresses, a commentary is made on techniques for using the tools.

The parameters needed for track design include:

Gage – the distance between the rails on Tangent (a constant)
Curve Gage – the distance between rails on curves (a constant)
Alignment on Tangent – the shape of the track on tangents (a constant)
Curvature – the shape of the track in curves (a complex function)
Crosslevel – the level of the track on tangents (a constant)
Superelevation – the level of the track on curves (a complex function)
Profile – the uniformity of grade (a constant)

The purpose of the workbench then is to concentrate on simulating the complex functions, Curvature and Superelevation. The points where the rates of change of these parameters change are critical to the track design specification, and can be used to express the entire design when the model of the track connects these "curve points". The connecting link can be a simple straight line or a curve that may itself be quite complex. The closer together the points of the linear model, the more accurate the straight-line or "stick" model can become. The procedures in this project use the "stick" model "curve points" to define the curves.

Some findings of this investigation suggest that:

1. The curve points and stick model (as defined above) are sufficient to describe the design.
2. Accepting the current track position as the desired design is an option.
3. Using the pre-determined shape of the curves of standard track-work is an option.
4. Routinely performed geometry measurements can be used to establish and also maintain a true track design database.

The following discussion expands upon the methods of using the stick model together with the stringlining algorithms based upon traditional track curve maintenance practices.

TECHNICAL BASIS FOR "THE WORKBENCH"

The development of the "workbench" software has been focused on automating what has been a difficult engineering task, that of digitizing the curve points of railroad track curve design parameters to provide a foot-by-foot detailed database of complete track design. This track design data, once established, is to be compared with the corresponding foot-by-foot geometry test data with sufficient precision to input to the automatic tamping machines. False geometry exceptions caused by false track "design" models are eliminated once and for all by the complete design database.

The engineering process for managing curve maintenance is called "string-lining" and involves some adjustment of data on a spreadsheet such as that described in the 1996 AREA* Handbook. This spreadsheet is inserted below for convenience:

*The American Railway Engineering Association (AREA) has since been included in the American Railway Engineering and Maintenance Association (AREMA)

Figure 4 -- Stringlining

Column	Station (1)	Measured (2)	Revised A	Revised B	Revised C	Revised D	Diff A	Diff B	Diff C	Diff D	Sum A	Sum B	Sum C	Sum D	Half A	Half B	Half C	Half D	Full Throw (inches)	Gage To Tack	Superelevation 50 Speed
			(3)				(4)				(5)				(6)				(7)	(8)	(9)
	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28.25	
	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	28.25	
	1	5	7	6	7	7	-2	-1	-2	-2	-2	-1	-2	-2	0	0	0	0	0	28.25	
	2	14	13	13	13	13	1	1	1	1	-1	0	-1	-1	-2	-1	-2	-2	-0.4	28.65	
	3	16	20	19	20	20	-4	-3	-4	-4	-5	-3	-5	-5	-3	-1	-3	-3	-0.6	28.85	
	4	26	27	26	26	26	-1	0	0	0	-6	-3	-5	-5	-8	-4	-8	-8	-1.6	29.85	
	5	30	34	32	33	33	-4	-2	-3	-3	-10	-5	-8	-8	-14	-7	-13	-13	-2.6	30.85	
	6	43	40	39	40	40	3	4	3	3	-7	-1	-5	-5	-24	-12	-21	-21	-4.2	32.45	
	7	56	46	44	45	45	10	12	11	11	3	11	6	6	-31	-13	-26	-26	-5.2	33.45	
	8	49	47	45	46	46	2	4	3	3	5	15	9	9		-2	-20	-20	-4	32.25	
	9	35	47	45	46	46	-12	-10	-11	-11	-7	5	-2	-2		13	-11	-11	-2.2	30.45	
	10	51	47	45	46	46	4	6	5	5	-3	11	3	3		18	-13	-13	-2.6	30.85	
	11	49	47	45	46	46	2	4	3	3	-1	15	6	6		29	-10	-10	-2	30.25	
	12	43			46	46			-3	-3			3	3		44	-4	-4	-0.8	29.05	
	13	45			46	46			-1	-1			2	2			-1	-1	-0.2	28.45	
	14	50			46	47			4	3			6	5			1	1	0.2	28.05	
	15	49			46	46			3	3			9	8			7	6	1.2	27.05	
	16	43			46	46			-3	-3			6	5			16	14	2.8	25.45	
	17	38			46	46			-8	-8			-2	-3			22	19	3.8	24.45	
	18	50			46	46			4	4			2	1			20	16	3.2	25.05	
	19	55			46	46			9	9			11	10			22	17	3.4	24.85	
	20	33			46	46			-13	-13			-2	-3			33	27	5.4	22.85	
	21	44			46	46			-2	-2			-4	-5			31	24	4.8	23.45	
	22	50			46	47			4	3			0	-2			27	19	3.8	24.45	
	23	47			46	46			1	1			1	-1			27	17	3.4	24.85	
	24	48			47	46			1	2			2	1			28	16	3.2	25.05	
	25	38			41	41			-3	-3			-1	-2			30	17	3.4	24.85	
	26	37			34	34			3	3			2	1			29	15	3	25.25	
	27	21			27	27			-6	-6			-4	-5			31	16	3.2	25.05	
	28	18			20	20			-2	-2			-6	-7			27	11	2.2	26.05	
	29	17			14	13			3	4			-3	-3			21	4	0.8	27.45	
	30	9			7	7			2	2			-1	-1			18	1	0.2	28.05	
	31	2			1	1			1	1			0	0			17	0	0	28.25	
	32	0			0	0			0	0			0	0			17	0	0	28.25	
Sum		1112					1112	1112													

End in zero for same angle to tangent

Must end at zero to be same tangent

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Balance the ordinates, limit the half throws

Each row of the spreadsheet describes the curvature of the track at "stations" 31 feet apart measured along the curve. The differences between the measured and the desired curvature are used to calculate the "half-throws" at that station. The standard engineering practice is to adjust the rail so that at each station has moved to restore a desired uniform pattern or curve design. Once correctly specified, the design does not change.

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Figure 5 – Plots of Stringlining Data

Figure 5A is a plot of the measured data (Series 1) and the four revisions (Series 2, 3, 4 and 5)
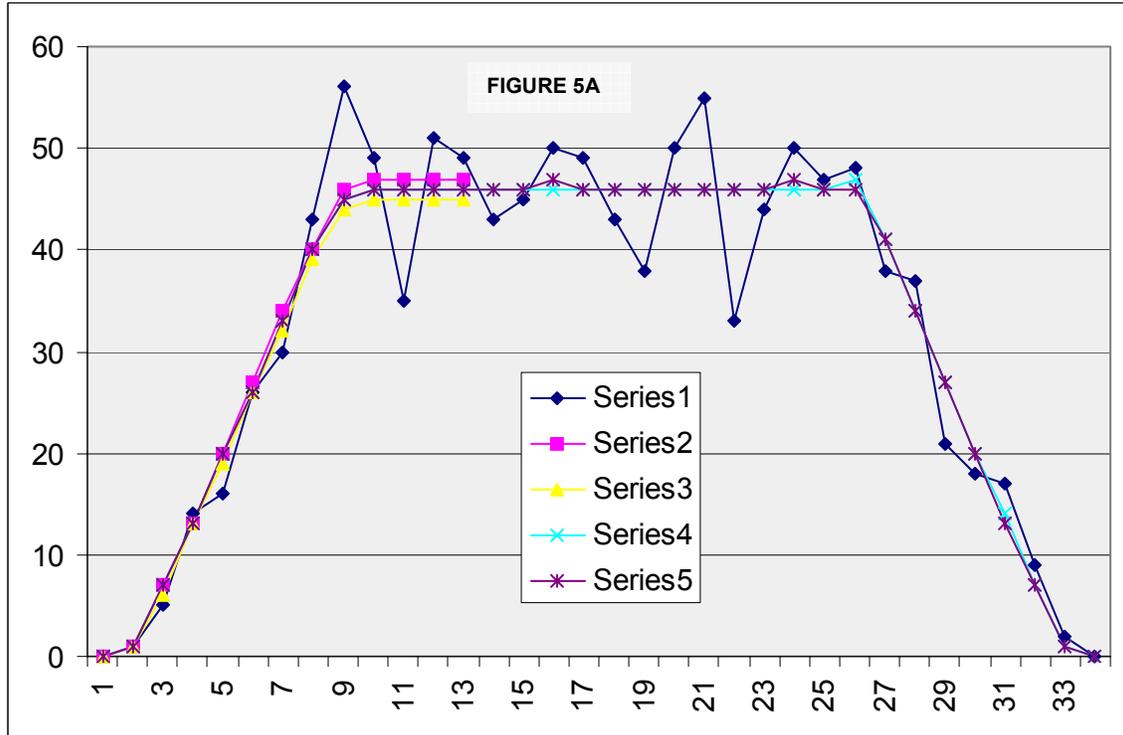
Figure 5B is the plot of the throws calculated from the four revisions (Series 1, 2, 3 and 4). Each point-by-point revision reduced the throws and at last the final throw was zero
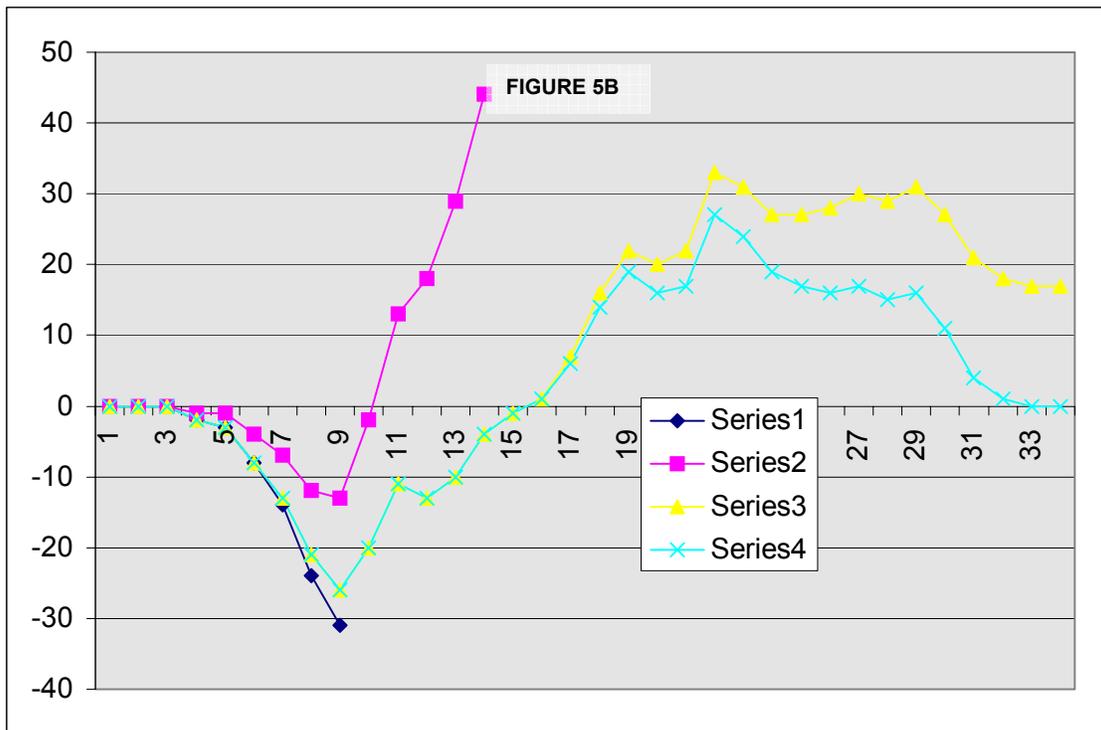
The Workbench methodology utilizes this same approach except that a stick model determines the location of the design points between the curve points. Then the points between the Curve Points are moved as a group thus eliminated the "blips" in the final design.

Automatic curve alignment equipment is used to improve the track position using the throws calculated from models such as these. Our effort is to discover stick models that are solutions suitable for tamper input. Since the desired pattern is basically a trapezoid, we introduced methods for adjusting the lines (rather than point by point) of the stick model. These adjustments can be achieved on the graph by moving the transition points, redrawing the lines, and recalculating the throws. The curve designer can use the mouse to drag the curve transition points individually or in groups to achieve the desired solution.

We allow use of some of the accepted curve design practice. One practice is to transition into and out of a curve with the same rate of change of curvature. The second is to maintain a constant rate of curvature between the transitions. The positions of the curve points are in a proper design when the same amount of rail and acceptable maximum throws are achieved. The final throw always has to be zero at the end of a curve.   These rules of practice are a matter of designer choice and are not always relevant.

The manual interface with the curve design process as implemented is a basic first step in many curve design applications. The model is moved to "fit" the irregular existing curve data with automatic assistance using the automatic functions developed in Stage Two based on the Semiautomatic Functions from Stage One: Also some thought was given to the fact that a curve cannot change as in turnouts or direct fixation, or that the mean value curve is a possible solution. Thus we have:

- Standard Curve Adjust
- Automatic Curve Adjust
- Use Mean Curve, and
- Fix curve

These functions are accessed from the Curve Design Tab shown above.

