Transportation

Kentucky Transportation Center Research Report

University of Kentucky *Year* 2017

Coaxing HIS Data from Mandli Pavement Scans

Eric R. Green* William Nicholas Staats†
Erin Lammers‡ Teng Alex Wang**

*University of Kentucky, eric.green@uky.edu
†University of Kentucky, william.staats@uky.edu
‡University of Kentucky, erin.lammers@uky.edu
**University of Kentucky, teng-wang@tti.tamu.edu

This paper is posted at UKnowledge.
https://uknowledge.uky.edu/ktc_researchreports/1588

Coaxing HIS Data from Mandli Pavement Scans

Kentucky Transportation Center Research Report – KTC-17-26/SPR17-548-1F

DOI: https://doi.org/10.13023/KTC.RR.2017.26

The Kentucky Transportation Center is committed to a policy of providing equal opportunities for all persons in recruitment, appointment, promotion, payment, training, and other employment and education practices without regard for economic or social status and will not discriminate on the basis of race, color, ethnic origin, national origin, creed, religion, political belief, sex, sexual orientation, marital status, or age.

Kentucky Transportation Center
College of Engineering, University of Kentucky Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

© 2018 University of Kentucky, Kentucky Transportation Center
Information may not be used, reproduced, or republished without KTC's written consent.

KENTUCKY Transporation Center

Kentucky Transportation Center • University of Kentucky
176 Raymond Building • Lexington KY 40506 • 859.257.6898 • www.ktc.uky.edu

University of Kentucky

Research Report
KTC-17-26/SPR17-548-1F

Coaxing HIS Data from Mandli Pavement Scans

Eric R. Green, PE
Principal Investigator

William Staats
Research Engineer

Erin Lammers
Research Engineer

and

Teng (Alex) Wang, PhD
Postdoctoral Scholar

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

in Cooperation with

Kentucky Transportation Cabinet
Commonwealth of Kentucky

and

Federal Highway Administration
U. S. Department of Transportation

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the University of Kentucky, the Kentucky Transportation Center, the Kentucky Transportation Cabinet, the United States Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. The inclusion of manufacturer names or trade names is for identification purposes and should not be considered an endorsement.

November 2017

1. Report No. KTC-17-26/SPR17-548-1F	2. Government Accession No.	3. Recipient's Catalog No
4. Title and Subtitle Coaxing HIS Data from Mandli Pavement Scans		**5. Report Date** November 2017 **6. Performing Organization Code**
7. Author(s): Eric R. Green, PE, William Staats, Erin Lammers, and Teng (Alex) Wang, PhD		**8. Performing Organization Report No.** KTC-17-26/SPR17-548-1F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, Kentucky 40506-0281		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** SPR 17-548
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet 200 Mero Street Frankfort, Kentucky 40622		**13. Type of Report and Period Covered** Final Year 1/1 **14. Sponsoring Agency Code**

15. Supplementary Notes
Prepared in cooperation with the Kentucky Transportation Cabinet and the Federal Highway Administration

16. Abstract
The Kentucky Transportation Cabinet (KYTC) Division of Planning's Highway Information Systems (HIS) database provides geometric information about horizontal and vertical curves, but its accuracy is unknown. An updated method of pavement analysis collects data by scanning the pavement as a van equipped with Mandli software drives the area of interest. The scans provide detailed information that can be used to calculate roadway geometry characteristics (e.g., curve radius, cross slope/superelevation, and grade). This study evaluated the ability of the Mandli data to support curve advisory calculations and find a way to utilize Mandli data to improve the existing HIS database. To this end, the report includes a literature review to determine applicability of data, a series of data validation steps to define Mandli's accuracy, and an evaluation of tools that convert Mandli into usable HIS data. The data attributes of focus are horizontal curve radius, grade, and cross slope. Horizontal curve radii values were evaluated using University of Nevada Reno's ArcMAP plugin, Florida DOT's curvature extension tool, and the University of Kentucky's Curvature Automatic Tool (UKCAT). These tools were tested for usability, efficiency, and accuracy. Vertical curve attributes, including grade and cross slope, were evaluated by comparing Mandli data to manual field measurements, design plans, and other data collection methods. After data collection and analysis, researchers outline a newly developed method for converting Mandli data into a usable form and implementing it in HIS.

17. Key Words	18. Distribution Statement		
GPS roadway data, Mandli, curves, inventory, advisory speeds, superelevation, grade, radius of curvature	Unlimited, with approval of the Kentucky Transportation Cabinet		
19. Security Classification (report) Unclassified	**20. Security Classification (this page)** Unclassified	**21. No. of Pages** 32	**22. Price**

Table of Contents

1 Introduction 2
1.1 Background 2
1.2 Problem Statement 2
1.3 Objectives 2
1.4 Approach 3
2 Literature Review 4
2.1 Google Earth Elevation Data Extraction and Accuracy Assessment for Transportation Applications 4
2.2 Evaluating the Correlation between Vertical Curve Features and Crash Rates on Highways 5
2.3 Heuristic Approach to Identifying Horizontal Curves and Their Parameters Given Lidar Point Cloud Data 6
2.4 Development of Crash Prediction Models for Curved Segments of Rural Two-Lane Highways. 6
3 Methodology/Approach 8
3.1 Horizontal Curve Assessment 8
3.1.1 Florida DOT Curvature Extension Tool 8
3.1.2 UNR CATER Curvature Tool 8
3.1.3 UK Curvature Automatic Tool 9
3.1.4 Tool Comparison 11
3.2 Grade and Cross-Slope Assessment 13
3.2.1 Data Collection 13
3.2.2 Data Validation 14
3.2.3 Data Analysis 18
3.2.3.1 RMSE 18
3.2.3.2 Statistical Analysis 18
3.2.3.3 Sensitivity Analysis 19
4 Results 21
4.1 Horizontal curvature results 21
4.2 Grade results 21
4.3 Cross-slope results 22
5 HIS Conversion and Implementation 23
5.1 Horizontal Curves: Radius and Cross-slope 23
5.1.1 CARS where available 23
5.1.2 UKCAT Matlab Tool 24
5.1.3 Theoretical: Cross Slope from Mandli 25
5.2 Vertical Curves: Grade 26
5.3 Summary of HIS Datasets 28
6 Conclusion 29
6.1 Summary 29
6.2 Recommendations 29
7 Bibliography 31
8 Appendix A: Graphs 32

List of Tables and Figures

Table 1: Statistical summary for all curves 19
Table 2: Formatting CARS to HIS 24
Table 3: Formatting UKCAT tool to HIS 24
Table 4: Formatting CARS and Mandli cross-slope to HIS 25
Table 5: Grade HIS example 27
Table 6: Summary of HIS datasets 28

Figure 1: Google Earth Elevation Data Extraction System (GEEDES) 4
Figure 2: Segmentation of a curve with defined features 5
Figure 3: Data segmentation and curve identification process 6
Figure 4: Output from UKCAT Matlab tool 10
Figure 5: UKCAT tool's potential ability to distinguish spiral curves from circular curves 11
Figure 6: Comparison of UKCAT and UNR CATER tools 12
Figure 7: Comparison of UNR Cater tool and CARS data 12
Figure 8: Comparison of UKCAT tool and CARS data 13
Figure 9: Comparison of Mandli cross-slope data to field data 14
Figure 10: Comparison of Mandli grade data to field data 15
Figure 11: Design plans (left) versus Mandli and field measurements (right). 16
Figure 12: Mandli superelevation vs CARS superelevation 17
Figure 13: Mandli superelevation versus absolute value of CARS superelevation 17
Figure 14: Relationship between curve radius, cross-slope, and resulting advisory speed 20
Figure 15: Example of Mandli grade versus field grade graphs 21
Figure 16: Example of Mandli grade versus field grade graphs 21
Figure 17: CARS output 23
Figure 18: UKCAT tool output 24
Figure 19: CARS plotted in GIS with Mandli spatial overlay 25
Figure 20: CARS output 25
Figure 21: Finding tangent from CARS and slope from Mandli 26
Figure 22: Example segmentation of Mandli grade data 27

Acknowledgements

The following individuals contributed to the successful completion of this project through their participation on the Study Advisory Committee:

Josh Wentz, Chair ..... KYTC Division of Planning
John Moore ..... KYTC Division of Planning
Jarrod Stanley ..... KYTC District 7
Thomas Gilpin ..... KYTC Division of Maintenance
Anthony Damron ..... KYTC Engineer Scholar
Tyler Blair ..... KYTC Engineer Scholar
Josh Hornbeck ..... KYTC District 4
Troy Woodyard ..... KYTC Division of Highway Design
Chad Shive ..... KYTC Division of Maintenance
Ramsey Quarles ..... KYTC Division of Planning
Deanna Mills ..... KYTC Division of Planning
Keith Dotson ..... KYTC Division of Planning
Corbett Caudill ..... KYTC District 10

Executive Summary

The Kentucky Transportation Cabinet (KYTC) Division of Planning's Highway Information Systems (HIS) database includes various geometric elements of horizontal and vertical curves. These have been collected over time with varying detail and unknown degrees of accuracy. For the past several years, the Division of Maintenance has been collecting pavement scans via Mandli software on all state roads. The scans provide detailed information that can be used to calculate roadway geometry, including horizontal curve characteristics such as superelevation and vertical curve characteristics such as grade. KYTC asked Kentucky Transportation Center (KTC) researchers to evaluate the accuracy of Mandli data and determine its potential use in the HIS database.

This study's main objective was to identify methods for using Mandli data to improve the existing HIS database. To fulfill the study objective, researchers performed a literature review to determine applicability of data, checked Mandli data against other data sources such as manual ground measurements, assessed existing tools for converting Mandli into usable HIS data, and developed novel methods for converting Mandli into HIS data. Researchers also developed an estimate of the level of effort needed to execute a statewide review and update of HIS.

Three data attributes were of interest: horizontal curve radius, grade, and cross slope. Methodologically, researchers approached grade and cross slope similarly, but studied curve radius separately. Horizontal curves were analyzed using three data processors: University of Nevada Reno's ArcMAP plugin, Florida DOT's curvature extension tool, and the University of Kentucky's Curvature Automatic Tool (UKCAT). Each tool was used to compile Mandli data and identify curve locations and curve attributes. The tools were tested for usability, efficiency, and accuracy. Rieker's Curve Advisory Reporting System (CARS) served as the baseline against which the performance of these tools was compared; it provides accurate results (see Section 1.4, paragraph 4.) and is readily available to the Cabinet. KTC researchers found UKCAT to be accurate, fast, and easy to use. Using this tool to analyze Mandli's curve radius data is a valid method for identifying curves. Researchers collected field data on grade and cross slope and compared them to Mandli-derived data, design plans, and CARS data. Statistical tests used to evaluate their accuracy indicated that while grade data were accurate and could be used for HIS purposes, cross-slope data were not accurate enough to be used for anything other than curve advisory speed calculations.

Lastly, researchers established a method for converting Mandli data into a usable form and implementing them in HIS. For horizontal curves, the team recommends using CARS to identify the location of curves and employing the system's calculated advisory speed as a proxy for superelevation. Mandli may be used also, but users should be aware of its lower level of accuracy. For roads on which CARS data is not collected, or if agencies do not want to use Mandli, UKCAT is a reliable and accurate alternative. Mandli's grade data are accurate for vertical curves and may be used on all roads. To convert Mandli data to usable HIS data, the report outlines a methodology for curve segmentation. The segmentation process is based on changes in magnitude and sign in the raw Mandli data and may be automated in the future. The last section summarizes the HIS conversion process.

1 Introduction

1.1 Background

Mandli is a software company that specializes in highway data collection. Using a combination of vehicles, computer software, and user input, it collects and organizes various types of data that can be used by transportation agencies. Since being established in 1983, Mandli has worked with over 30 state departments of transportation (DOTs) and collected data on thousands of miles of roadway. Pavement data collection was first integrated in 2002, and a mobile LiDAR system was integrated in 2007. The company's current multi-functional vehicle takes high-resolution images, conducts 3D pavement profiling, collects mobile LiDAR data, and assembles positional data. These abilities let Mandli offer one of the most advanced datasets in the industry.

Mandli's vehicles travel at posted highway speeds and collect data in a single pass. They collect between 1 and 100 data points per second. Data are processed once the vehicle returns to the office. This two-step process creates a safer, more efficient solution for data collection and processing. The result is an archived 3D data inventory that is constantly updated and advanced. Mandli data are put to many uses, including structural analysis, pavement inventory, GIS software mapping, roadway design, area planning, safety, and maintenance.[1]

1.2 Problem Statement

The Kentucky Transportation Cabinet (KYTC) Division of Planning's Highway Information Systems (HIS) database contains various geometric elements, including horizontal and vertical curve information. These have been collected over time, but with an unknown degree of accuracy or detail (collection ranges from plan-level collection with field verification to low accuracy original windshield survey estimates.) These data can be applied in a variety of ways. For example, a complete set of horizontal information could be used to calculate design speed of a curve. However, for this purpose, both the curve radius and the cross-slope (or superelevation) are needed, and HIS currently lacks cross-slope information.

KYTC's Division of Maintenance has used Mandli software to collect pavement scans and slope data on all state roads for several years. Pavement scans collect thousands of points over an area of interest, while slope data is collected via two points on either side of the van's wheel path. Routes are reassessed every 1–3 years with Mandli pavement scanners. The data provide detailed information that can be used in the calculation of roadway geometry, including horizontal curve characteristics such as superelevation and vertical curve characteristics such as grade. Mandli software is available that can process a large number of data points to derive these data items.

Preliminary analyses have suggested that some of the data Mandli provides may be unusable in certain situations. With preliminary data processing, it is suspected that the resulting attributes may be too inaccurate for the intended applications (e.g., curve advisory calculations). However, a recent study found a more positive correlation is possible between the Mandli data and actual in-field measurements when post-processing is used. Following up on this study, KYTC was interested in identifying how Mandli data could be better utilized.