AUTOMATIC CURVE DESIGN APPLICATIONS

Sixteen sample curves are used to illustrate the effects of using the "automatic" functions. Examining the result of their application to Curve 2, for example illustrates that the positions of the curve points is hard to detect visually. The original position of the curve points for Curve 2, for example, (see below), appears nearly the same as the as the transformed position of the curve points after alternating applications of two automated functions. The throws were out of range before but are well within range afterward. The movements of the curve points from the original estimated positions were performed by the Standard Curve Adjust and the Automated Curve Adjust functions until the final solution was chosen.

Figure 6 – Curve 2 – Looks Are Deceiving
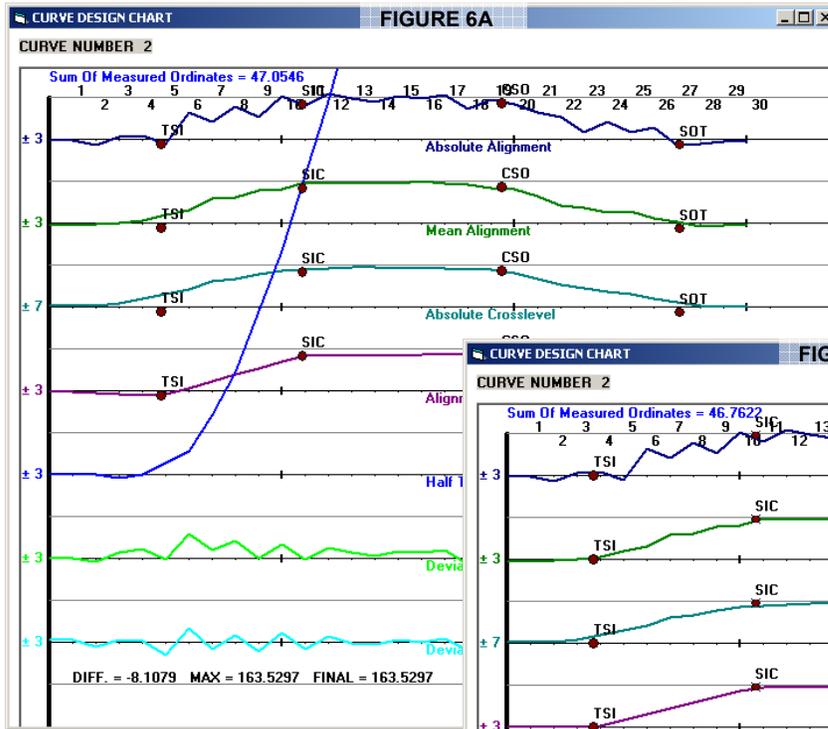
Figure 6A shows the original curve point position estimates that are obtained during the data acquisition scan. These do not look like poor selections, but they result in a model that is not achievable with reasonable throws.

Figure 6B shows how the application of the Standard Curve Adjust (SCA) function gives more reasonable results and the area under the curve difference (DIFF) is small enough. This may be the best design choice.
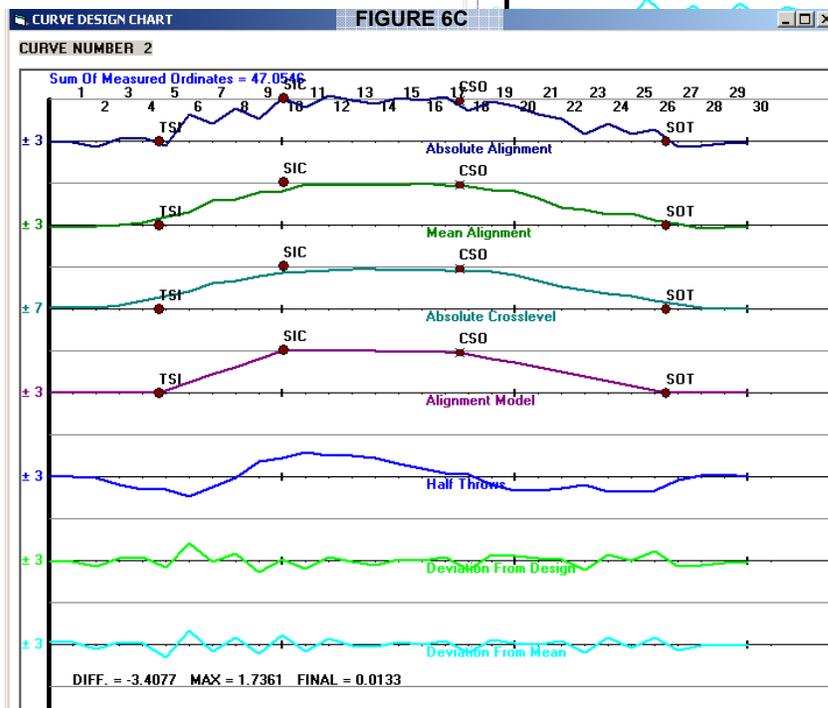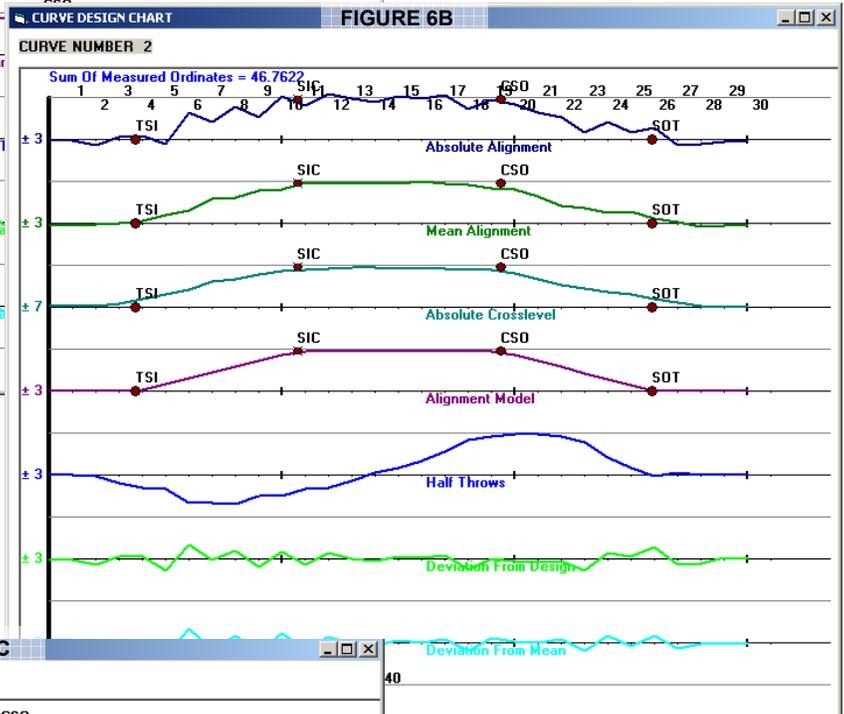
Figure 6C shows how application of the Automatic Curve Adjust (ACA) function gives a better solution (smaller throws) and the curve points are closer to the Absolute Alignment data but the DIFF is larger. By observing the deviation from design vs. the deviation from mean, either design is usable for geometry testing.

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Figure 7 -- Curve 3 – Curve Points Are Hard To Find
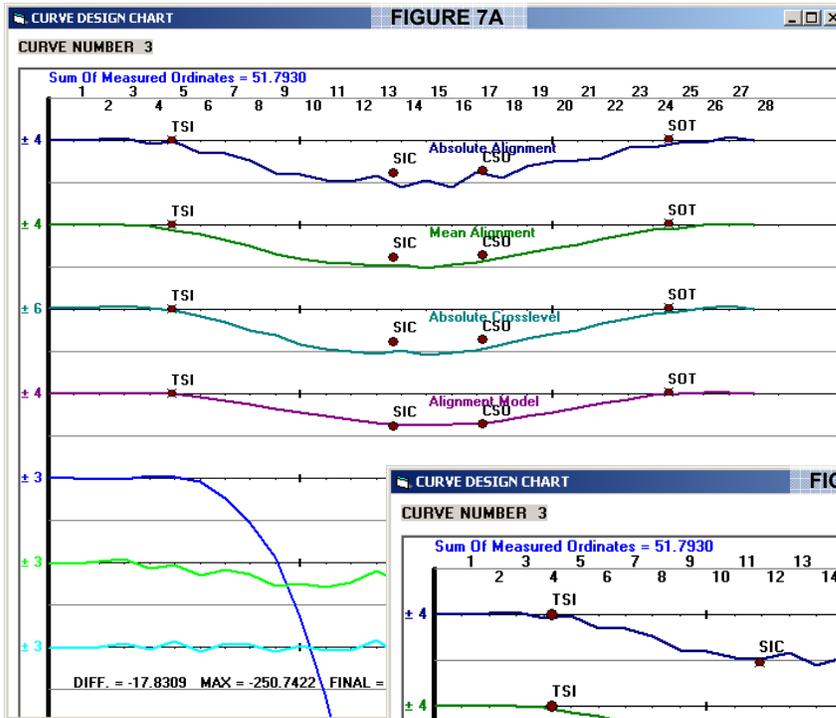
Figure 7A illustrates the original curve point positions. These curve points typically are far from a solution. The attempts to further develop the initial curve point positioning have not proven very successful. The advanced modeling solvers have proven more useful.

The Mean Alignment Curve was used as the Alignment Model in Figure 7B to demonstrate that it is not a solution.
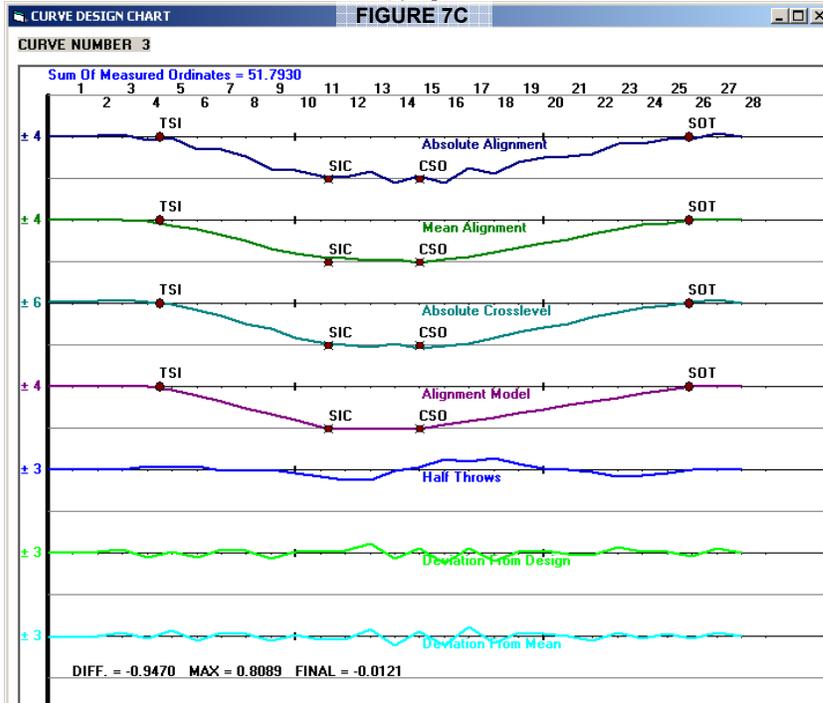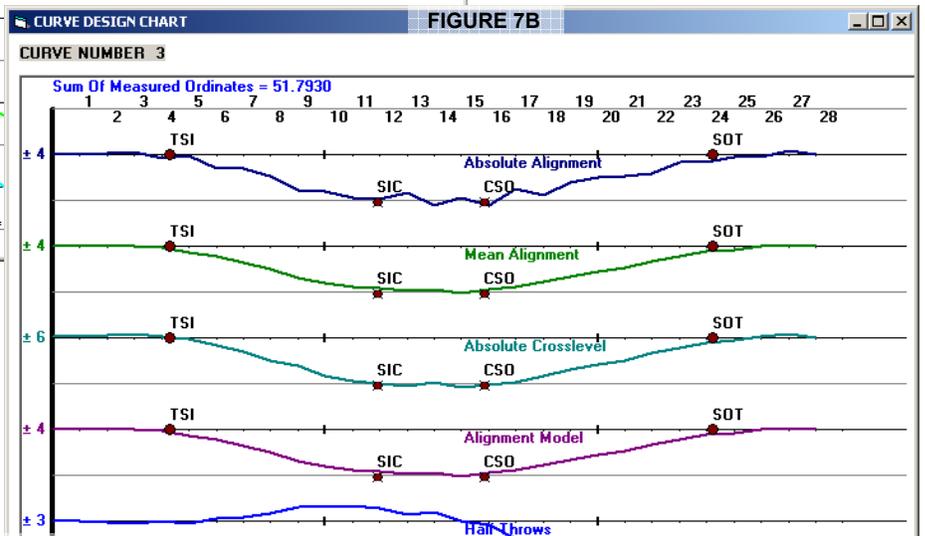
Figure 7C illustrates the result that is obtained after using a combination of manual and automated solution steps. More advanced solvers are developed by adding newly discovered manual steps in the automatic solution sequences. The goal is to have it all automated.