1.3 Objectives

The primary goal of this study was to determine the accuracy of Mandli data with regard to curve characteristics. A secondary goal was to evaluate its usefulness for HIS databases.

To this end, the study included:

1) Reviewing Mandli literature and other sources to determine the current limits of the software,
2) Checking Mandli data against other data collection efforts (including smart level, ball bank, and other field measurements),
3) Developing a methodology to convert Mandli data into usable HIS data, and
4) Estimating effort/cost to execute statewide review and update of HIS data, if appropriate.

1.4 Approach

For this project, data were collected from various sources to analyze the accuracy of Mandli data, including raw Mandli data, manual field measurements, curve advisory calculations, and design plans.

Mandli vans collect data on elevation, position, grade, and cross slope. These values come from the Road Surface Profiler and the Applanix GPS/Inertial system. The Road Surface Profiler measures elevation in front of each wheel path, which is used to calculate cross slopes. The Applanix system uses dual antennas, inertial measurement units, and a wheel-encoder distance measurement unit. Based on a DOT's needs, the data can be used in its raw form or processed and homogenized over a segment. For this project, raw Mandli measurements were used for grade and cross slope, and raw positional data were processed to calculate curve radius. Raw data were adjusted for vehicle roll and other interfering factors and data points were presented in 0.001-mile increments.

Manual field measurements were an essential comparison tool. The locations chosen represent a wide variety of curve types and characteristics. Measurements were taken every 0.001 miles to reflect the rate of Mandli data collection. Data collectors used a Smart Level for both grade and superelevation measurements, moving down the center of each lane.

For horizontal curve data, the Curve Advisory Reporting Service (CARS) was used as a comparison tool. CARS is a road survey system that automatically records vehicle activity with an inclinometer and a high-frequency GPS that determines recommended safe curve speeds. Data captured by the system enables calculation of several parameters, including curve radius and superelevation. According to a 2016 study, CARS accurately captures the radius when compared to the currently used digital ball-bank indicator and can therefore be used as a "ground truth".[2] This project used the raw intermediate data as well as the calculated advisory speed for comparisons of horizontal curve parameters.

Design plans, where available, were used to compare the proposed grade and cross slope with Mandli and field measurements. Plans were useful for new roads only and provided basic information, however, they were helpful for matching up trends and checking consistency. It is important to note that design plans were used, as complete and detailed as-built plans are generally not available in Kentucky.

Throughout the project, these various data sources served as ways to measure or check data. They were also used to determine the utility of Mandli data for specified purposes.

2 Literature Review

Kentucky Transportation Center (KTC) researchers began with a literature review of related work. Several papers discussed the feasibility of Google Earth and/or heuristic-based methods. Reviewing the literature provided a starting point for the project.

2.1 Google Earth Elevation Data Extraction and Accuracy Assessment for Transportation Applications

Recognizing the lack of elevation data available from GIS methods, Wang et al. (2015) turned to a new source. They proposed a method to obtain roadway elevation by extracting it from Google Earth (GE). The study included a comprehensive accuracy assessment of GE-extracted data and compared these data to GPS benchmark elevations and the elevation raster from the U.S. Geological Survey National Elevation Dataset.

To extract the roadway elevation and grade, a GE Elevation Data Extraction System (GEEDES) was developed at the Smart Transportation Applications and Research Laboratory (STAR Lab) using the GE Application Programming Interface (API). The process begins by determining the GE viewbox parameters based on the segment of interest. Next, latitude and longitude coordinates are converted into GE form-relative coordinates, after which raw elevation data are extracted. Lastly, a multi-layered roadway recognition system is emplaced to aid in data correction; slope segmentation and grade are calculated. Figure 1 outlines this process.

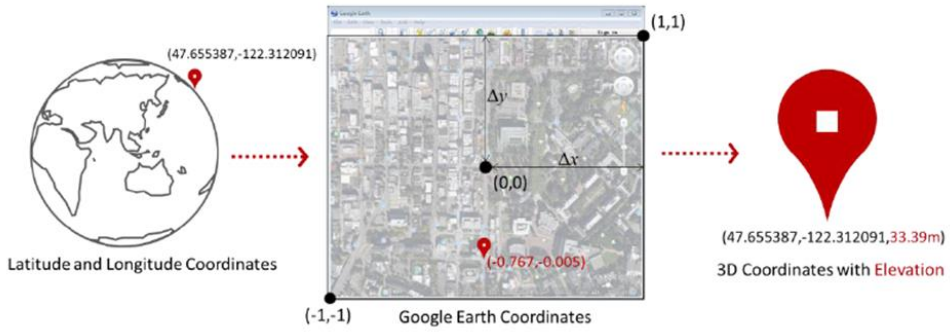


Figure 1: Google Earth Elevation Data Extraction System (GEEDES)

The proposed extraction method was implemented and validated under three scenarios: (1) extracting roadway elevation differentiating by directions, (2) multi-layered roadway recognition in freeway segments, and (3) slope segmentation and grade calculation in freeway segments. Results of the validation exercise indicated that the proposed extraction method can locate the desired route accurately, recognize multi-layered roadway sections, and automatically segment the extracted route by grade.

Wang et al. (2015) thus demonstrated that GE's elevation data are more accurate along roadways compared to other elevation data sources in the conterminous USA. Their comparisons revealed a mean absolute error of 1.32 meters, a root mean square error of 2.27 meters, and a standard deviation of 2.27 meters. They concluded that GE can be used as a reliable data source for various transportation applications, although a mean error of over a meter clearly means GE data are unusable for measuring cross slope.[3]

2.2 Evaluating the Correlation between Vertical Curve Features and Crash Rates on Highways

Pu et al. (2015) examined the high crash rates associated with vertical curves. They extracted continuous elevation data from GE along two interstate highway centerlines. Several variables representing vertical curve features were considered, including average elevation and grade, standard deviation of elevation and grade in surrounding links, and five types of interstate segments.

Pu et al. used recently developed data-processing methods. Available datasets included the global 30-second elevation (GTOPO30) dataset, the elevation dataset from Shuttle Radar Topography Mission (SRTM), the U.S. Geological Survey National Elevation Dataset (USGS NED), the Global Digital Elevation Model (GDEM), and a variety of other Light Detection and Ranging (LiDAR) datasets. All of the datasets were analyzed to determine their usefulness in this study. But all were found to have insufficient resolution, leading to the work from GE. Its elevation data were considered more accurate than other sources.

Vertical curve information was calculated based on elevation data. The elevation of points of interest were acquired with GE or its Application Programming Interface. To obtain roadway elevation, researchers again used University of Washington's GEEDES, as introduced in the previous Section 2.1. The data extraction procedure consisted of:

1) Obtaining the coordinates of points of interest using GIS maps,
2) Converting the latitude and longitude coordinates of sampling points into the GE form,
3) Performing the raw elevation data extraction and multi-layered roadway recognition,
4) Using a smoothing algorithm to eliminate errors and estimating for point that are unavailable, and
5) Calculating link elevation and grade from the point elevation data.

The method does have limitations. Only the top layer elevations can be measured, and the extracted roadway elevation is affected by overlapping infrastructure such as interchanges, multilayered roadways, or multideck bridges. Road surface and traffic conditions at the time of measurement may also cause measurement errors.

For the purpose of KTC's research, the use of GE and the data-processing method were not accurate enough. Mandli's point elevation data is considered too unreliable to use an elevation-based data processing tool.

However, Pu et al. postulated that 0.1-mile segment lengths could accurately identify features of a curve (e.g., downhill, sag, uphill, crest, and flat). These features are illustrated in Figure 2. In addition to optimum segment length, Pu et al. identified a 1.5% grade threshold to distinguish between curve features.[4] KTC's research benefitted from this verification of curve identification parameters.

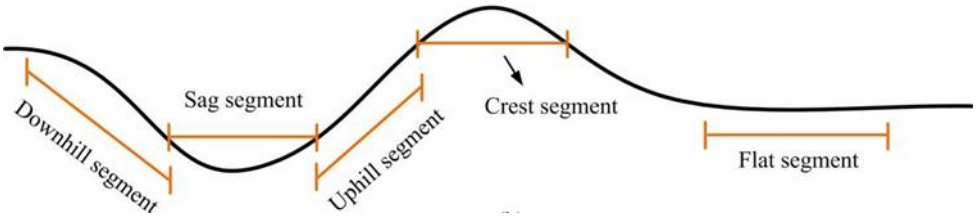


Figure 2: Segmentation of a curve with defined features

2.3 Heuristic Approach to Identifying Horizontal Curves and Their Parameters Given Lidar Point Cloud Data

Cook et al. (2015), as part of an effort to compile an inventory of highway curves, collected LiDAR data. However, there were some challenges in implementing the automated horizontal curve identification. Cook et al. discussed their procedure for curve detection and analysis and examined the success rate for identification and classification from this method.

After LiDAR data were collected and processed, the roadway was divided into segments, each with assigned attributes. Segments with similar attributes were combined into larger sections, that were then classified as either a curve or tangent. The data also identified the point of curvature (PC), point of tangency (PT), radius of curvature, elevation, and other important features of the curve geometry. These data came from a GIS shapefile with tabulated attributes for road segments; each was provided at a given latitude and longitude. Several curves were defined as several independent segments, which complicated the process of defining and cataloguing them. To correct this, the Horizontal Alignment Finder (HAF) algorithm was developed to more accurately identify curved segments. The HAF is a heuristic approach used to optimize threshold values for the curve analysis, based in Excel and operating in ArcMap. After tabular manipulation was complete, a linearly referenced ArcMap shapefile of all state routes was used to create the final curve shapefile. Figure 3 illustrates this process.

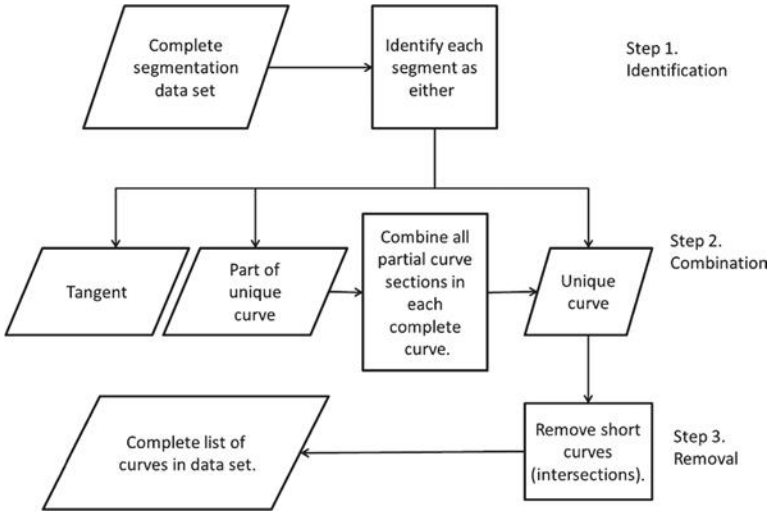


Figure 3: Data segmentation and curve identification process

This process of curve identification (i.e., deciphering between a curve and a tangent) had an accuracy rate between 84.4% and 92.9%. Accuracy rates for locating curve geometries (i.e., points of curvature or points of tangency) were between 78.7% and 89.9%.[5] Given the high level of accuracy obtained using LiDAR data, KTC researchers decided to emulate Cook et al.'s heuristic model.

2.4 Development of Crash Prediction Models for Curved Segments of Rural Two-Lane Highways

A 2016 study (Knecht, et al.) expanded upon previous crash research by focusing on four variables to predict crashes on rural highway curves. One of these variables is curve radius. Utah DOT used its inventory of all LiDAR highway curvature data, calibrated these data with the HSM predictive model, and used it for curved segments of two-lane two-way rural highways in Utah.

Utah's LiDAR point cloud data were converted into GIS shapefiles to identify curves. This conversion also defined certain curve parameters. The approach used a combination of Excel functions, heuristic algorithms, and GIS maps.

In total, the Utah-specific model randomly sampled 1,495 curved segments throughout the state. The number of crashes that this correlated with was higher than the number predicted by the HSM model. The model utilized a backward stepwise technique that identified four variables as statistically significant at a 95 percent confidence level. These included two horizontal alignment attributes: curve length and curve radius.[6]

Because this research focused mostly on crash modeling, the accuracy of curve identification factors was not examined in depth. However, the use of LiDAR to identify curve segments was proven effective through this study. More research is needed to overcome the difficulties in differentiating between curves, partial curves, and tangents.

3 Methodology/Approach

Data collection and analysis were divided into two parts. For horizontal curves, researchers tested the accuracy of the Mandli data and developed one data processing tool and tested two other already-existing data processing tools. For vertical curves, researchers examined grade and cross-slope data, comparing them to manual field measurements. The precision and accuracy of data on horizontal curve radius, grade, and cross slope was analyzed to determine the data's usefulness for HIS. Section 4 discusses the conversion to HIS and an implementation plan.

3.1 Horizontal Curve Assessment

Curve radius (degree of curvature) and length were used to assess the feasibility of using Mandli data to identify horizontal curves and estimate curve parameters. In addition to other applications, curve parameters support advisory speed calculations. Three tools (two existing and one developed especially for this project) were used to process and evaluate the Mandli data. Data were compared to CARS measurements to evaluate their accuracy.

3.1.1 Florida DOT Curvature Extension Tool

The Florida Department of Transportation (FDOT) developed a tool that requires manual input to determine the beginning and end points of a curve before fitting a circle to define the arc of the curve. KTC researchers used this tool to identify and categorize a series of curves on a rural Kentucky route. Use of the tool requires a considerable amount of time and effort to identify curves and estimate parameters, and is deemed infeasible for large scale applications such as the statewide HIS population. Additionally, the tool's accuracy is dependent on the subjectivity of different coders and thus,subject to human error.