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Figure 8 -- Curve 4 – Curve Points Must Be Added
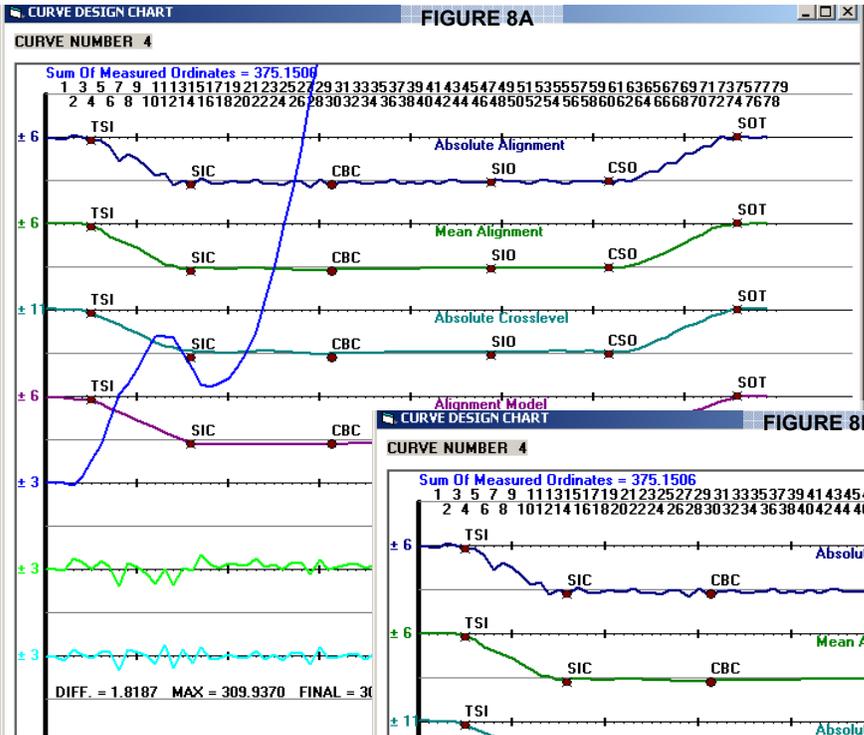
Figure 8A shows the addition of points in the curve body. These points allow the slight deviations in original construction to be retained in the design.

Figure 8B shows what would happen if the mean value were chosen as the design. The tampers would have an impossible job. Testing for deviation from mean is not the same as deviation from design.
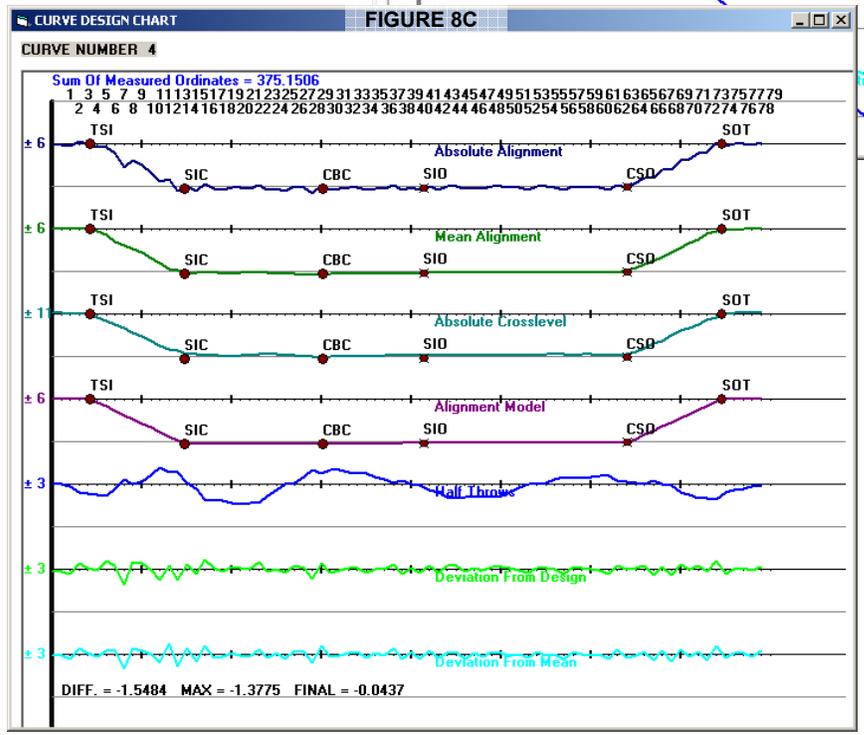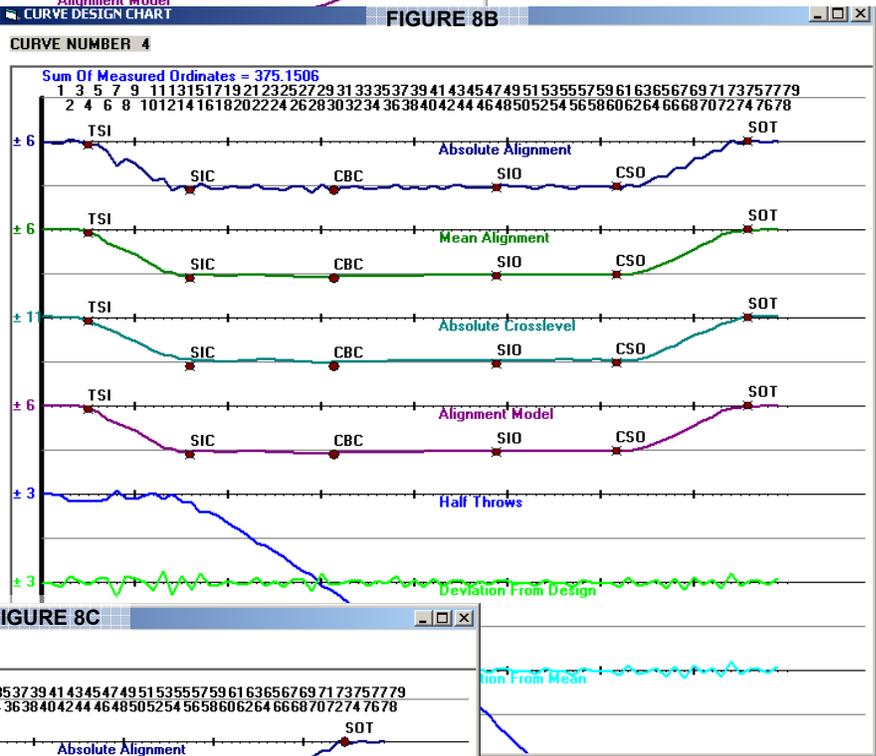
Figure 8C shows that the added points in the curve body can be positioned manually to allow the iterative algorithm to achieve a solution. The CBC point is movable the SIO point is fixed. These auxiliary points are necessary for a solution as the long curve body is not absolutely constant.

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Figure 9 -- Curve 5 – Good Solutions Found Automatically
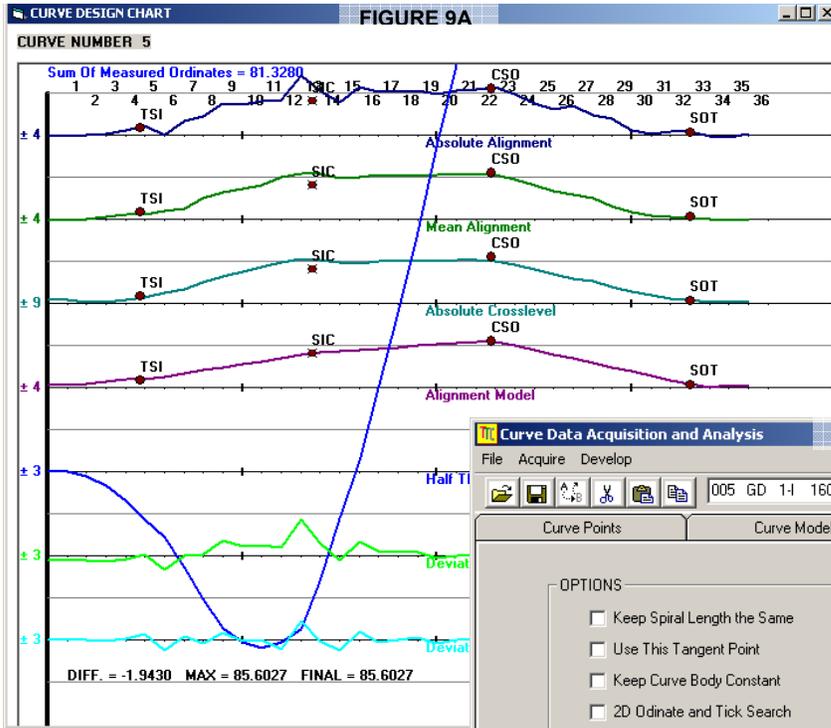
Figure 9A is a simple curve that is solved directly from the original points with three applications of the SCA Function

This is a nice demonstration of the power of SCA multiple sequential applications

Figure 9B shows the setup of the Design Tab for repeated applications of the Standard Curve Adjust SCA
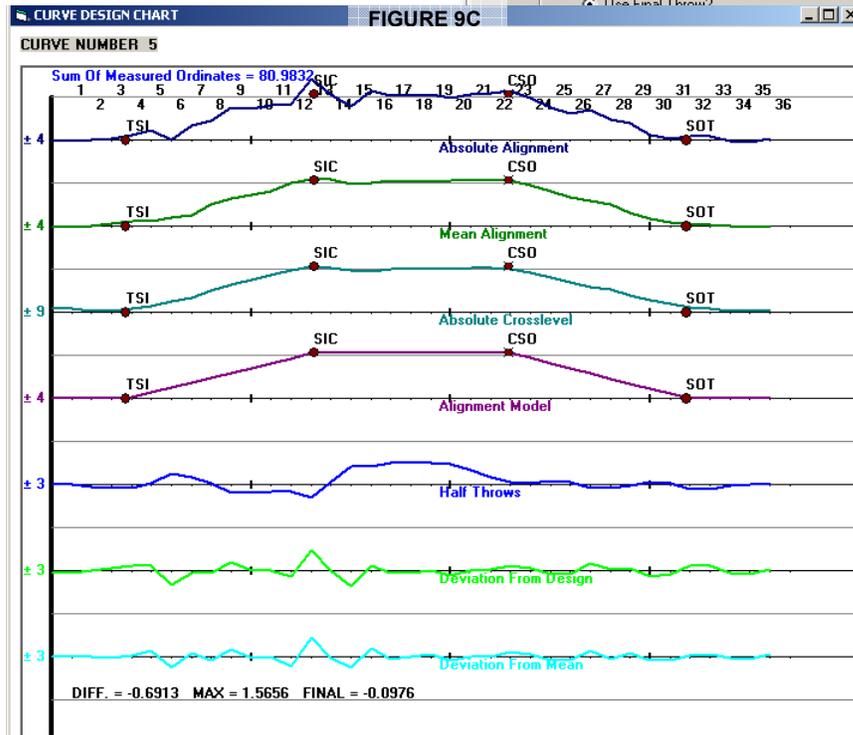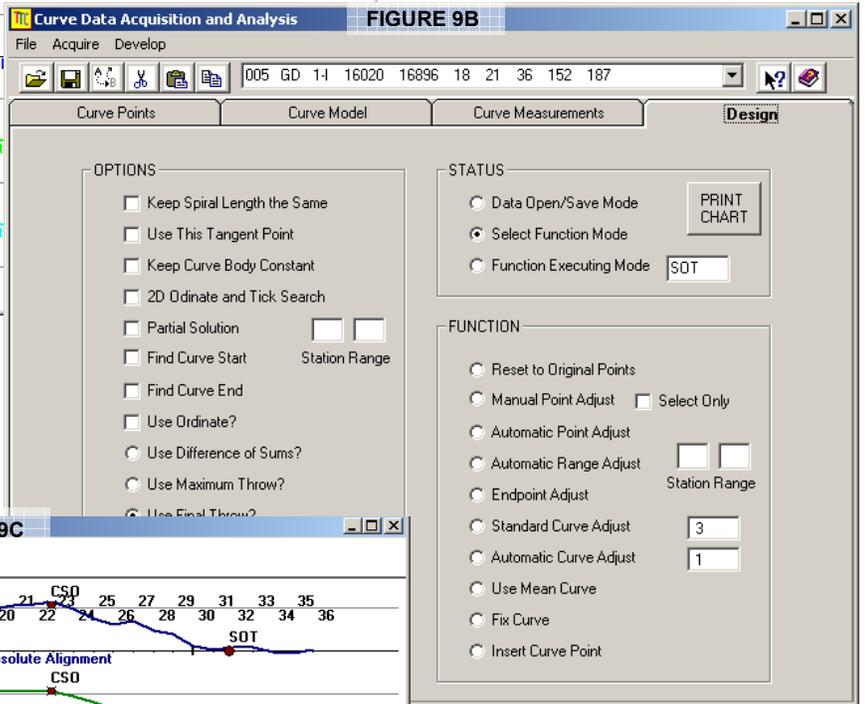
Figure 9C shows the result that is found on a "Standard Curve" without any manual manipulation of the curve points using the SCA function repeated until no further improvement is achieved.