3.1.2 UNR CATER Curvature Tool

Researchers next evaluated an automated curve identifier developed at the University of Nevada Reno's Center for Advanced Transportation Education and Research (UNR CATER). The tool is an ESRI ArcMap plugin that scans and identifies horizontal curves of a linearly referenced GIS road layer.

To use the tool with Mandli data, the user converts points into a linear referenced series using ArcMap's *Points to Line* tool. Once a polyline is created, the CATER tool calculates attributes for each curve, including the curve's point of tangency (PT), point of curvature (PC), length, radius, and degree. Following data processing, a shapefile with the beginning and ending milepoints of each curve and their radius of curvature is generated. User-defined parameters include curve identification threshold (measured in degrees) and minimum curve vertex spacing (measured in feet).

These two output parameters, curve identification threshold and minimum curve vertex spacing, are used to initially identify curves and adjust the sensitivity level of the tool when identifying curves. Parameters can be defined for specific routes, and CATER provides general recommendations. For example, the recommended curve identification threshold is 1.2 degrees. When a change in direction at a specific location exceeds this threshold, it is considered a point on a curve. The recommended minimum curve length threshold is 500 feet. Because Mandli data points are collected every 5.28 feet, each identified curve contains at least 94 Mandli points.

During KTC's testing, the UNR CATER Curvature tool required 2.5 hours to analyze a 22-mile segment. The tool often identified several distinct curves along what appeared to be a single curve, and adjusting parameters did little to improve the results. Given the high level of manual inspection and input needed, researchers deemed the tool unsuitable for use with the KYTC Mandli data.

3.1.3 UK Curvature Automatic Tool

Due to the limitations identified for the two existing tools, KTC researchers developed a third method named "University of Kentucky's Curvature Automatic Tool" (UKCAT). UKCAT is a Matlab-based tool that uses discrete point curvature calculations to analyze curves.

To prepare the data for input to UKCAT, latitude and longitude coordinates are first converted into the Kentucky state plane coordinate system. This can be performed within ArcMap. A route's point coordinates are sequentially exported into an Excel worksheet based on mile point. If mile point data are unavailable, points may be ordered using the Mandli data's GPS time stamp. Once the data are prepared, they are input in the UKCAT Matlab program.

A Matlab algorithm is employed to define segment curvature. The algorithm was developed using basic geometric principles. The curvature of a circle is the reciprocal of the radius, as follows:

Equation 1

$$k = \frac{1}{R}$$

$$k = curvature$$
$$R = curve\ radius, ft$$

For a plane curve given parametrically in Cartesian coordinates as γ(t) = (x(t),y(t)), discrete point curvature can be calculated as:

Equation 2

$$k = \frac{|x'y'' - y'x''|}{(x'^2 + y'^2)^{\frac{3}{2}}}$$

This equation is used in Matlab to calculate the discrete point curvature of each point along a route. After curvature is calculated for all points, curvature versus location can be plotted. Figure 4 presents a small portion for illustration.

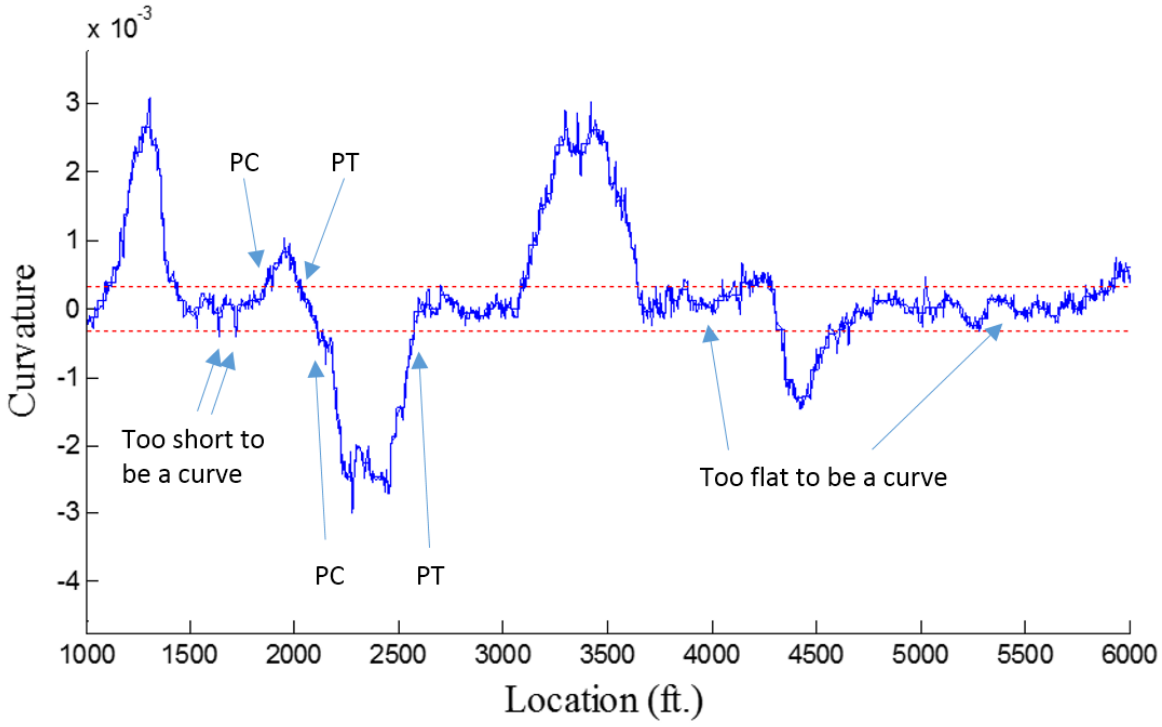


Figure 4: Output from UKCAT Matlab tool

Figure 4 shows values of curvature changing along a route, with positive values indicating left turns. The jagged nature of the graph results from noise in the original Mandli data. Note that Mandli collects points along the vehicle's wheel path, which may be affected by steering wheel mechanics, driver variation, or uneven pavement. Wavelet and moving average methods were used as filters to smooth the data.

Following an AASHTO Green Book (14) recommendation, two control thresholds were introduced into the Matlab code script to automatically identify curves and collect curve parameters. The maximum curve radius was set to 3,000 feet and minimum curve length was set to 120 feet. Based on the first threshold, two horizontal dashed lines were plotted in Figure 4 to represent the curvature corresponding to a 3,000-foot radius curve for both turn directions. The intersections between the plotted and dashed lines indicated PCs and PTs. Points falling between the two horizontal dashed lines can be considered tangents, as their curvature is not large enough to be a designed curve. Points outside the dashed lines were identified as possible curves, meriting further analysis. Next, the possible curves were distinguished based on curve length. Only curves longer than 120 feet were identified as horizontal curves. Following these two steps, identified curves were saved to a data sheet.

Once the curve was automatically identified, PC and PT were readily distinguished based on the trend of the line: they were the vertices created when the curvature graph line crossed the dashed line of the threshold values. Several metrics were evaluated to best define the segment's curvature, including maximum value, mean value, and 50th percentile of the curvatures among all points in the curve. Since the maximum degree of curvature corresponded to the minimum curve radius, it was the limiting factor. Therefore, the maximum curvature value was selected to calculate the curve radius.

The tools above cannot distinguish spiral curves from circular curves. A clothoid spline method from Georgia Tech provides an algorithm identification of spiral curves. KTC researchers used this method as starting point to develop their own method for distinguishing curve types. Using a graph like the one presented above, users select two "sides" with consistent slopes to represent the spiral curves. The point of change from tangent to spiral curve (TS) and the point of change from spiral curve to tangent (ST) was calculated based on the rate of change of the slope between the two adjacent points. KTC researchers utilized this method to identify spiral and circular curves in the graphs, as shown in Figure 5, but the validation of this manual intensive procedure was beyond the scope of the current research.

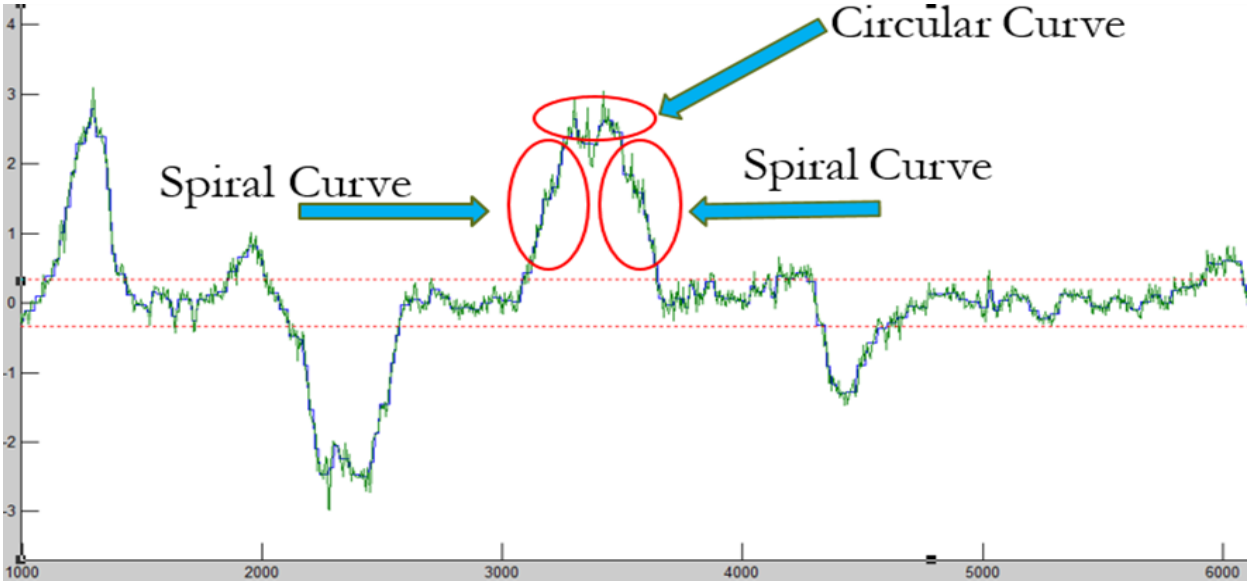


Figure 5: UKCAT tool's potential ability to distinguish spiral curves from circular curves

3.1.4 Tool Comparison

Each of the above three tools was validated using CARS data as "ground truth." It is important to note that there is not a one-to-one correspondence between CARS-identified curves and those identified by the other tools evaluated in this section. CARS generally groups curves together and identifies fewer curves than the other tools. This is especially prevalent for large radius short curves in sequence. Therefore, the validation performed in this research compares radius, not length. The following graphs show comparisons between UKCAT and UNR CATER (Figure 6), UNR CATER and CARS (Figure 7), and UKCAT and CARS (Figure 8).