Figure 10 -- Curve 6 – Crosslevel Must Be Considered
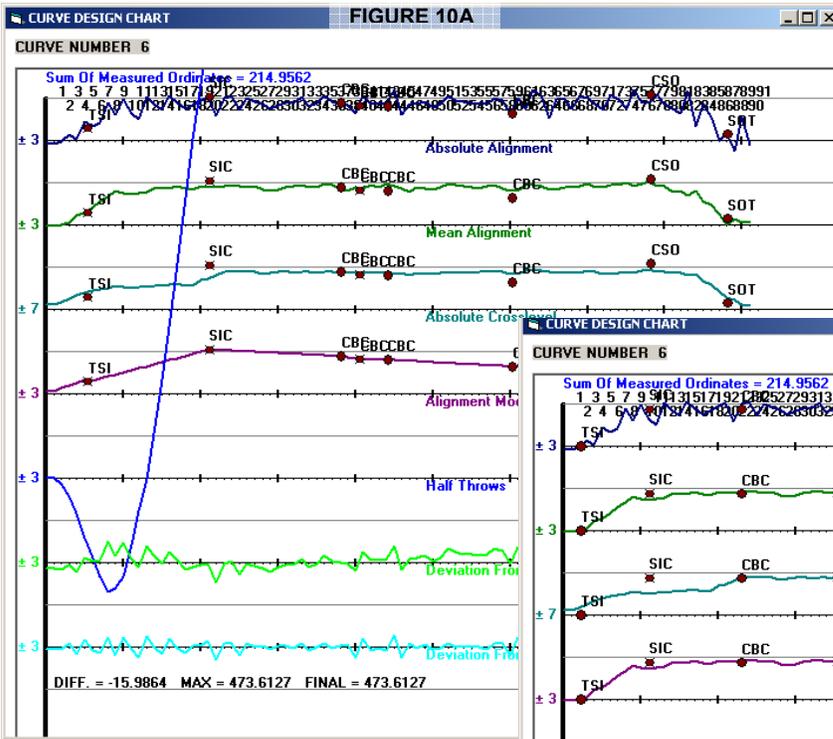
FIGURE 10A

Figure 10A shows the effects of Crosslevel in a speed change curve. Additional CBC points are introduced in the model for solution of both crosslevel and alignment.
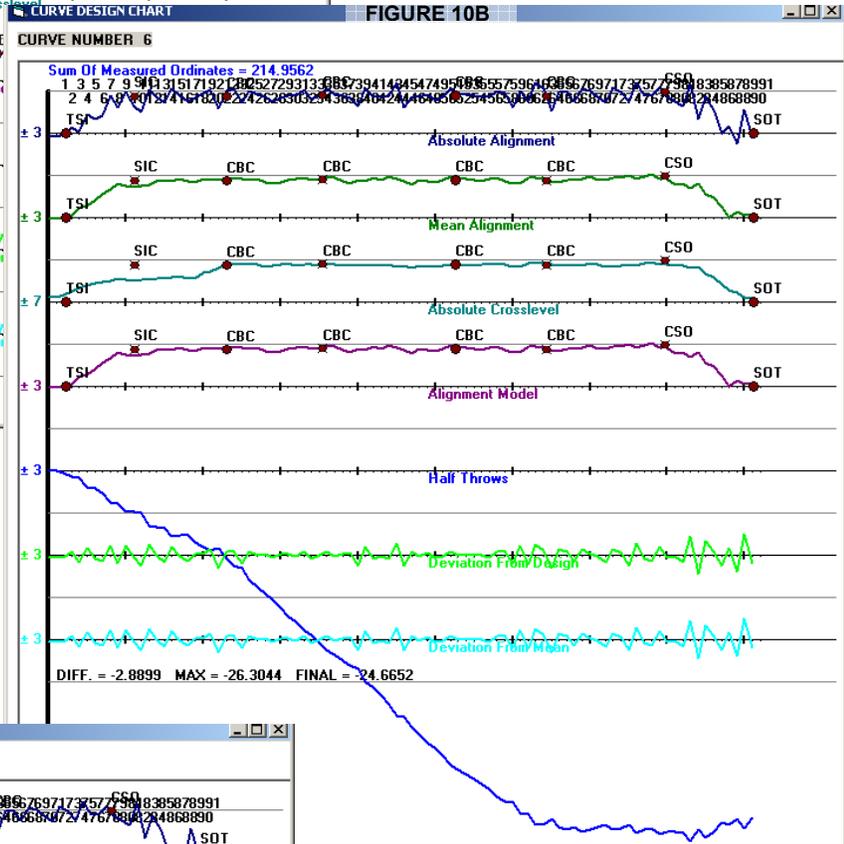
FIGURE 10B

Figure 10B shows using the Mean Alignment as a model for Alignment is not a solution.
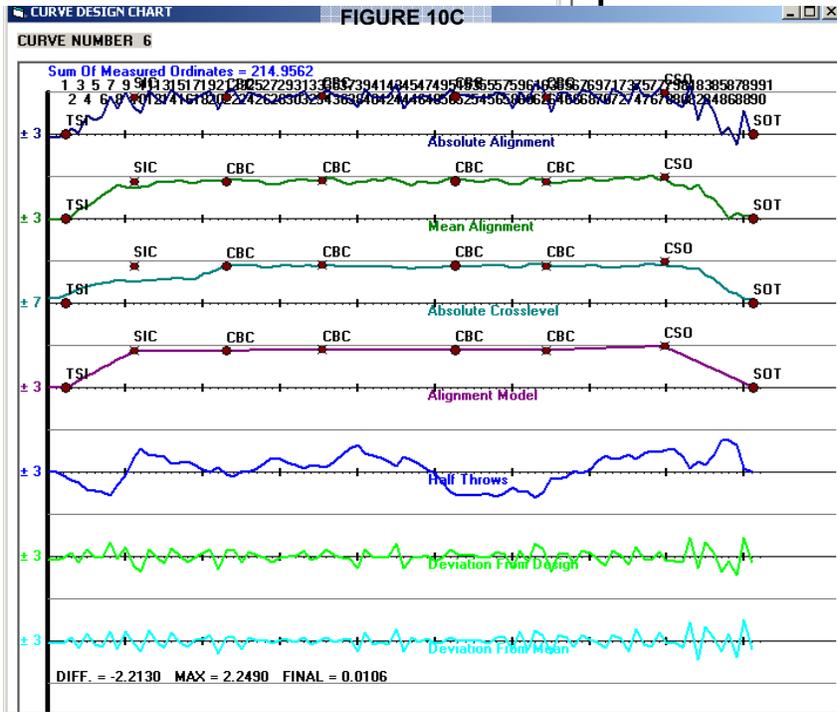
FIGURE 10C

Figure 10C shows the speed change curve alignment solution requires the CBC points because the curve body is not absolutely constant. This should be expected in a speed change curve.

The speed change Crosslevel solution is achieved with essentially the same software.

Figure 11 -- Curve 7 – Automatic Speed Change Points
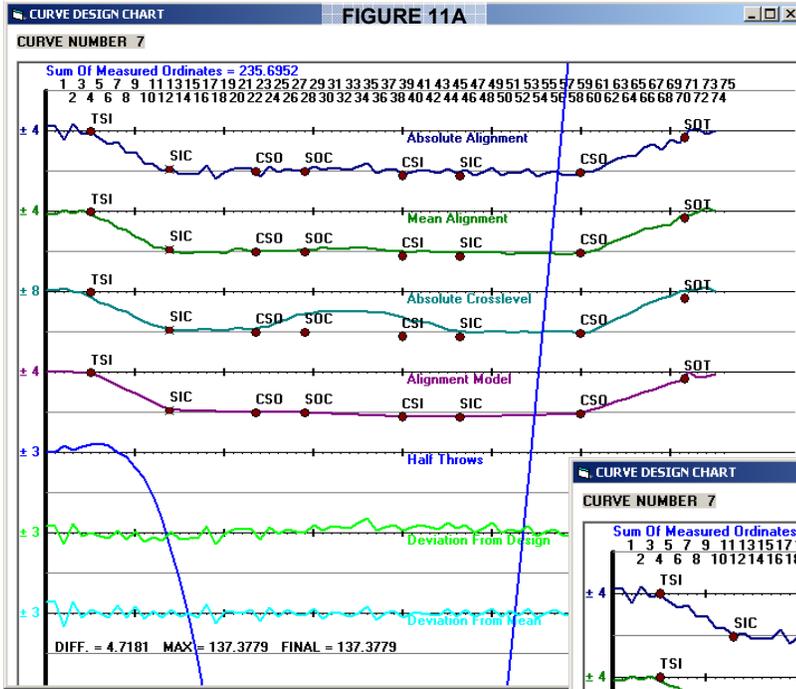
Figure 11A another speed change curve and the curve points were inserted during the Alignment data acquisition scan

The extra curve points make adding CBC points unnecessary
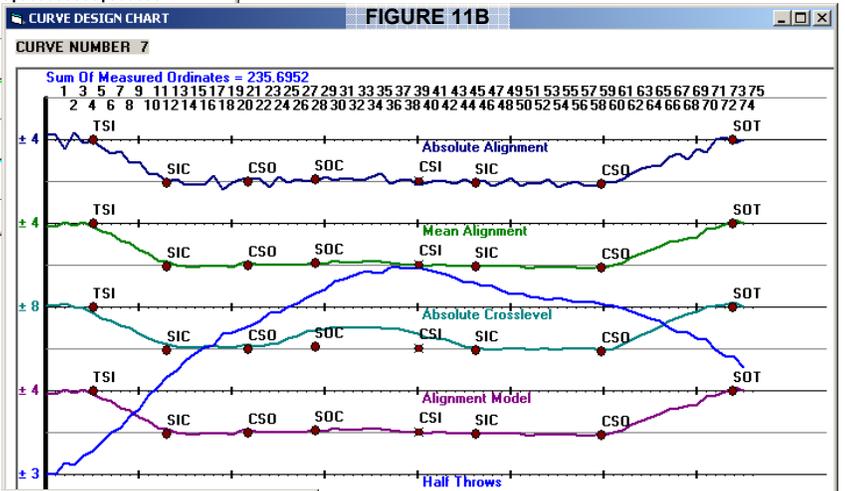
Figure 11B shows again that using the Mean curve is not a solution. Using the mean value for geometry testing still has merits in that if no exceptions are found then there are not any exceptions likely.
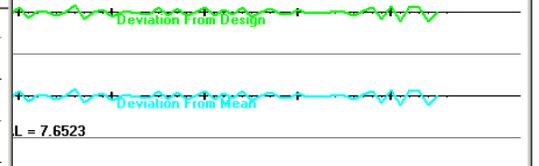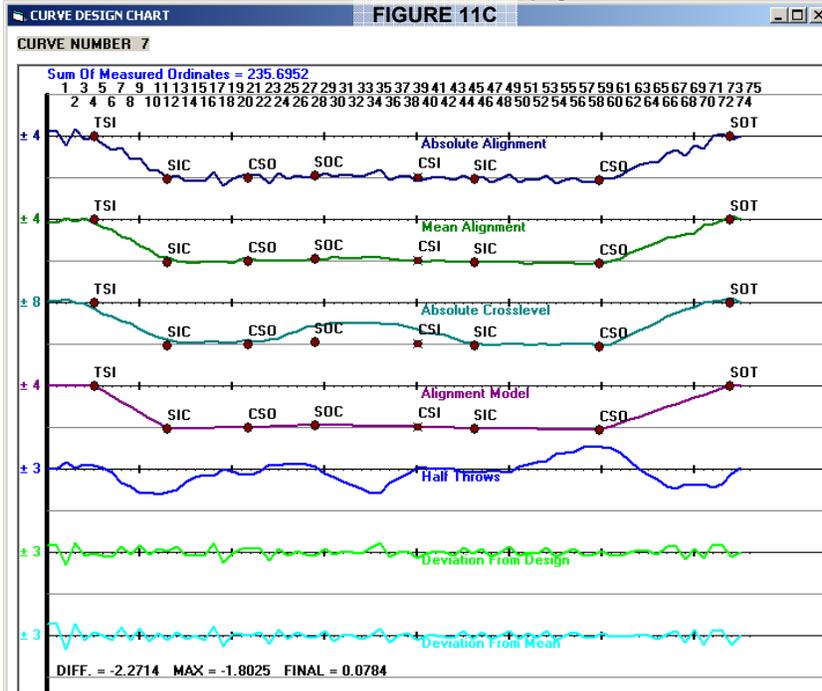
The solution shows that the curve body is not absolutely constant.