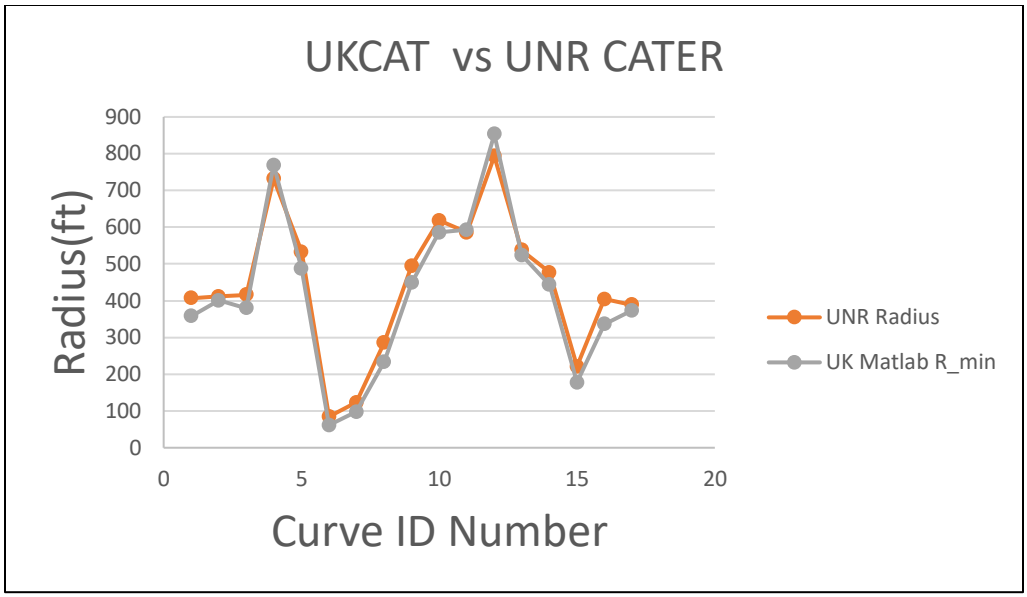


Figure 6: Comparison of UKCAT and UNR CATER tools

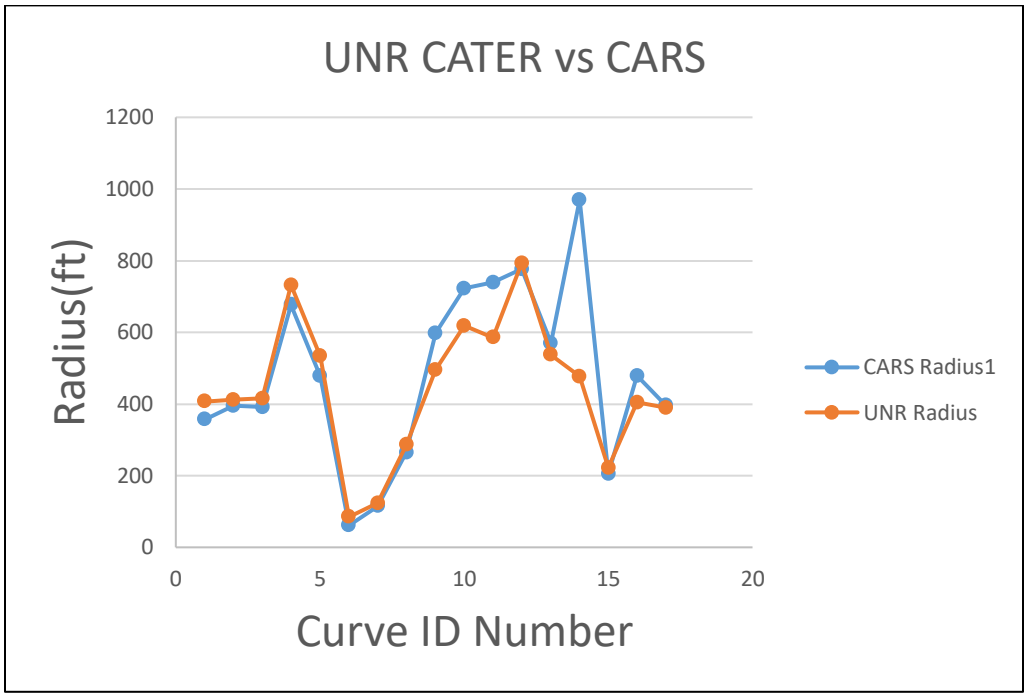


Figure 7: Comparison of UNR Cater tool and CARS data

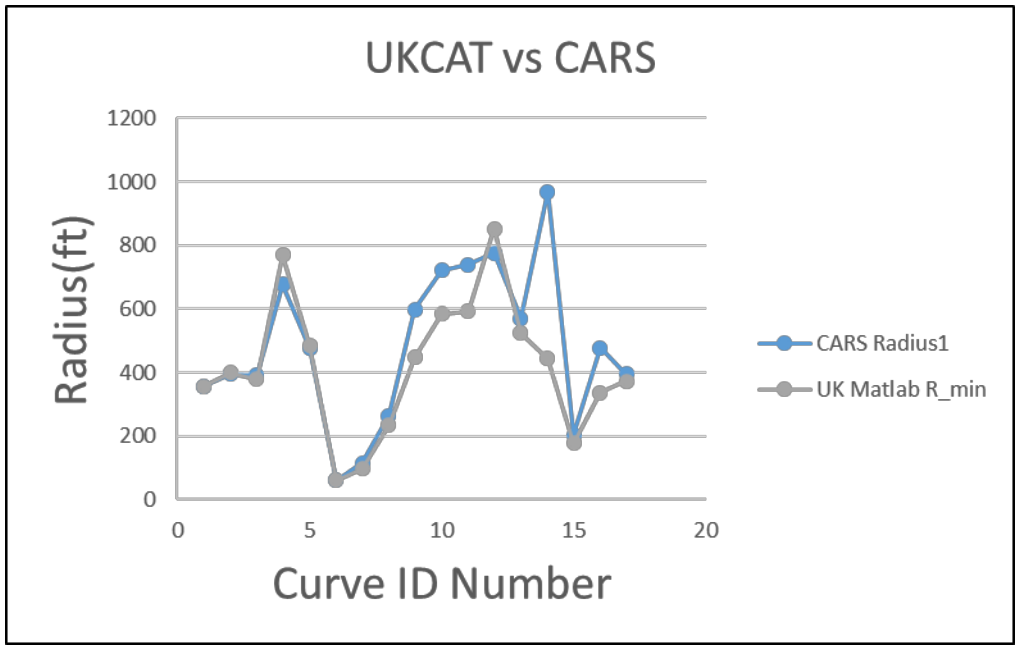


Figure 8: Comparison of UKCAT tool and CARS data

The UNR CATER and UKCAT tools displayed the most promising performance. They aligned closely with one another, matching both in terms of trend and values, yielding nearly identical graphs. Both correlated well with CARS radius data, with the notable exception of curve 14*. Therefore, both may be considered as valid ways to use Mandli's data for curve radius estimation. The UKCAT is automated and therefore could be considered as the preferred method due to its ease of use. While the UNR CATER tool is partially automated, it requires more user input than UKCAT.

**Curve 14 was identified to be 686 feet in length by CARS. The closest UKCAT curve was identified to be 275 feet in length, and closest CATER curve was 163 feet. Therefore, the great difference in radius may be explained as CARS is considering a much longer curve length, and likely includes spiral or other transition curves, or even part of the curve approaches tangents, which results in a much longer radius.*

3.2 Grade and Cross-Slope Assessment

Grade and cross-slope evaluations were combined because of the similar methodologies used to perform them. This portion of the research compared Mandli grade and cross-slope data to ground-truth data to determine Mandli's accuracy and usefulness. Through a series of trials and errors with data collection, researchers found one that most precisely mimics the way in which the Mandli vehicle collects data. Using this method, data were collected, analyzed, and compared with other methods.

3.2.1 Data Collection

Eighteen locations were chosen based on available Mandli data and the ability to obtain a varied selection of attributes. Sites included a mix of rural and urban routes, a mix of flat and steep roadways, and a mix of tangents and curves. Data collectors visited each site with a calibrated SmartLevel; traffic was controlled as they took careful measurements. The SmartLevel was attached to a 69" measuring stick to mimic the 69" wheel path of the Mandli van. Cross slope was measured perpendicular to the direction of travel, while grade was measured along the direction of travel. To facilitate data comparison, points were measured every 5.28 feet to replicate Mandli's collection rate of one point every 0.001 mile. Between 60 and 80 points were measured per curve per direction.

3.2.2 Data Validation

Data validation was a critical intermediate step of this process. This process included comparing graphs derived from Mandli data and field data based on trend lines, examining design plans, and quantifying data lines using a root mean square error evaluation.

Data processing occurred following field data collection. Points were separated based on direction of travel and separately plotted in Excel based on location and grade or cross slope. Each data point (every 5.28 feet) was plotted on the x-axis while the measured value was plotted on the y-axis. Mandli data were plotted for the same area to obtain two comparable graphs. Examples are shown in Figure 9 (cross slope) and Figure 10 (grade). The shapes of the graphs allowed users to match up one source of data with the other so that peaks and valleys followed a similar trend, since handheld GPS readings were not reliable enough to match field measurements with Mandli measurements. Appendix A contains a complete set of graphs.

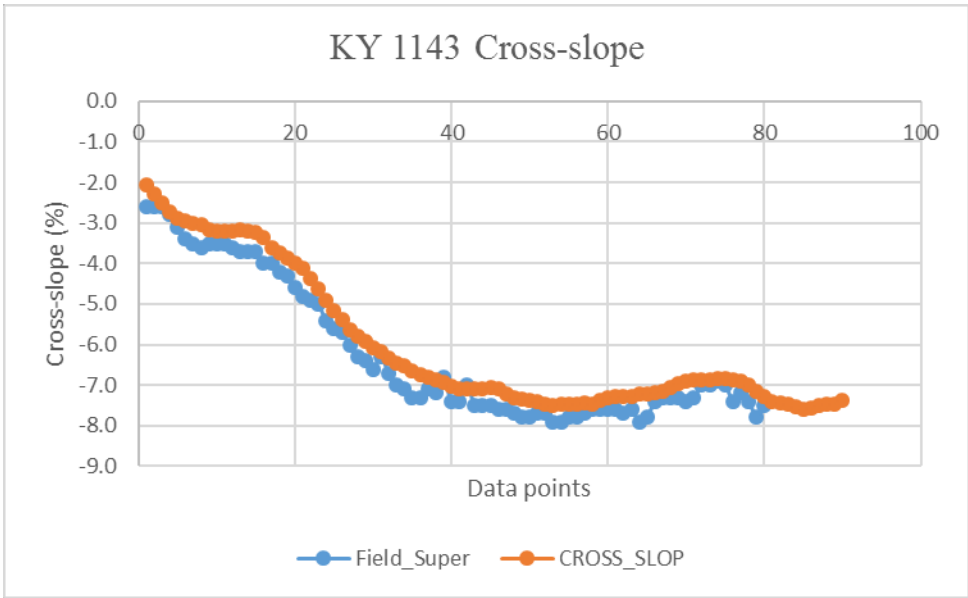


Figure 9: Comparison of Mandli cross-slope data to field data

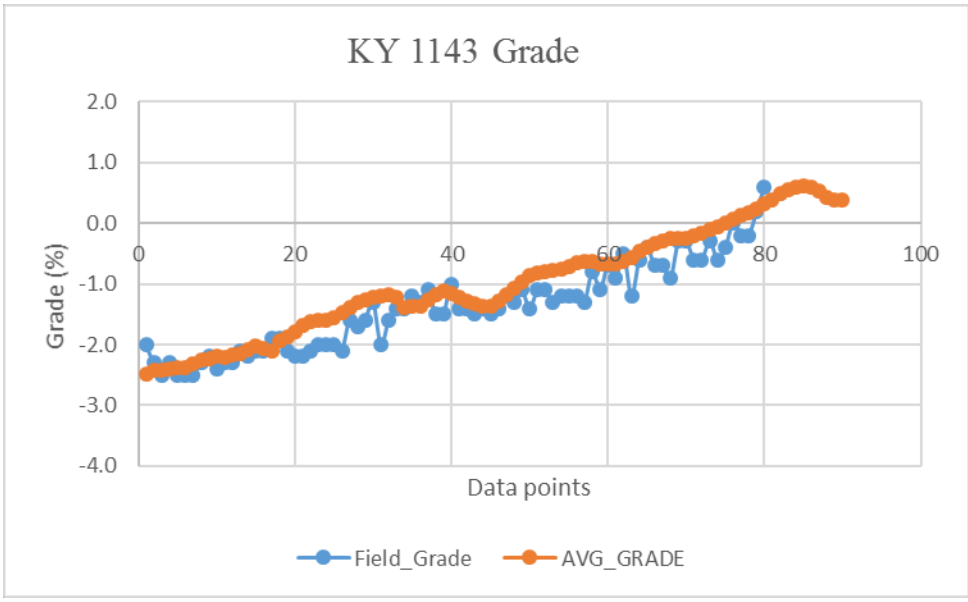


Figure 10: Comparison of Mandli grade data to field data

Another method of data validation was checking data against design plans. Recent plans were available for one location: the Georgetown Bypass (KY 1143), which was built in 2012. KTC researchers obtained drainage design plans for all other roadways in this study, but they were dated and only contained roadway grade information, not cross slope. Because the Georgetown Bypass was built recently, it was the only location with available, accurate design plans. Comparing the Mandli cross slope and grade to those indicated on plans revealed that the Mandli data accurately matched the magnitudes set forth in the plans. However, where the plans showed constant grades and cross slopes with smooth transitions, the Mandli data exhibited much more angularity and variability. For example (see Figure 11), the plans from one horizontal curve showed the cross slope peaking at -7% and remaining constant throughout the curve, but the Mandli van measured a cross slope peaking at -7.5% and fluctuating between -7.5 and -6.8%. X-axis values are number of points measured.

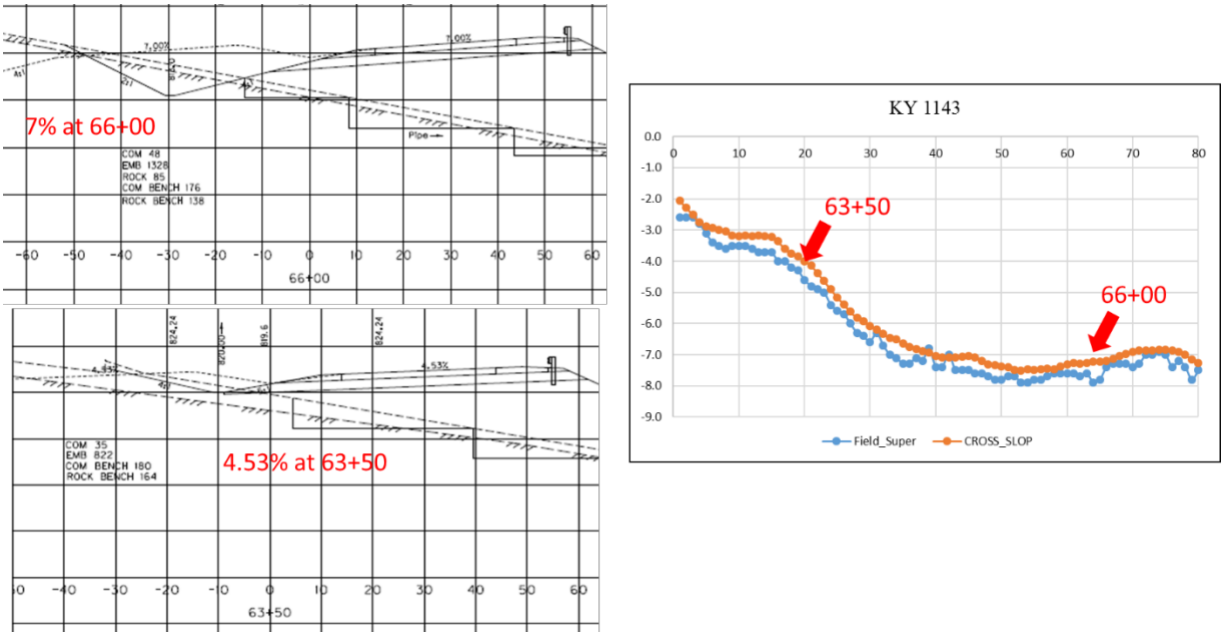


Figure 11: Design plans (left) versus Mandli and field measurements (right).

Field measurements, however, confirmed the fluctuations in grade and cross slope that appeared in the Mandli data. From this, researchers concluded that the Mandli data accurately match the magnitudes expressed in the plans. Additionally, the roadways have minor variations in pavement quality that were not found in the plans but which the Mandli van captured accurately. These similarities are reflected in the matching shape of the Mandli vs. field measurement plots.