Figure 12 -- Curve 8 – Compound Curve
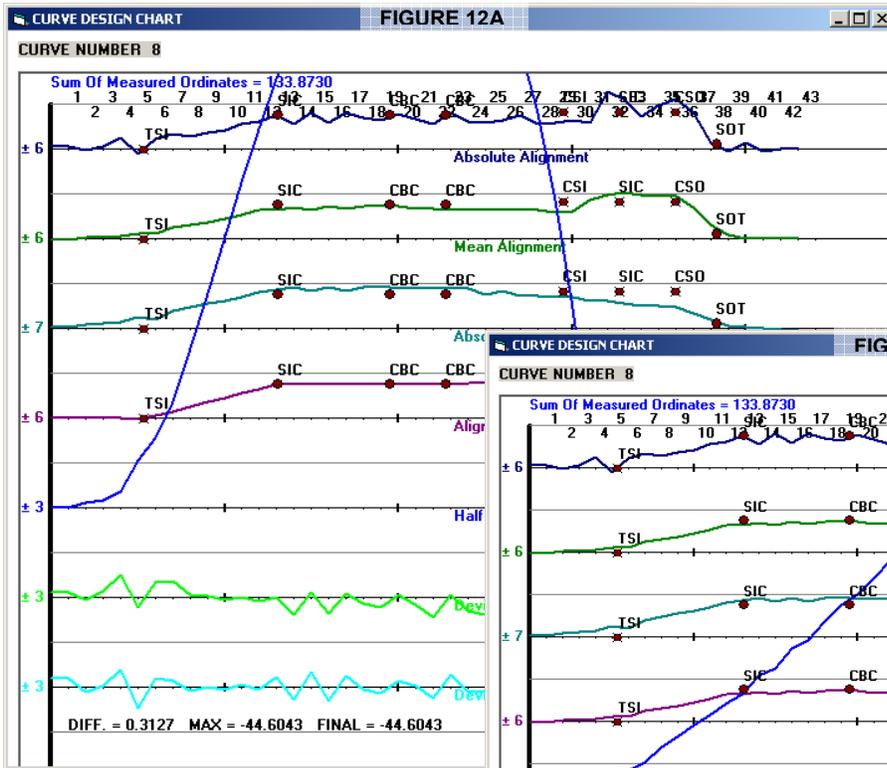
Figure 12A is a compound curve and demonstrates the power of the ACA function.

CBC points are introduced because the curve body is not absolutely constant.

Figure 12B shows how using the Mean Value model will open the door for false exceptions.
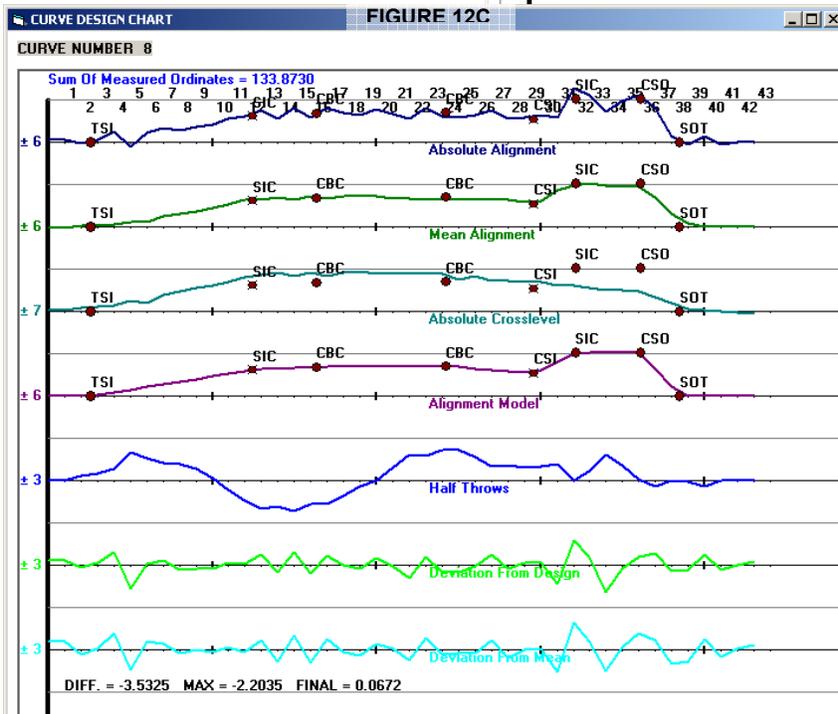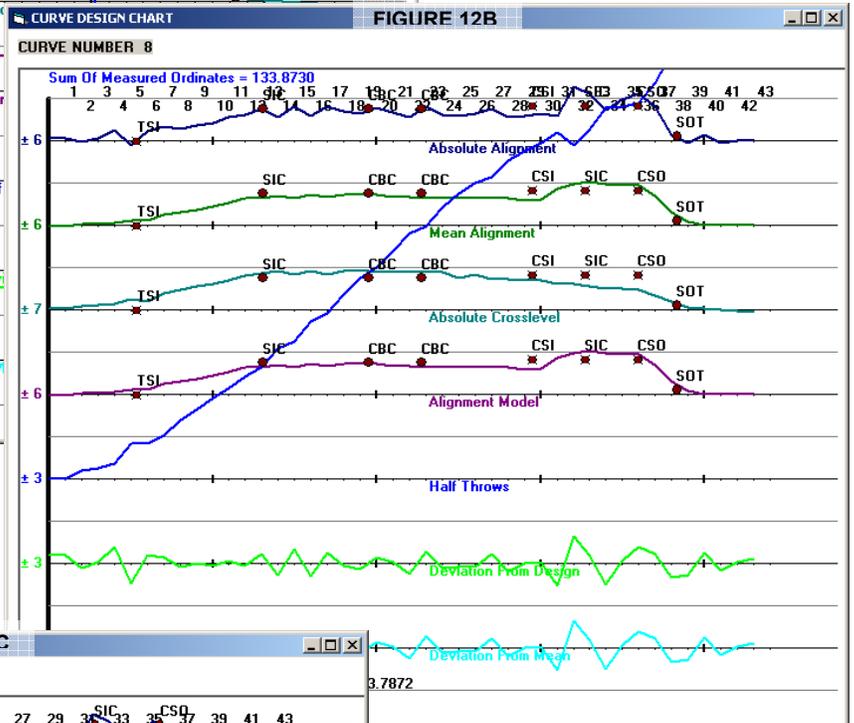
But in this case the Deviation from Design solution in Figure 12C still shows the same deviations as the Deviation from Mean.

Figure 13 -- Curves 9 and 1 – Fixed Curves
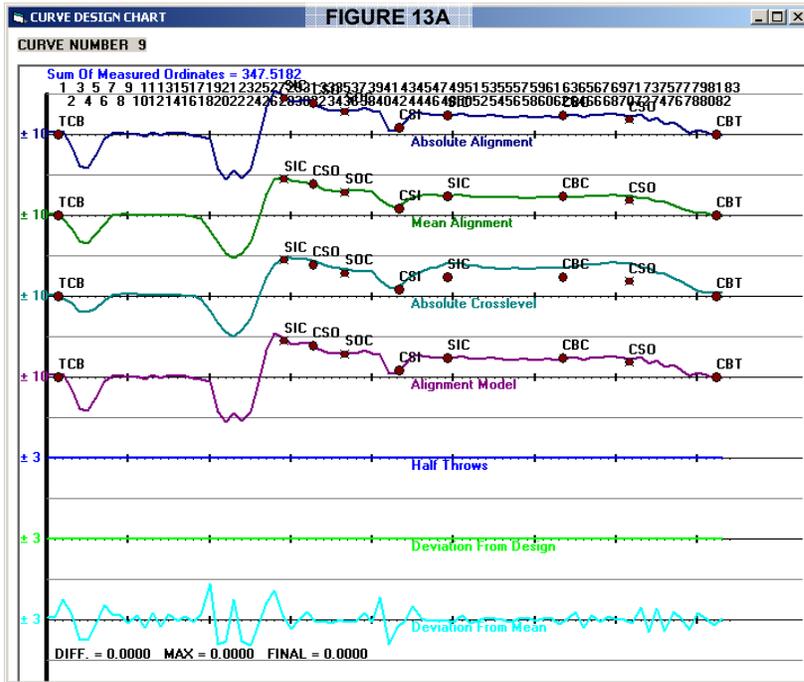
Curve 9 in Figure 13A is determined manually to be a fixed curve. The modeling of a fixed curve is established by changing the initial and final curve points to a unique pair, or by any other means, so the deviation from design is a constant zero. The curve points between the end points are not usually needed. This also demonstrates that the deviation from mean is not zero, of course, and is in fact the source of most false track geometry alignment defects.

Curve 1
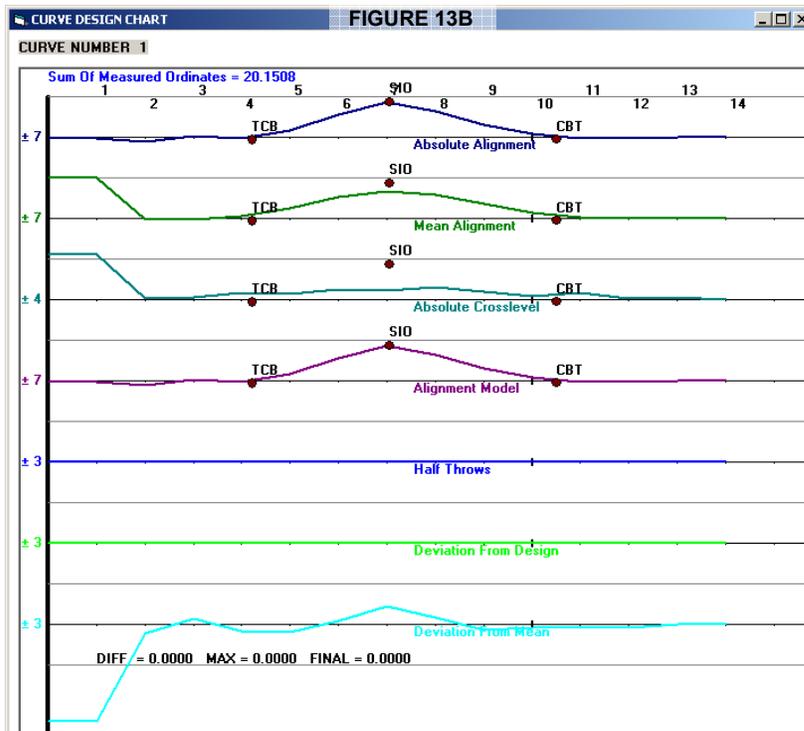
Curve 1 is also a fixed curve. Curve 9 is in a tunnel on direct fixation and Curve 2 is a turnout or switch. Both are handled such that the data acquisition serves to establish the foot-by foot shape for the database.

Switches can be classified and saved as templates to further justify using this data for geometry testing.

Figure 14 -- Curve 10 – Requiring Manual Assistance
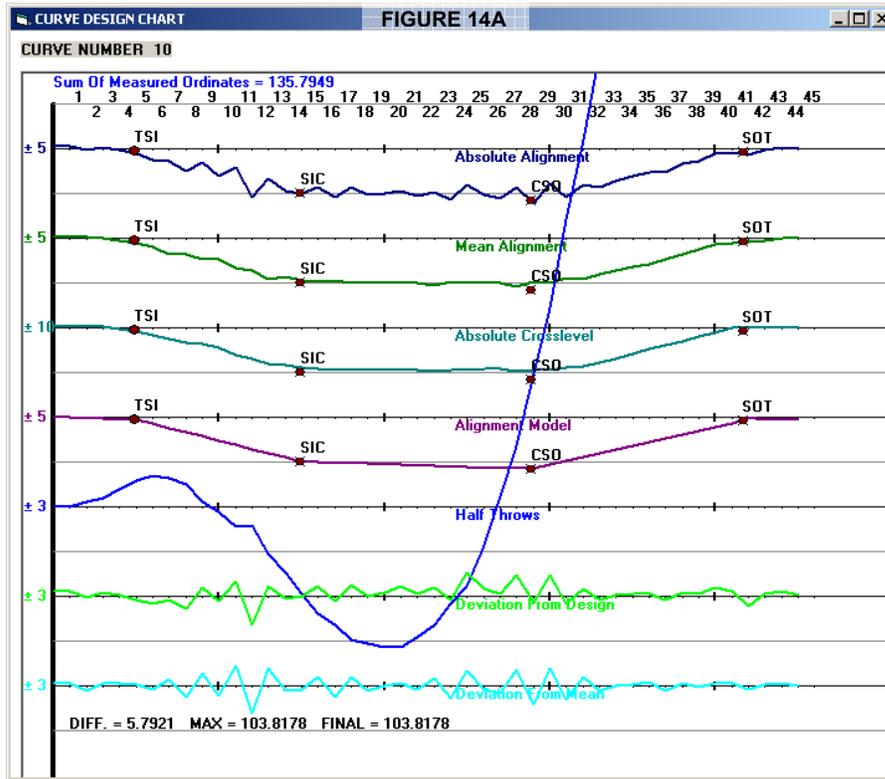
figure 14A shows the original location of the curve points after data acquisition.

The curve looks simple to solve but it requires manual relocation of the CSO point.
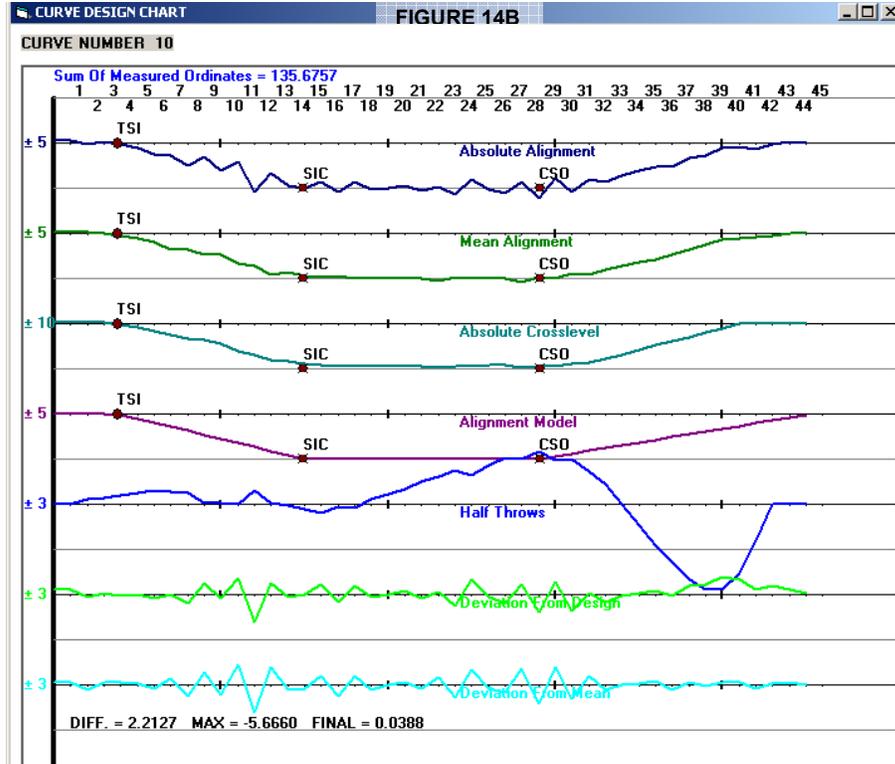

Tthe result in Figure 14B happens when trying to use either SCA or ACA

When manually relocating the curve points a solution like Figure 14C is typical
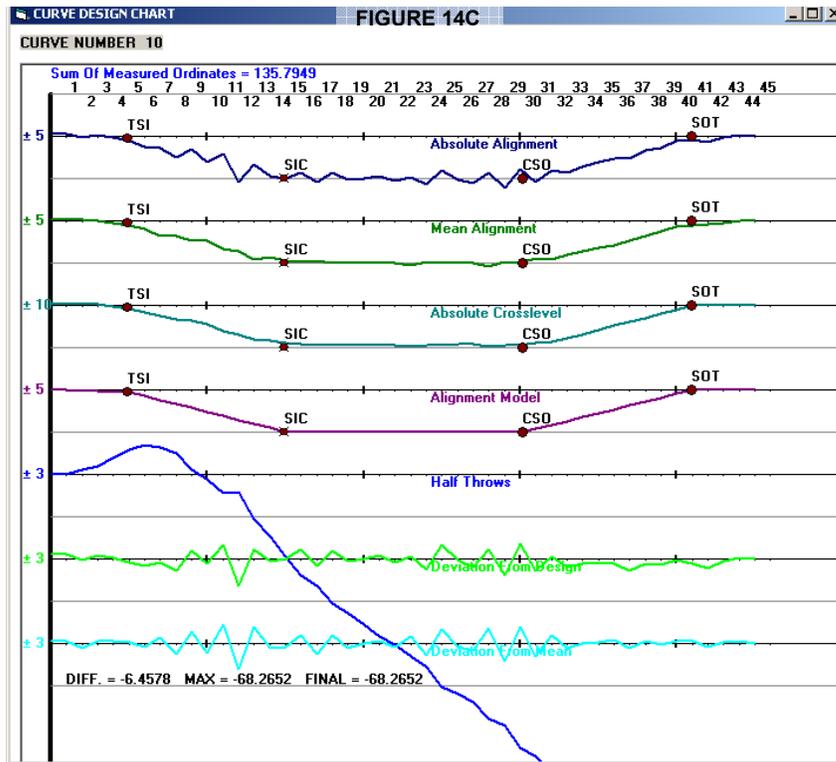
FIGURE 14C

But using SCA the solution is found to be like Figure 14D.
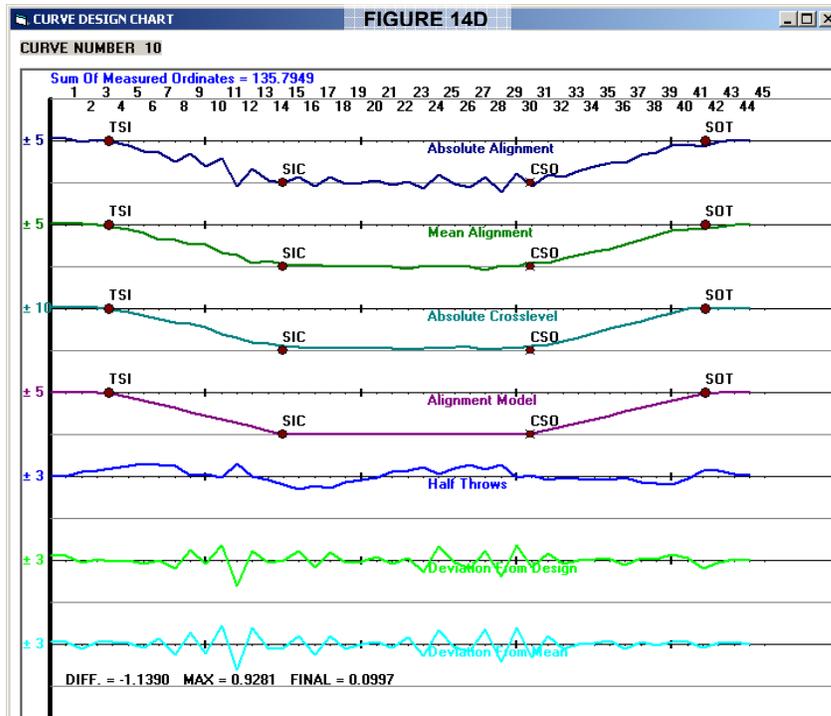
FIGURE 14D

Figure 15 -- Curve 11 – Complex Curve Solutions
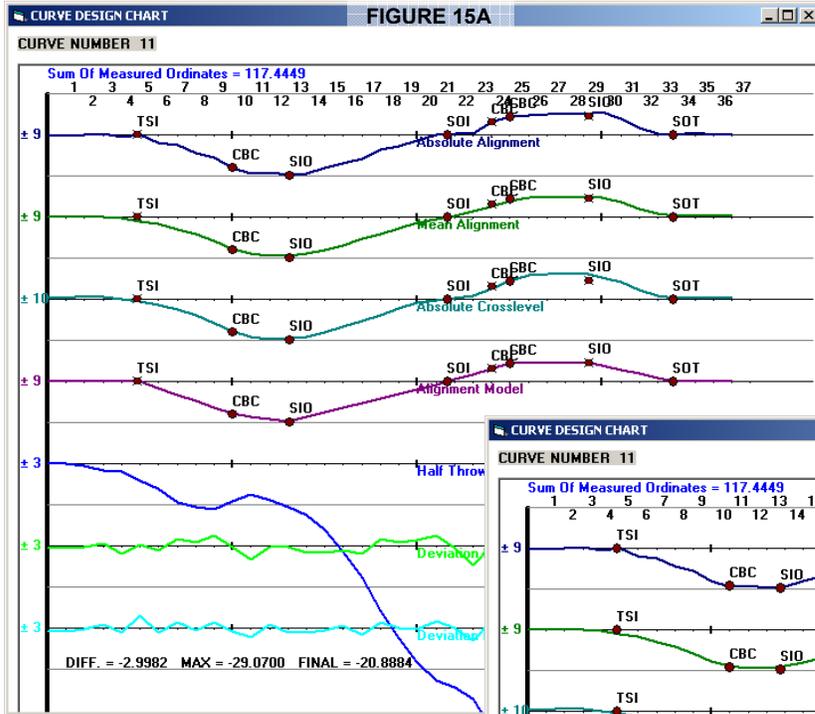
FIGURE 15A

Figure 15A shows the original points with a CBC point added

FIGURE 15B

Figure 15B is a graph using the mean value as a model. It is not a solution.
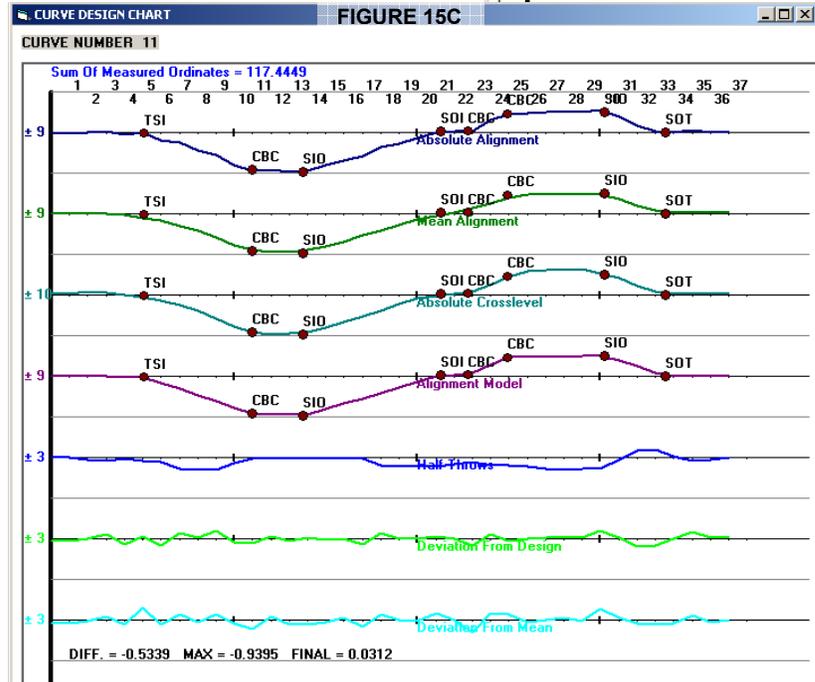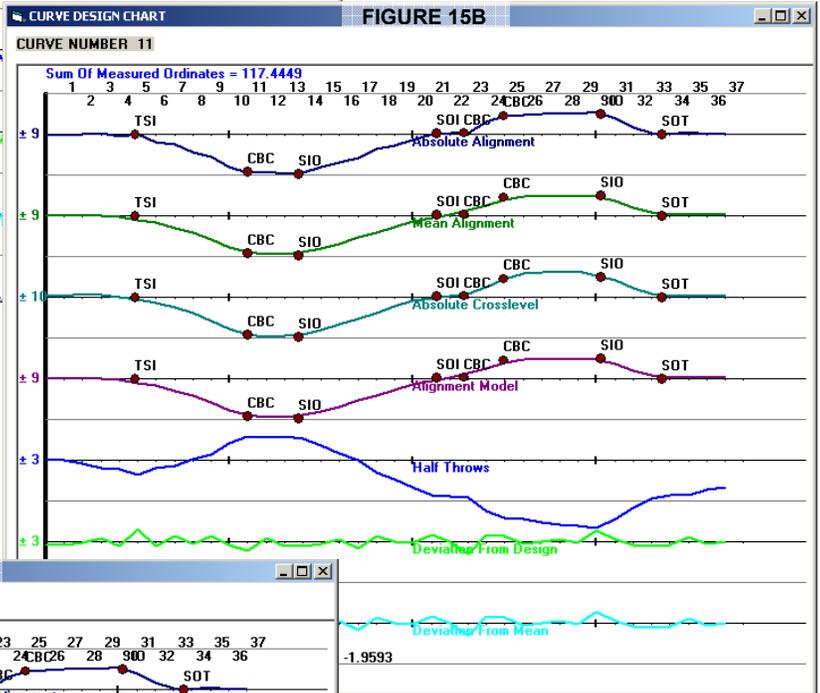
FIGURE 15C

Figure 15C is a solution using manual and semiautomatic methods. The automatic solution does not work.

This could be a fixed curve. Also, the semiautomatic solution scheme is the basis for an automatic solver for compound curves.