Lastly, researchers examined how Mandli cross slope compared to cross-slope data from CARS. Because CARS data are collected within curves, researchers only compared superelevation and ignored cross slopes along tangents. A series of curves on two rural routes were analyzed. For each data source, the maximum superelevation in each direction was chosen because maximum values are used in advisory speed calculations. Figure 12 compares the reported data. It refers to the most extreme superelevation within each curve, whether it is positive or negative. The red line indicates a perfect correlation between the two sets of values (a slope of one), while the points' proximity to the line indicates how well they actually correlate.

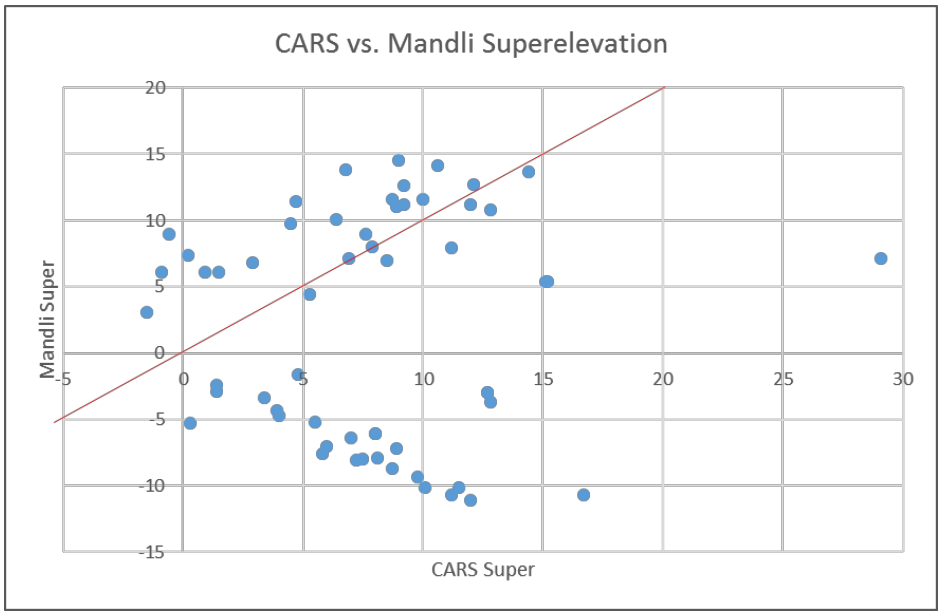


Figure 12: Mandli superelevation vs CARS superelevation

There is very little correlation between the two sets of values. In fact, CARS data often have the opposite sign of the Mandli data. This discrepancy cannot be completely ignored, however. Figure 13 shows a comparison using the absolute value of the data points. This adjustment was made because the curve advisory speed calculation uses the absolute value of superelevation.

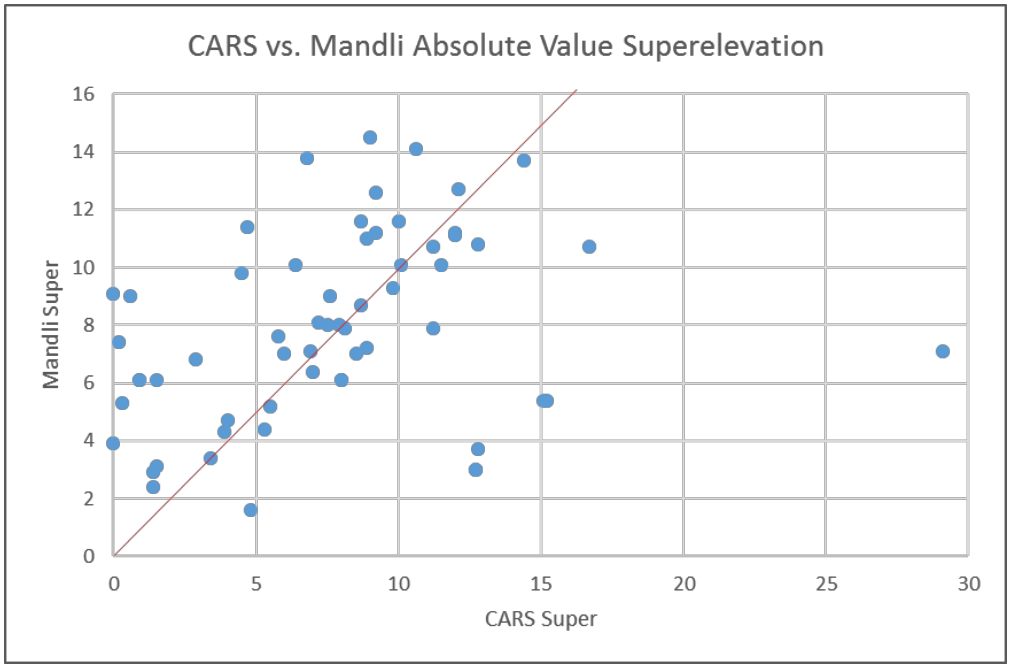


Figure 13: Mandli superelevation versus absolute value of CARS superelevation

This graph displays better correlation, but points still lie very far from the line. In both graphs, it is clear that the variables are poorly correlated. Because of this, researchers concluded that CARS should not be used directly for superelevation values.

3.2.3 Data Analysis

3.2.3.1 RMSE

More precise data interpretation called for a quantitative method of data assessment, as opposed to qualitatively comparing graphs based on trend lines. Suggested evaluation methods include error bars, rounding, or using a moving average. Ultimately, the team decided to use root mean square error (RMSE) evaluations. This quantifies the amount of difference between the two lines (field measurements and Mandli data) in one number that tells their correlation.

Equation 3

$$RMSE = \sum_{1}^{n} (Mandli_n - Field_n)^2$$

This was performed on each location's grade and cross slope in both directions, for a total of 72 RMSE values. The lower the RMSE value, the more the two lines correlated, and the more accurate the Mandli data was assumed to be. For grade measurements, RMSE values ranged from 1.4 to 64. For cross-slope measurements, RMSE values ranged from 4.6 to 377.3. These ranges indicated a greater correlation between Mandli and field data for grade than the correlation for cross slope. However, neither provide a conclusive or easily understood statement regarding Mandli's accuracy.

3.2.3.2 Statistical Analysis

To deepen interpretation of the data and arrive at a single statement regarding Mandli's accuracy, KTC researchers performed a statistical analysis. Its purpose was to assess the reliability of the Mandli van at collecting accurate cross-slope and grade measurements. Researchers computed confidence intervals based on the differences in field measurements and Mandli measurements of cross slope and grade to determine a range within which the Mandli van can accurately measure cross slope and grade. Confidence intervals were calculated by taking the difference of the average and standard deviation between the Mandli and field measurements of cross-slope and grade at all locations. The following equation was applied to the cross-slope and grade datasets to calculate a margin of error:

Equation 4

$$Margin\ of\ Error = t * \frac{s}{\sqrt{n}}$$

$t = statistic\ relating\ to\ confidence\ level$ ($1.96\ for\ 95\%\ confidence$)
$s = standard\ deviation$
$n = sample\ size$

The margin of error was then added to a dataset's average to determine the upper bound of the confidence interval and subtracted from the dataset's average to ascertain the confidence interval's lower bound. Six datasets containing the absolute values of the differences between the Mandli and field measurements were analyzed at both the 95% and 99% confidence levels — cross slope on horizontal curves, cross slope on vertical curves, all cross slopes, grade on horizontal curves, grade on vertical curves, and all grades. Because the datasets contained absolute values of the differences between Mandli and field measurements, the confidence intervals applied to both positive and negative measurements in the same magnitude. Therefore, the worst-case scenario would be the upper bound of the confidence interval of the absolute value datasets because it is the highest magnitude. This means that the Mandli measurements could be off by plus or minus the upper bound of the confidence interval in the worst case. Table 1 summarizes the statistics and confidence intervals for each dataset.

Table 1: Statistical summary for all curves

Dataset	Average (%)	St. Dev. (%)	Sample Size	95% CI	99% CI
cross-slope on horizontal curves	1.20	0.80	1392	1.16-1.24	1.14-1.25
cross-slope on vertical curves	0.92	0.68	1537	0.89-0.95	0.88-0.96
all cross-slopes	1.06	0.75	2829	1.03-1.09	1.02-1.09
grade on horizontal curves	0.37	0.31	1392	0.35-0.39	0.35-0.39
grade on vertical curves	0.30	0.31	1537	0.28-0.31	0.28-0.32
all grades	0.33	0.31	2829	0.32-0.34	0.32-0.35

This dataset should be interpreted as follows: For all cross slopes, researchers are 99% confident that under a worst-case scenario the cross-slope measurements from Mandli are off by plus or minus a 1.09%, the upper bound of the 99% confidence interval. Thus, any Mandli cross-slope measurement is likely to be within 1.09% of the actual value in either direction. Note that this percentage is not a percent error, but an actual cross-slope value. That the graphs show a systematic error rather than a random error indicates a potential for systematic removal of the error, producing an even better (more reliable) result.

3.2.3.3 Sensitivity Analysis

Lastly, KTC researchers performed a sensitivity analysis on cross slope to determine how much small changes in the value affected speed limit calculations. Curve advisory speed calculations are one of the ways in which cross-slope values are used in transportation planning. The two values are positively correlated: as cross-slope values increase, the curve advisory speed increases too. This is shown in the following equation:

Equation 5

$$v_i = \sqrt{15(r)(e+f)}$$

$v_i = curve\ design\ speed$
$r = curve\ radius, ft;$
$e = superelevation\ rate, decimal\ between\ 0\ and\ 1;$
$f = side\ friction$

Sensitivity analyses were performed on each curve using first Mandli data and then field measurements. Each speed value was rounded to the nearest five mph, since advisory speeds are posted in multiples of 5 mph. Out of the 16 curves, two curves had a difference in advisory speeds: one curve's advisory speed increased 5 mph when comparing Mandli to field sourced data, and the other curve's advisory speed lowered 5 mph. Since the other fourteen curve speeds were unaffected by the data source, it appears the difference in data is insignificant.

Further, researchers graphed the relationship between a curve's cross slope (i.e., superelevation) and its radius. In Figure 14, a series of lines give representative examples of curve radii that range from 500 feet to 2000 feet. Superelevation is plotted along the x-axis, and the resulting advisory speed is plotted on the y-axis.

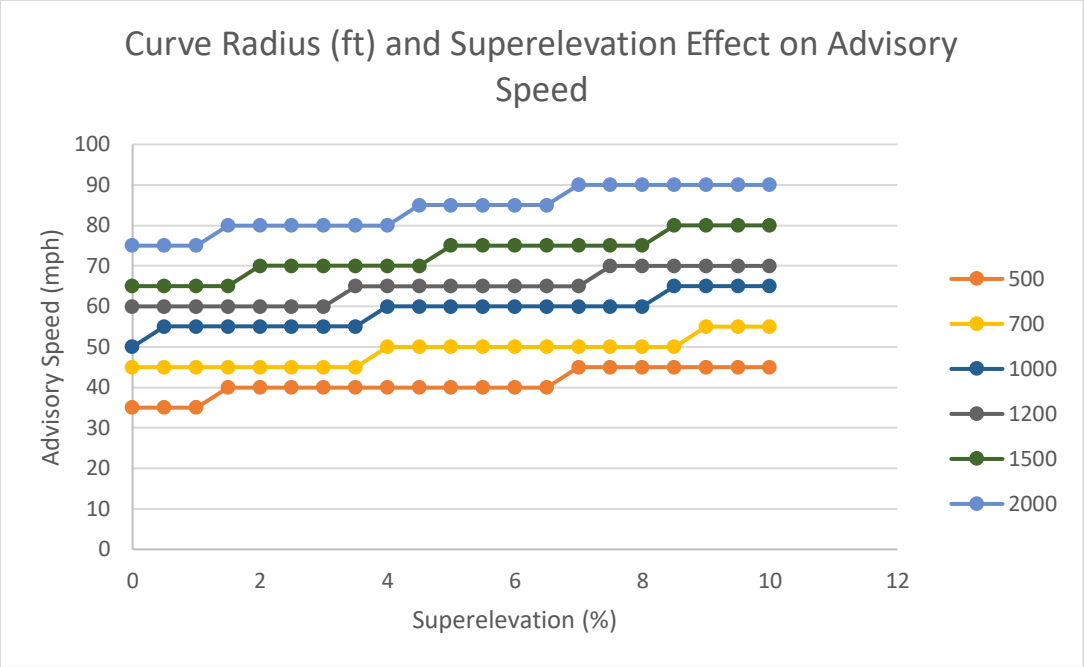


Figure 14: Relationship between curve radius, cross-slope, and resulting advisory speed

Each trend line contains long plateaus, which indicate a low sensitivity to the changing superelevation. For example, along a 500-foot radius curve with superelevations between 2 and 6 percent, the advisory speed is 40 mph. That is, there is a 4 percent range in superelevation values for which the advisory speed will not be affected. As curve radius increases, the tolerance in superelevation before an advisory speed changes lessens. Based on the individual calculations and the graphs, researchers concluded that the difference between Mandli cross-slope measurements and manual field cross-slope measurements was not significant. Therefore, Mandli cross-slope may be used for the purpose of calculating curve advisory speed calculations. The 1% error associated with cross-slope (as mentioned in section 3.2.3.2) is small enough to not substantially affect the resulting speed. However, cross-slopes are used for other calculations, so a sensitivity analysis may have to be performed for each calculation of interest. This will determine if Mandli cross-slope's 1% accuracy is adequate.

4 Results

4.1 Horizontal curvature results

Mandli data processed with UKCAT returns results that are similar to those generated by CARS — KYTC currently uses CARS to measure curve parameters. Therefore, researchers concluded that UKCAT should be used to identify curves from Mandli's data points.