Figure 16 -- Curve 12 – Manual Curve Points
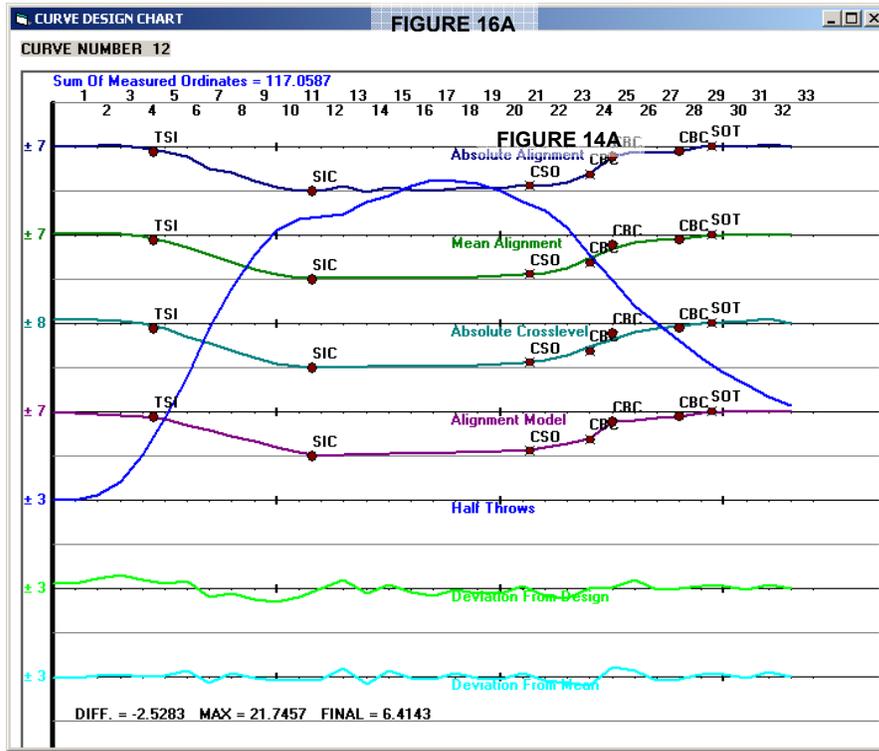
Figure 16A is the curve with the original points and the CBC points added manually
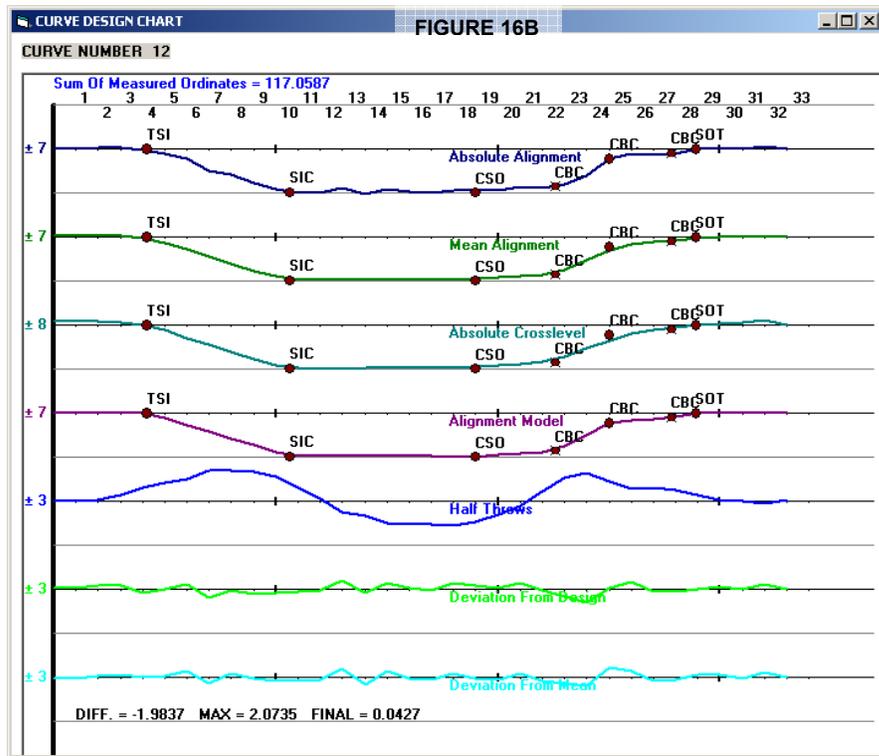

Figure 16B is a solution using ACA but this may also be a fixed curve.

This is not a geometry defect

Figure 17 -- Curve 13 – Automatic Curve Points
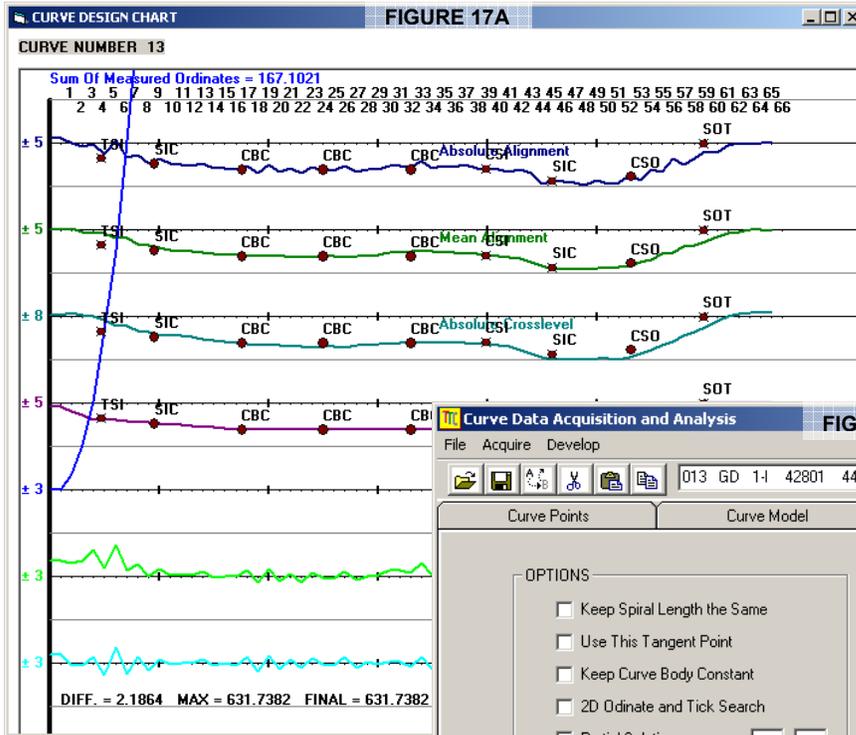
Figure 17A shows the original curve points with the CBC points added during data acquisition
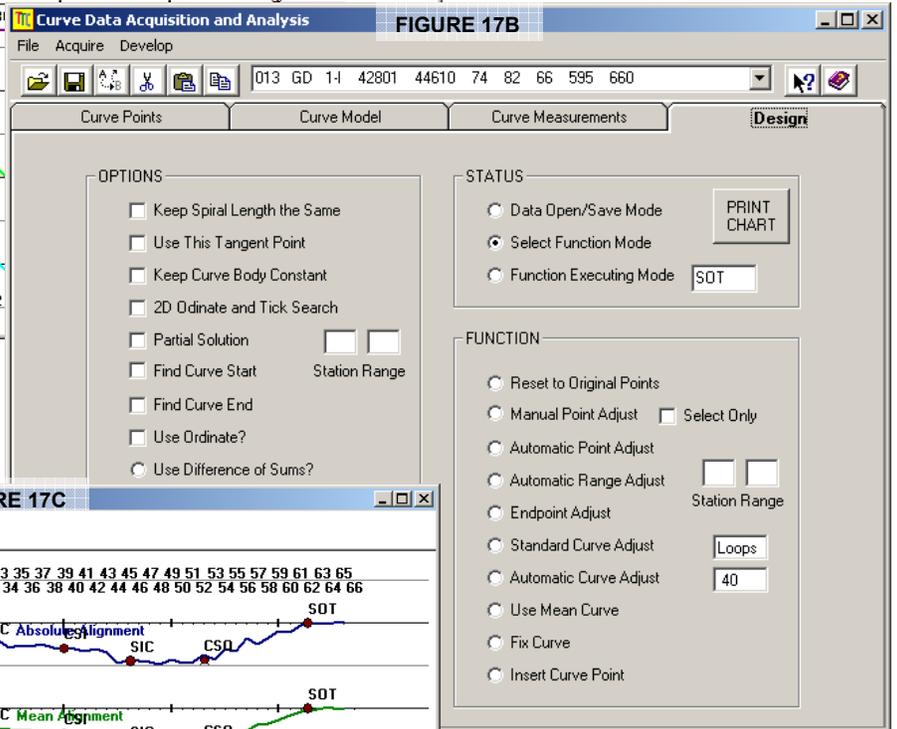
The Design Tab in Figure 17B shows the setup to cycle the ACA 40 times.
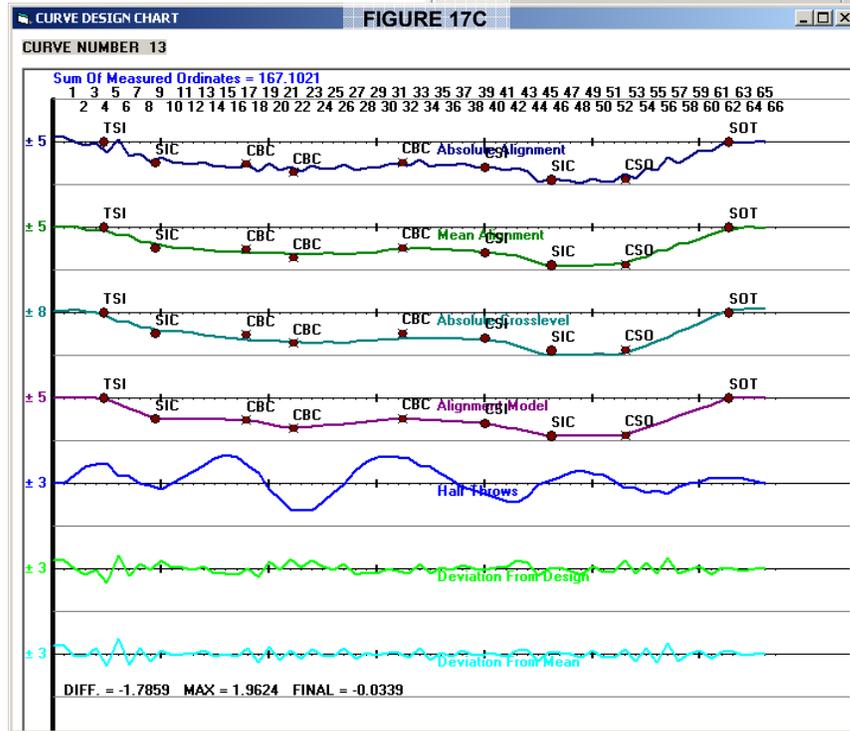
Figure 17C shows the solution after 40 ACA cycles but Curve 13 is most likely a fixed curve

Figure 18 -- Curve 14 – Complex Compound Curve
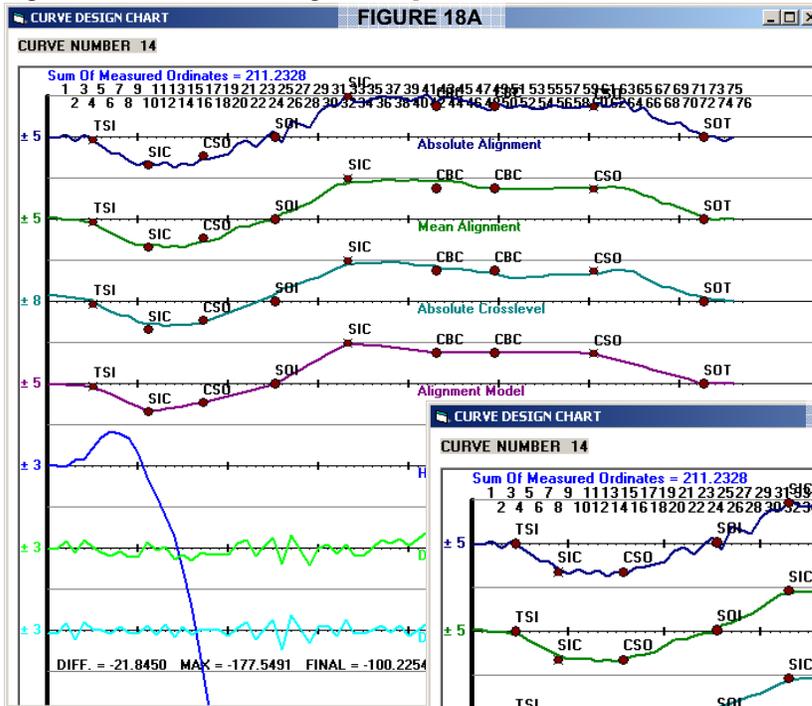
Figure 18A shows the original points of Curve 14