4.2 Grade results

Researchers evaluated grade by comparing data from Mandli, field measurements, and design plans. While evaluating design plans did not prove very useful, assessments of Mandli and field measurements provided valuable results. The graphs in Figures 15 and 16 exemplify the results derived from these comparisons. Appendix A includes graphs for each curve.

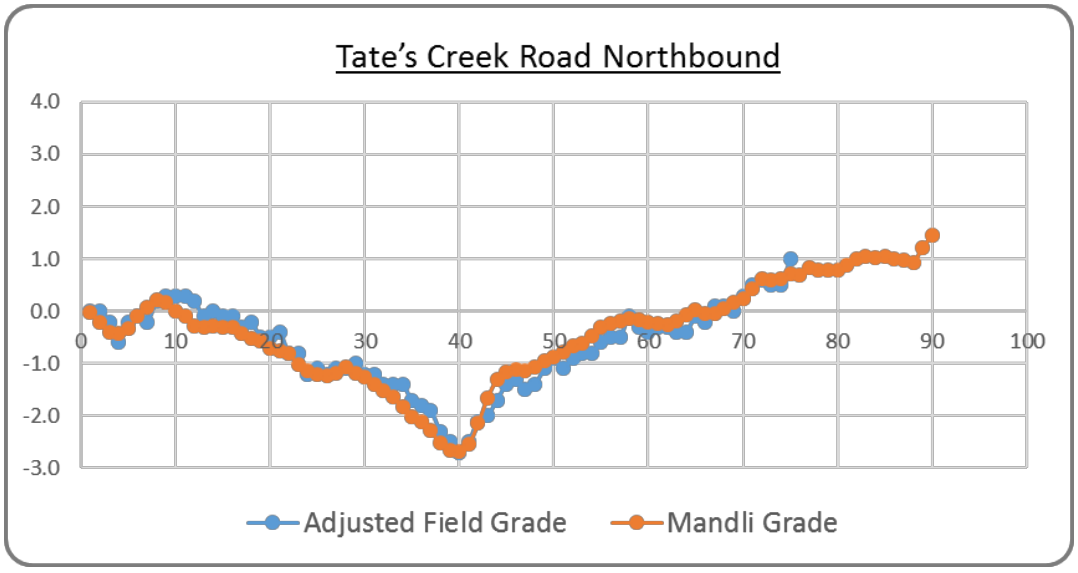


Figure 15: Example of Mandli grade versus field grade graphs

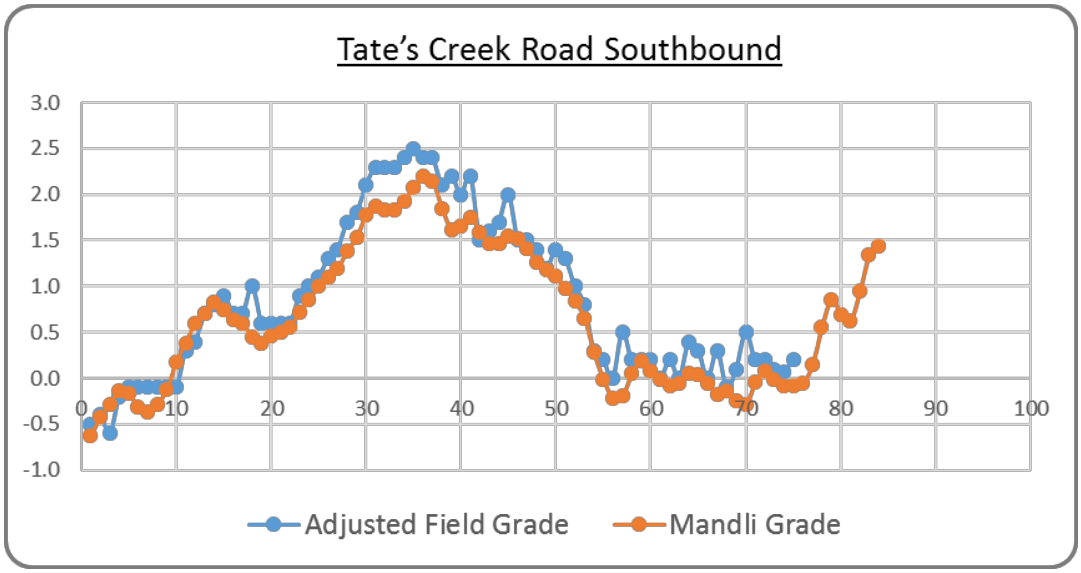


Figure 16: Example of Mandli grade versus field grade graphs

Figures 15 and 16 illustrate the clear similarity between Mandli data and field data. This location's graphs had RMSE values of 4.08 (northbound) and 5.66 (southbound). In the collection of 72 graphs, RMSE values are usually relatively low, ranging from 1.4 to 64 and averaging 13.6. With input from KYTC's HIS experts, researchers felt confident in their conclusion that Mandli grade data are accurate and can be used for HIS purposes.

4.3 Cross-slope results

Cross slope was evaluated by comparing data from Mandli, field measurements, design plans, and CARS data. Comparisons between Mandli and field data were inconclusive, but Mandli and CARS clearly did not match up. This is likely due to the Mandli van's method of measurement: it only takes measurements at the two points in front of each tire and then assumes a straight slope between the two points. As field measurements confirm, the roadway does not usually have a uniform (straight) cross slope. It is important to note that, despite these variations, there is little sensitivity to the differences when cross-slope values are applied to curve advisory speed calculations. Researchers concluded that cross-slope from Mandli may be used in curve advisory speed calculations. However, caution is recommended when using Mandli cross-slope for other HIS purposes because of the systematic error associated with the data collection process.

5 HIS Conversion and Implementation

Researchers analyzed how data could best be utilized throughout the data analysis process. For horizontal curvature characteristics and vertical grade measurements, the Mandli data were sufficiently accurate to justify their use. This section details how data should be converted and implemented. It also offers theoretical direction on using Mandli cross-slope data, if the system is changed to more accurately reflect the entire roadway rather than interpolating a slope between two measured points. Before converting data into an HIS format, it is important to note that milepoints produced during the Mandli procedure do not correspond to actual milepoints. The Mandli milepoints are arbitrary and begin when the driver starts collecting data on a route. The GPS coordinates (also included in the Mandli data) should be used to align Mandli data with Kentucky's roadway network, as the Cabinet does each year when updating Photovan data.

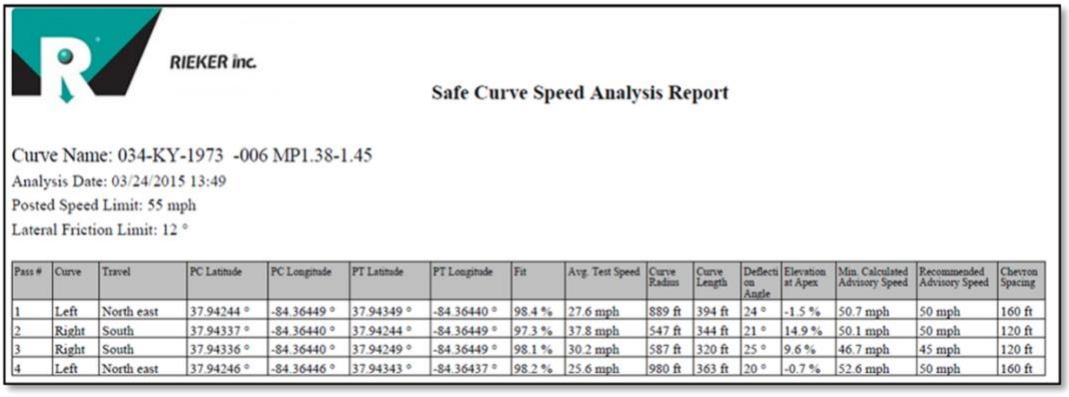
5.1 Horizontal Curves: Radius and Cross-slope

For horizontal curves, curve radius is the main parameter of interest. Researchers thoroughly investigated whether Mandli data are accurate enough to use for curve radius. However, an intermediate step is needed to identify other parts of the curve.

5.1.1 CARS where available

Because there are some issues with the Mandli van's data collection process and because CARS data will soon be available, KTC recommends using CARS for the intermediate step. For each road segment, CARS can be used to determine the beginning milepoint, ending milepoint, deflection angle, and curve radius. The advisory speed CARS returns can be used as a proxy for cross slope. The delineation of horizontal curves will be an output from the CARS data analysis project. While delineation is a manual process requiring a user to select beginning and endpoints of horizontal curves, it is included within the scope of work for the CARS project. Therefore, no extra effort is required from the Division of Planning to determine the segmentation of horizontal curves when Mandli data are converted into a usable HIS format. The data from the CARS project will cover all state-maintained roads, excluding interstates and parkways. The project is slated for completion by the end of 2018.

Figure 17 is an example of the CARS output that provides many intermediate parameters, including the recommended advisory speed. Curve radius and deflection angle can be both be used within HIS, as mentioned above. Table 2 shows how this data can be reformatted to be compatible with HIS.



RIEKER inc.

Safe Curve Speed Analysis Report

Curve Name: 034-KY-1973 -006 MP1.38-1.45
Analysis Date: 03/24/2015 13:49
Posted Speed Limit: 55 mph
Lateral Friction Limit: 12 °

Pass #	Curve	Travel	PC Latitude	PC Longitude	PT Latitude	PT Longitude	Fit	Avg. Test Speed	Curve Radius	Curve Length	Deflection Angle	Elevation at Apex	Min. Calculated Advisory Speed	Recommended Advisory Speed	Chevron Spacing
1	Left	North east	37.94244 °	-84.36449 °	37.94349 °	-84.36440 °	98.4 %	27.6 mph	889 ft	394 ft	24 °	-1.5 %	50.7 mph	50 mph	160 ft
2	Right	South	37.94337 °	-84.36440 °	37.94244 °	-84.36449 °	97.3 %	37.8 mph	547 ft	344 ft	21 °	14.9 %	50.1 mph	50 mph	120 ft
3	Right	South	37.94336 °	-84.36440 °	37.94249 °	-84.36449 °	98.1 %	30.2 mph	587 ft	320 ft	25 °	9.6 %	46.7 mph	45 mph	120 ft
4	Left	North east	37.94246 °	-84.36446 °	37.94343 °	-84.36437 °	98.2 %	25.6 mph	980 ft	363 ft	20 °	-0.7 %	52.6 mph	50 mph	160 ft

Figure 17: CARS output

Table 2: Formatting CARS to HIS

FID	RT_UNIQ	BMP	EMP	Roadway_Direction	Curve_Direction	Radius	Delta	Advisory_Speed
1	034-KY-1973 -000	1.38	1.45	Cardinal	Left	935	22	50
2	034-KY-1973 -000	1.38	1.45	Non-cardinal	Right	567	23	45

5.1.2 UKCAT Matlab Tool

Because CARS only covers a portion of roadways in the state, another tool is needed to identify curves for non-CARS roads. The UKCAT can be used to find beginning milepoint, ending milepoint, and curve radius as explained in section 3.1.3. To use UKCAT with Mandli data points, the data must first be converted to XY coordinates using a GIS program such as ArcMap; points must then be linearly referenced from beginning to end. It is estimated that it would take about two weeks to prepare a statewide curve dataset in this manner.

Once the data are prepared, they can be used in HIS according to the following set of figures. Each curve is identified as a peak with UKCAT and given a number (Figure 18). Numbers correspond to the FID number in HIS, while the magnitude of the peak corresponds to its radius (Table 3).

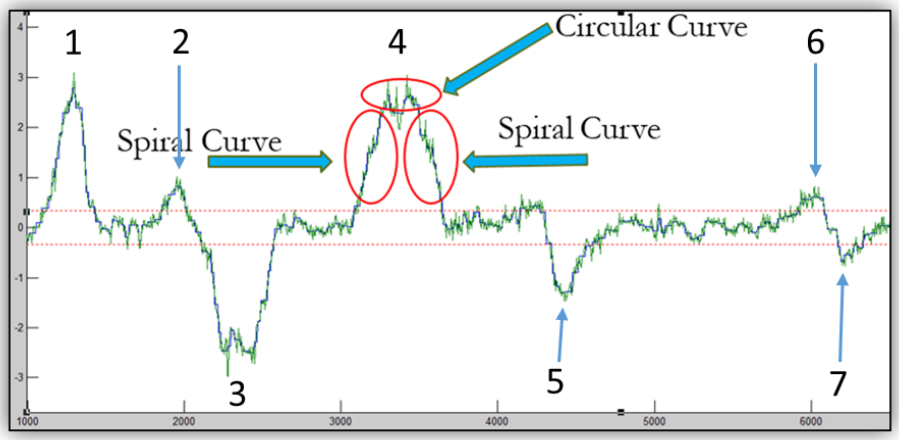


Figure 18: UKCAT tool output

Table 3: Formatting UKCAT tool to HIS

FID	RT_UNIQ	BMP	EMP	Curve_Direction	Radius
1	034-KY-1973 -000	0.20	0.24	Right	1900
2	034-KY-1973 -000	0.36	0.40	Right	5730
3	034-KY-1973 -000	0.39	0.51	Left	2400
4	034-KY-1973 -000	0.57	0.70	Right	2200
5	034-KY-1973 -000	0.81	0.85	Left	3820
6	034-KY-1973 -000	1.10	1.16	Right	11460
7	034-KY-1973 -000	1.18	1.22	Left	19100

5.1.3 Theoretical: Cross Slope from Mandli

As stated earlier, Mandli cross slope data are not accurate enough to recommend them for any purpose other than advisory speed calculation. They should not be used further unless more research develops a calibration to improve data accuracy. However, it is worth including a brief tutorial on obtaining cross-slope data from Mandli and converting it into a usable HIS format. This can be referenced if cross slopes from Mandli become usable in the future.