Mean Curve is not a solution as shown in Figure 18B.
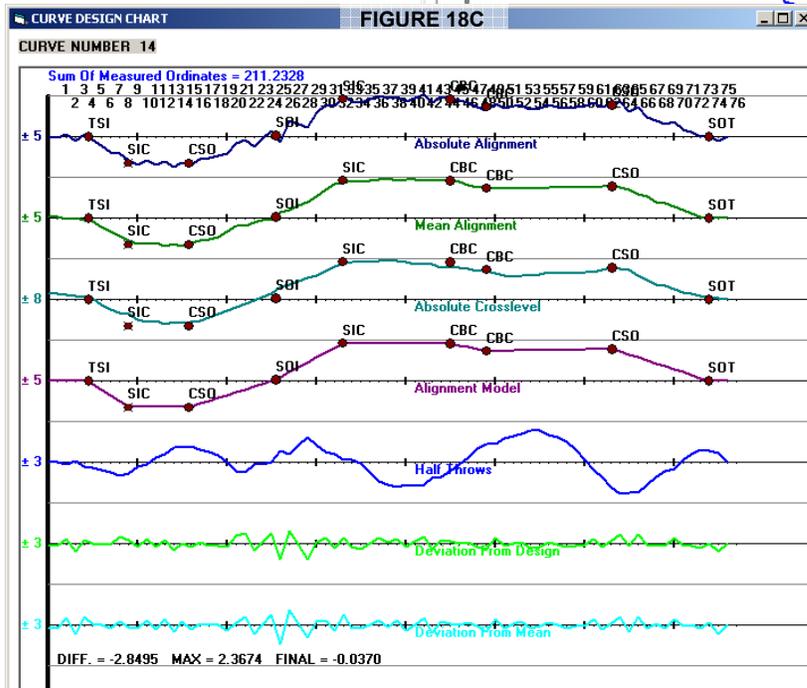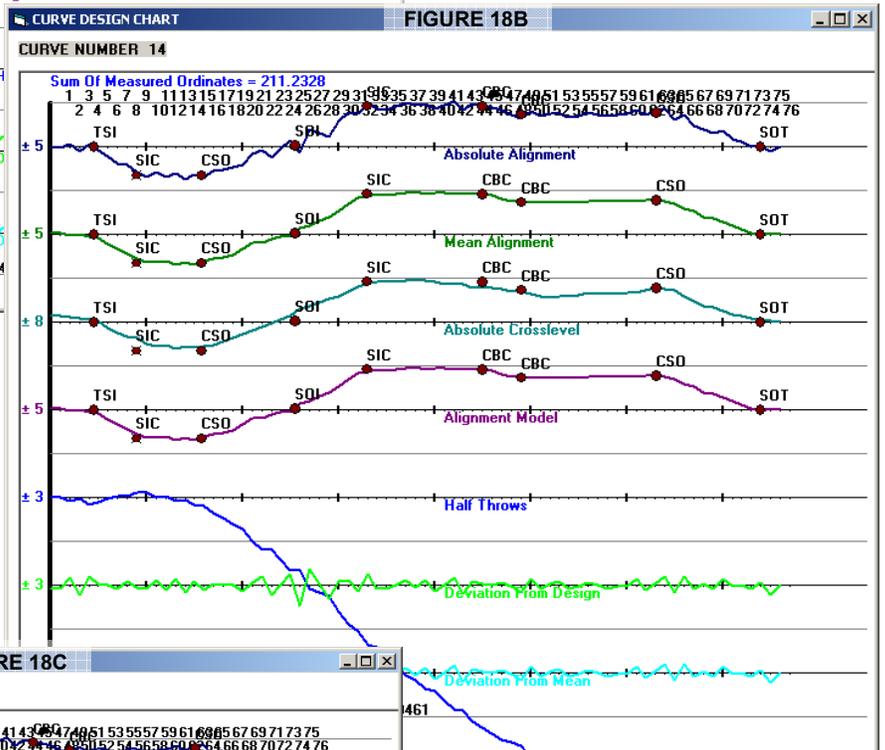
Figure 18C is a compound curve solution using ACA after adding the CBC points and manually adjusting the curve points

Curve 14 may also be a fixed curve

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Figure 19 -- Curve 15 – Questionable Curve

There is a question about the nature of this curve in Figure 19. It is not a geometry issue so it is reasonable to Fix it while investigating its design.
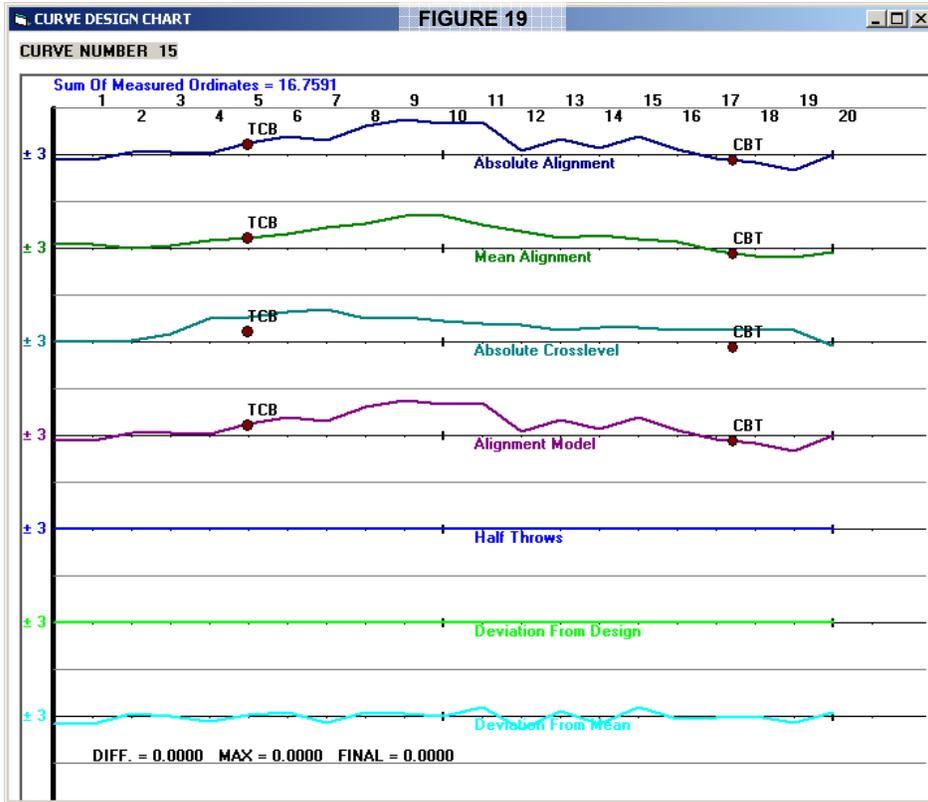
Figure 20 -- Curve 16 – Questionable Data
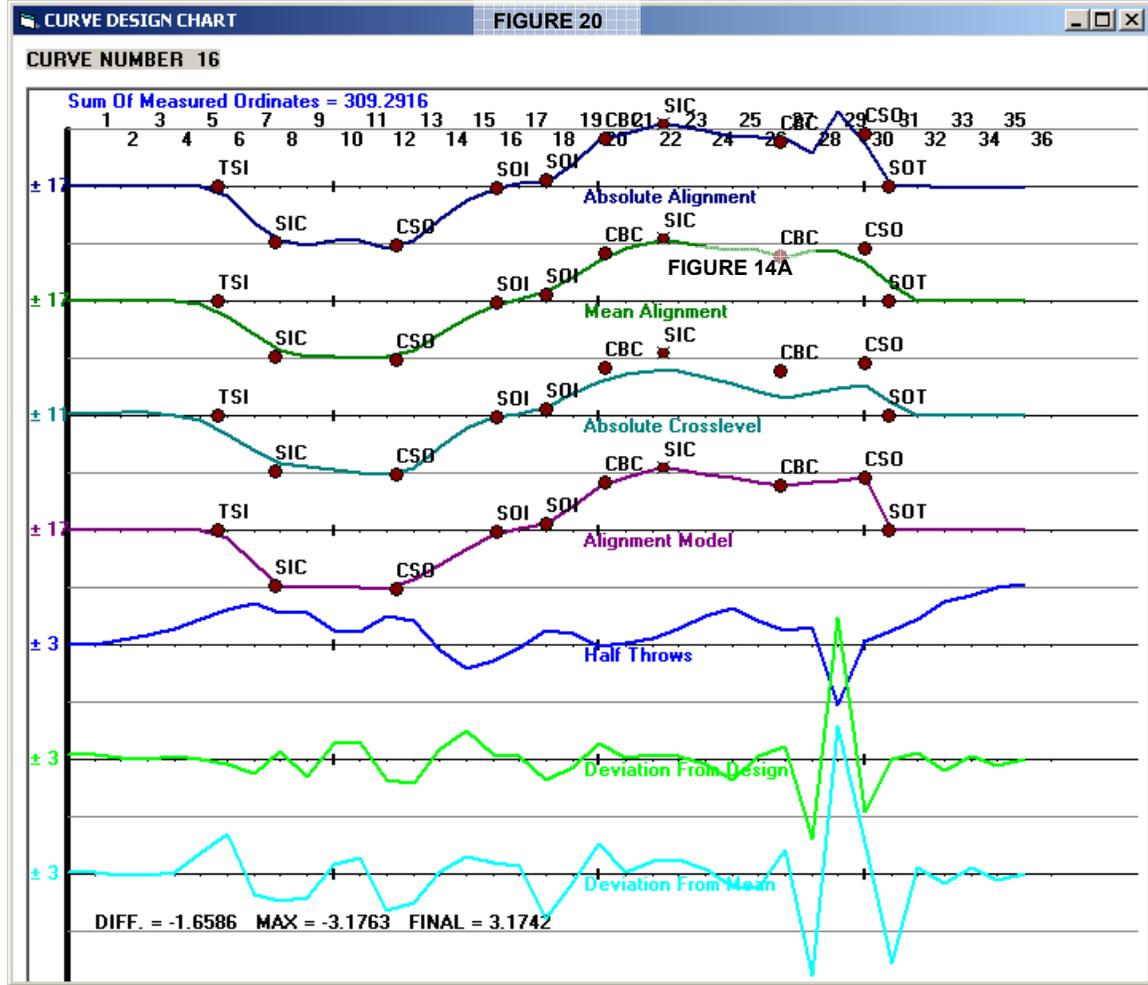
There is a question about the end of the curve shown in Figure 20. It looks like a geometry issue and would appear as such in the geometry test.

CONCLUSIONS

This project developed and tested a concept to determine actual track geometry alignment and cross level in sharp curves and turnouts in rail transit systems. The improved track geometry testing system utilized the current track design or a "best fit" track design as a baseline for testing rail rapid transit and light rail transit track. This concept provides transit systems the ability to accurately identify track geometry defects based on their track design, thereby reducing maintenance time and cost. Transit agencies could also benefit by utilizing the "best fit" track design data generated by the track geometry system as an alternative to improve their current track design.

Track classification standards in sharp level curves and turnouts cannot be defined using the industry's current geometry testing methods. Therefore, during an automated track geometry test, this type of track is not properly classified, and required maintenance may be ill defined. When using conventional methods of track geometry testing, the track design criteria are not considered. Automated track geometry tests using original design criteria or calculated "best fit" designs would provide accurate results for evaluating track alignment deviations. Evaluating current track conditions and managing these conditions on rail rapid transit and light rail transit systems could be greatly improved if this concept is implemented. Time and costs currently incurred by transit systems in evaluating and managing their track could be significantly reduced. This would improve the efficiency of the track evaluation and of tamper maintenance, which would enable the transit agency to focus its time and efforts on actual track problems, contributing to improved track safety.

It is now clear that the "desired track" is not always the theoretical mathematical model but is rather more complex. The existing track, properly maintained free of any irregularities, is very close to the "desired" track design. The effort to date has enhanced the power of the tools needed to capture the more complex designs. This project has been able to create the method whereby a digital foot-by-foot description of the "regular safe track configuration" can be generated. This track design data is then used as the basis for identifying "exceptions to design" that will be used in exception reports. The project introduces manual, semi-automated and automated processes for creating a permanent "track design" database.

Two discoveries came to the fore in completing the technical work. First of all, it is impractical if not impossible to construct perfectly "ideal" curves that fit the track geometry data. It has been necessary to develop and apply techniques that accommodate the existing track as is after track construction and maintenance engineers have accepted it. Secondly, the current practice of determining geometry exceptions by comparing with the mean value curve is logically misleading. The mean value curve is not a solution. It seems to be impossible for a tamper to move the existing track to a "mean value" position even if it appears desirable. The existing track position, however, is closest to being the desired position. Therefore the most logical approach is to use existing track geometry together with visual curve point verification to initialize the curve design modeling procedure.

FINDINGS AND INVESTIGATORS RECOMMENDATIONS

This effort has brought the development of curve designs for the track design databases to the point of useful results. Further automation is achievable. On the other hand, the level of automation needed may be much less than the investigators had originally thought. The crucial factors include the following:

1. The existing track design is much nearer to the desired track design than it was originally thought, so the addition of more sophisticated curve design models will not be necessary.
2. The stick model with points added, (either manually or automatically), is an adequate approach when not using existing track design.
3. The design of these models is no different than maintaining the track and developing tamper inputs, so it dovetails into the common engineering tasks of track maintenance.
4. The software will be made amenable for use by track engineers to use for track design and maintenance decisions.

5. Track geometry testing does not need to calculate mean values. The use of means is an assumption that not only leads to the false exception problem, but is also a false objective problem. The mean value is not an achievable or even desirable track design.

The investigators believe that the result of this Transit IDEA project could lead to a follow-on effort for automated applications. The effort could put track design databases into a new prototype automated track geometry test environment. The desired objectives in practice could include;

1. true exceptions in geometry test reports,
2. management tools for geometry test programs,
3. realtime detection and flagging of geometry defects, and
4. automation of the curve maintenance tamper application

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The tasks of follow-on effort could include one of the following:

1. Create a comprehensive list of the key track test events for annotation of the digital track charts.
2. Make a specialized data acquisition run for the operator to locate the key track events in the geometry data.
3. Manually review and adjust, the key track events as required.
4. Use the technology of this completed project to establish the curve points for accepted track.
5. Generate the complete digital track chart including seasonal variations using seasonal geometry test results.
6. Calculate current track geometry exceptions using the new technology.
7. Apply lining and tamping machine inputs from the current geometry test to transfer the track to the accepted track design position.
8. Document routine procedures to perform 3 through 7 above for each periodic geometry test.

Follow-on effort would involve field tests including automation of the tamping and lining process at MBTA and WMATA to create and evaluate the track designs.

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