Mandli data give the maximum superelevation within segments, while CARS identifies the beginning and ending points of each curve. By using a spatial overlay of Mandli in GIS, users can identify maximum superelevation with a curve. Figure 19 illustrates this idea.

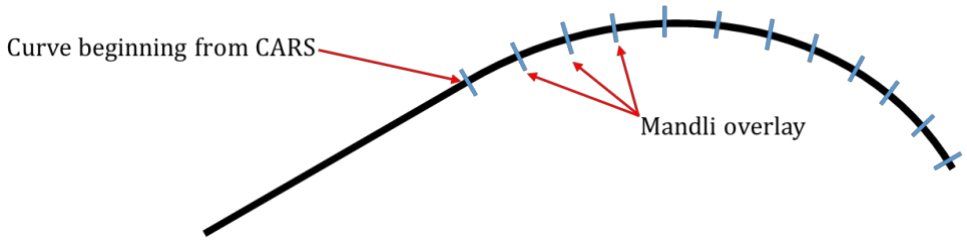


Figure 19: CARS plotted in GIS with Mandli spatial overlay

Once curves are identified and the maximum superelevation found, the information can be converted easily into an HIS format as shown in the figures below. Figure 20 shows an example of a CARS output (repeated from earlier), and Table 4 shows how it might appear in HIS.

Curve Name: 034-KY-1973 -006 MP1.38-1.45
Analysis Date: 03/24/2015 13:49
Posted Speed Limit: 55 mph
Lateral Friction Limit: 12 °

Pass #	Curve	Travel	PC Latitude	PC Longitude	PT Latitude	PT Longitude	Fit	Avg. Test Speed	Curve Radius	Curve Length	Deflection Angle	Elevation at Apex	Min. Calculated Advisory Speed	Recommended Advisory Speed	Chevron Spacing
1	Left	North east	37.94244 °	-84.36449 °	37.94349 °	-84.36440 °	98.4 %	27.6 mph	889 ft	394 ft	24 °	-1.5 %	50.7 mph	50 mph	160 ft
2	Right	South	37.94337 °	-84.36440 °	37.94244 °	-84.36449 °	97.3 %	37.8 mph	547 ft	344 ft	21 °	14.9 %	50.1 mph	50 mph	120 ft
3	Right	South	37.94336 °	-84.36440 °	37.94249 °	-84.36449 °	98.1 %	30.2 mph	587 ft	320 ft	25 °	9.6 %	46.7 mph	45 mph	120 ft
4	Left	North east	37.94246 °	-84.36446 °	37.94343 °	-84.36437 °	98.2 %	25.6 mph	980 ft	363 ft	20 °	-0.7 %	52.6 mph	50 mph	160 ft

Figure 20: CARS output

Table 4: Formatting CARS and Mandli cross-slope to HIS

FID	RT_UNIQ	BMP	EMP	Roadway_Direction	Curve_Direction	Radius	Delta	Advisory_Speed	Super
1	034-KY-1973 -000	1.38	1.45	Cardinal	Left	935	22	50	-7
2	034-KY-1973 -000	1.38	1.45	Non-cardinal	Right	567	23	45	8

As the tables show, milepoints come directly from the CARS output file title, and directions can be easily interpreted. Radius is the average of the radius column, delta is the average of the CARS deflection angles, and advisory speed is the minimum value of the recommended speed. Superelevation may be found from the Mandli overlay. The superelevation value obtained from Mandli is derived by the user and can be an average, maximum, or another chosen metric. This user-derived value is an aggregate value from the Mandli data within a curved segment, since Mandli data is reported every 5.28 feet.

A similar method will work for tangents if Mandli data become accurate for use. Data on tangents can be imputed by the CARS data. Since CARS identifies beginning and ending milepoints of curves, it is assumed that any area not identified as a curve is a tangent. CARS should only be used to find the location of tangents rather than the value of the cross slope on those tangents. The hardware used in CARS *could* be used to derive cross slope if the routes were driven perfectly straight, but that is highly unlikely. Additionally, values are recorded every 60 milliseconds, making the distance between points contingent on the speed. Overall, CARS is not currently a reliable method to use for cross slope.

If using CARS and Mandli is impractical, UKCAT may also be used to find tangent locations. The choice depends on the needs of the user and available tools. As before, a spatial overlay in GIS can be used to acquire cross slope on tangents. Figure 21 illustrates the identification part of this process.

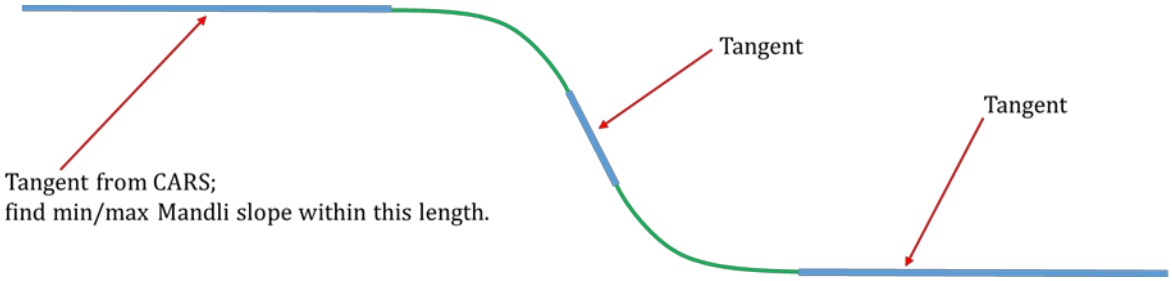


Figure 21: Finding tangent from CARS and slope from Mandli

5.2 Vertical Curves: Grade

KTC's research indicated that Mandli's grade data are accurate, but its method of segmentation makes the data cumbersome to work with. The software automatically segments roadways based on the grade data but the segments do not appear to be broken up based on inflection points between vertical curves. In many instances, it groups several sags and crests into one segment. Therefore, the most important part of the HIS conversion strategy for grade data was developing a better method to segment roadway data. It would be most logical to report grade values on segments between neighboring crests and sags because grade values are mostly uniform along these segments.

KYTC's current system is a series of grade measurements between points of inflection (PIs), meaning that grade is only compiled for slopes. This amounts to approximately 1,800 miles of grade data in the current HIS system. To achieve total system coverage, Mandli can be used to identify PIs with KYTC creating its own segmentation formula for vertical curves. Use of segmentation formula may be performed manually or, with further research and development, automated. The formula should be based on a set of algorithms that look for certain changes in magnitude and sign in raw Mandli data. As shown in Figure 22, the algorithm could be programed to identify segments as stretches of roadway between neighboring crests and/or sags (PI-to-PI) (a), or it could separate the crests and sags from segments of constant grade (b).

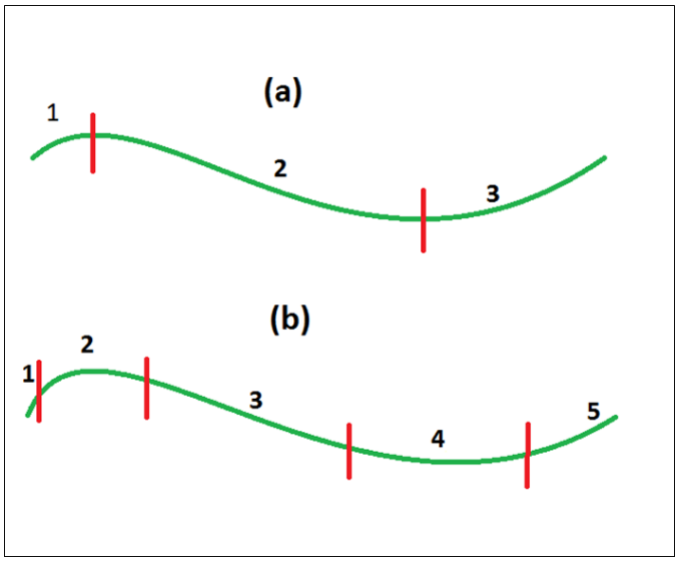


Figure 22: Example segmentation of Mandli grade data

The advantage to option (b) would be that the length of the vertical curve and the grade on both the entry and exit of the curve could be captured in HIS. Using the segment IDs from part b of Figure 22 as an example, the following hypothetical HIS data (Table 5) could be produced.

Table 5: Grade HIS example

ID	Type	BMP	EMP	Length	Grade1	Grade2
1	Tangent	0	0.1	0.1	3%	3%
2	Crest	0.1	0.3	0.2	3%	-2%
3	Tangent	0.3	0.7	0.4	-2%	-2%
4	Sag	0.7	1.0	0.3	-2%	1.5%
5	Tangent	1.0	1.2	0.2	1.5%	1.5%

The fields Grade1 and Grade2 would be equal if a vertical curve segment is a tangent since the grade is equal along the length of the tangent. For a crest or sag curve, the values of Grade1 and Grade2 would describe the grades on the entry and exit of the vertical curve, moving in the cardinal direction. This option provides a higher level of detail for grade in HIS, although it would require a more complex algorithm.

At this point, there are several options for using Mandli's data. KYTC could use a spatial overlay and other tools in GIS to average grade values or find minimum/maximum grade values. However, it is critical to note that minimum and maximum values may suffer from local perturbations. To reduce local effects, a moving average may be used or an outlier detection method developed. Overall, this provides several ways to interpret and utilize the data from Mandli. The strength behind this system lies in its adaptability: after key points are identified, users can add any other parameters of interest using the same process.

5.3 Summary of HIS Datasets

Table 6 below summarizes available data from Mandli and their potential use in HIS.

Table 6: Summary of HIS datasets

Highway Type	Radius of Curvature	Advisory Speed	Superelevation	Grade
Interstates/Parkways	Mandli (via UKCAT)	N/A	Mandli with caution	Mandli
All other State-Maintained Roads	CARS	CARS or Mandli's superelevation	Mandli with caution	Mandli

6 Conclusion

6.1 Summary

This study thoroughly examined how KYTC collects roadway information, the accuracy and value of Mandli data, and strategies for using Mandli to improve the state's HIS database. The curve attributes that were analyzed included horizontal curve radius, grade, and cross slope.

Horizontal curves were analyzed with three data processors: the UNR CATER curvature tool, Florida DOT's curvature extension tool, and UKCAT. Each tool compiled Mandli data and used it to identify curve locations and curve attributes. The tools were tested for usability and efficiency, and their accuracy was evaluated by comparing their output with CARS data. UKCAT proved the most accurate as well as the fastest and easiest to use. Employing this tool is a valid way to use Mandli's curve radius data for curve identification.

The curve attributes of grade and cross slope were grouped together for data collection, which included manually measuring roadways and matching field data with Mandli data in a series of graphs. The data were then validated by a comparison to design plans and CARS data, followed by statistical analysis to evaluate accuracy. Researchers arrived at different conclusions for grade and cross-slope data. While grade data were accurate and can be used for HIS purposes, cross-slope data are not accurate enough to be used at this time. The poor accuracy of Mandli's cross-slope data is likely attributable to how the van takes measurements — the system assumes a uniform slope between the two tires, ignoring the fact that roadways often have irregularities that affect measurements and calculations.

After data validation and analysis, researchers established a method for converting Mandli data into a usable form and implementing it in HIS. The research team endorses using Mandli superelevation for curve advisory speed calculations, since those calculated speeds do not require a high level of accuracy. CARS may also be used for this purpose. The CARS system can identify the location of curves and its calculated advisory speed can be used as a proxy for superelevation. CARS only collects data on a portion of the state roadway system, however, so UKCAT may be used on the remaining roads. Additionally, a theoretical approach was introduced in case further research yields a way to improve data calibration and therefore, Mandli cross-slope accuracy. This theoretical approach involves identifying curves with CARS and/or UKCAT and then using a spatial overlay in GIS to find the curve's superelevation values. On vertical curves, Mandli's grade data are accurate and may be used on all roads. To convert vertical curve Mandli data to usable HIS data, a methodology for curve segmentation was provided. The segmentation process was based on changes in magnitude and sign in the raw Mandli data and may be automated in the future.

6.2 Recommendations

KTC researchers make the following notes and recommendations:

- The Mandli van's Road Surface Profiler operates by collecting elevation data at two points that correspond with the vehicle's wheel path. To determine cross slope, the system assumes a constant slope between the two points and reports that value. This diminishes the reliability of cross-slope measurements since the reported value does not reflect the entire width of the roadway.
- Once the current Road Surface Profiler is no longer functional, KYTC will upgrade to a profiler that scans the entire width of a lane. This should produce more accurate cross-slope measurements, which may be used for HIS purposes.
- As stated in Section 5, it is important to note that milepoints produced during the Mandli procedure do not correspond to actual milepoints. Mandli milepoints are arbitrary and begin when the driver

starts collecting data on a route. GPS coordinates (also included in the Mandli data) should be used to align Mandli data with Kentucky's roadway network.

- Both the UNR CATER and UKCAT tools hold promise for statewide implementation in Kentucky. However, the UNR CATER tool does not identify or characterize transition curves, and the manual process recommended for use of UKCAT to identify transition curves would need further study to be implemented as an automated process. Further, the tools have not been validated against design plans or field-measured ground truth data, and these should be considered prior to any implementation. Lastly, a person could check the results of either CATER or UKCAT by overlaying GIS representations of the identified curves over digital aerial imagery.
- The method of operating the Mandli van likely has a significant effect on the data. While grade measurements are little affected, cross-slope data (Appendix A) show evidence of this because field data and Mandli data often correlate poorly. Because Mandli data are collected by human drivers, there is error associated with the process. Drivers are instructed to remain as close as possible to the centerline, but they may (intentionally or unintentionally) veer off or cut a corner on horizontal curves. This produces inaccurate readings of cross slope and superelevation. KTC recommends stricter instruction for drivers to ensure accurate data.

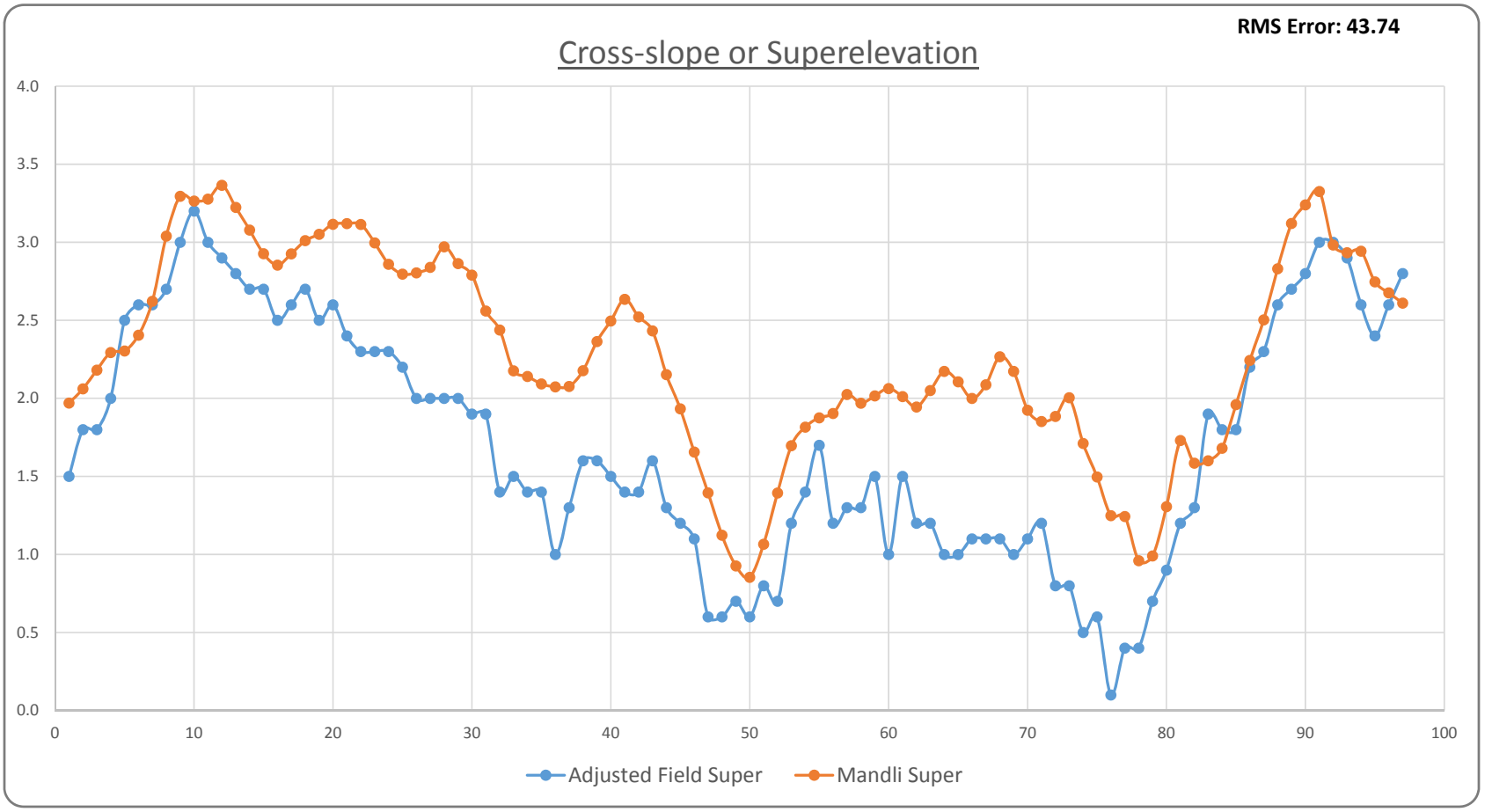
7 Bibliography

1. Caya, Mitch. *Mandli Communications, Inc. 3D Asset Management*. Florida Transportation Data Symposium, 2014. http://www.fdot.gov/planning/statistics/symposium/2014/Lidar-3DAssetMgmt.pdf. Accessed December 2017.
2. Green, E., K. Agent, and E. Lammers, *Development of an Improved Method for Determining Advisory Speeds on Horizontal Curves*, Research Report KTC-16-14/SPR15-507, Kentucky Transportation Center, July 2016, 37 pp.
3. Wang, Y., Y. Zou, K. C. Henrickson, Y. Wang, and X. Yang. *Google Earth Elevation Data Extraction and Accuracy Assessment for Transportation Applications*. University of Washington, Aug 2015. Accessed Sept 2016.
4. Pu, Z., Z. Li, W. Zhu, and Y. Wang. *Evaluating the Correlation between Vertical Curve Features and Crash Rates on Highways*. University of Washington. Aug 2015. Accessed Sept 2016.
5. Cook, A. A., M. Saito, and G. G. Schultz. Heuristic Approach to Identifying Horizontal Curves and Their Parameters Given Lidar Point Cloud Data. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2521, 2015, pp. 22-30. DIO: 10.3141/2521-03.
6. Knecht, C., M. Saito, and G. G. Schultz. *Development of Crash Prediction Models for Curved Segments of Rural Two-Lane Highways*. Oregon Department of Transportation. International Conference on Transportation and Development, 2016. Accessed Sept 2016.

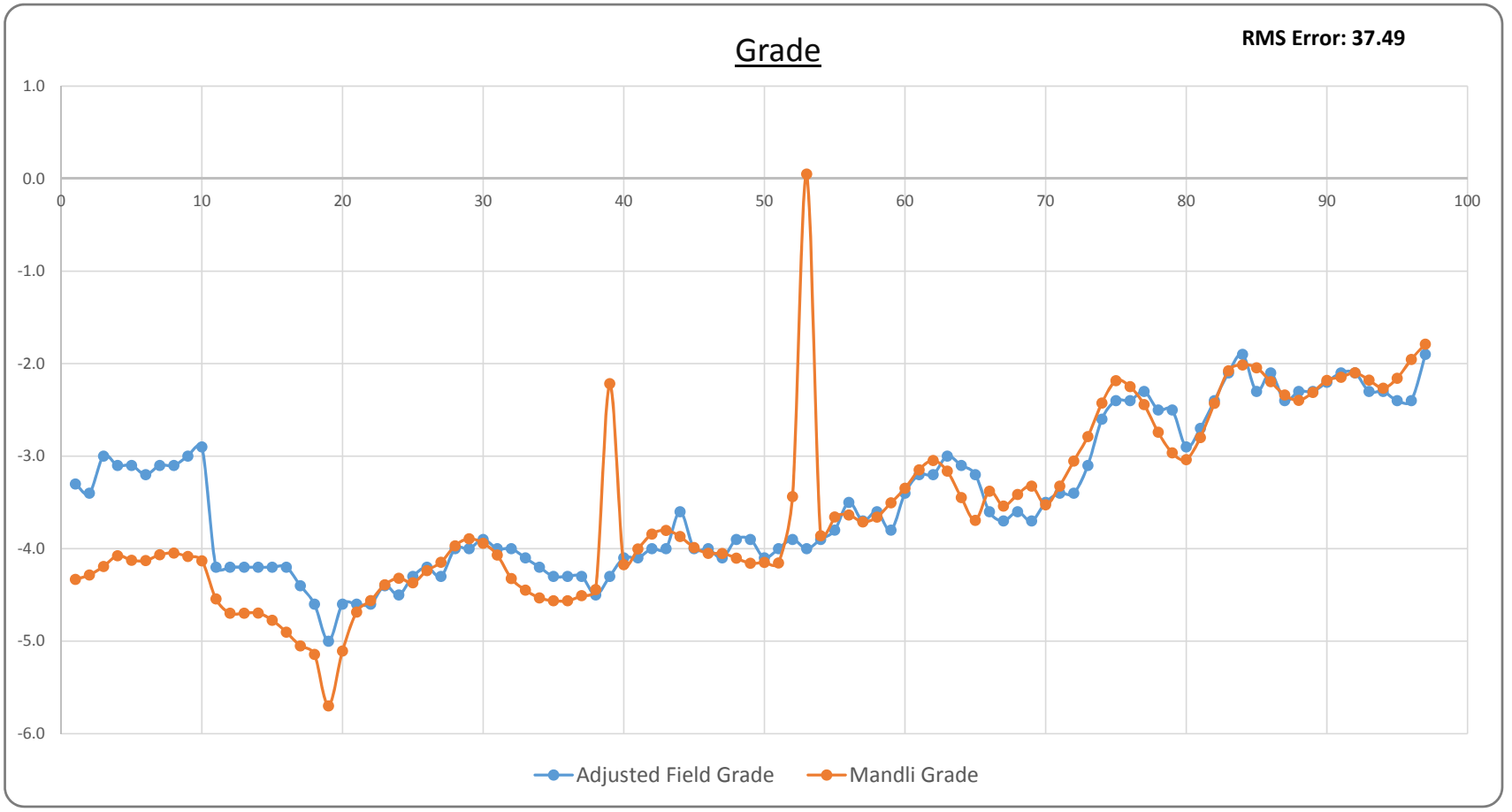
8 Appendix A: Graphs

This set of graphs provides a complete examination of cross-slope and grade data. One graph was created for each curve in each direction. Data collection provided 60-80 points per graph; points are plotted along the x-axis. The y-axis represents the measured value of interest (cross slope or grade). Mandli data were plotted for the same area to obtain two comparable graphs. Since GPS-based location readings were not reliable, researchers used the shape of the graphs to match up the two sources of data. Peaks and valleys followed a similar trend irrespective of data source. After the graphs were matched based on shape, statistical analyses were used to measure their correlation. This is shown by the RMSE value provided in the corner of each graph. The closer the value to zero, the stronger the correlation.

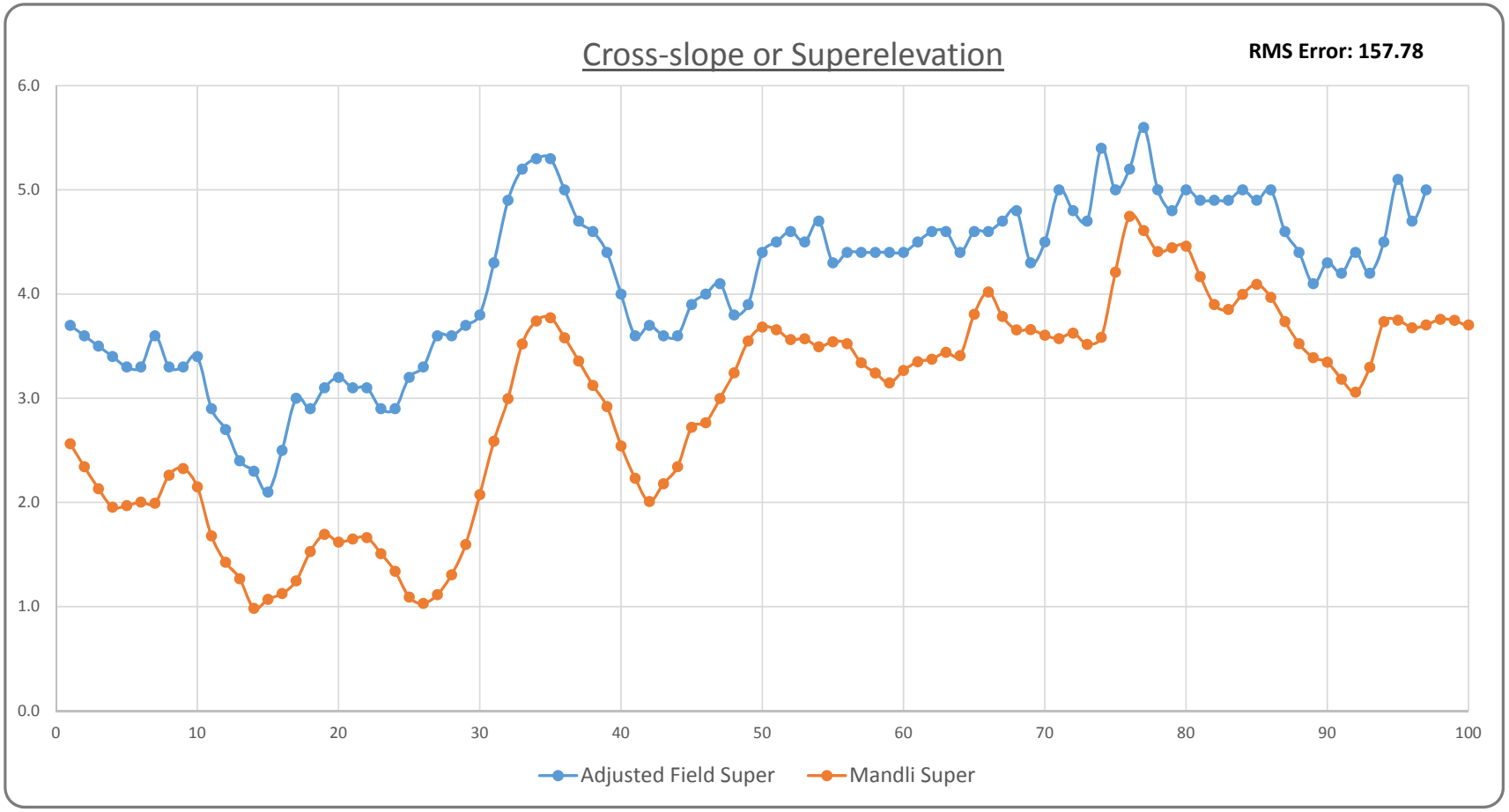
Catnip Hill: Milepoint 2.6-2.8 (Vertical Curve - Eastbound)



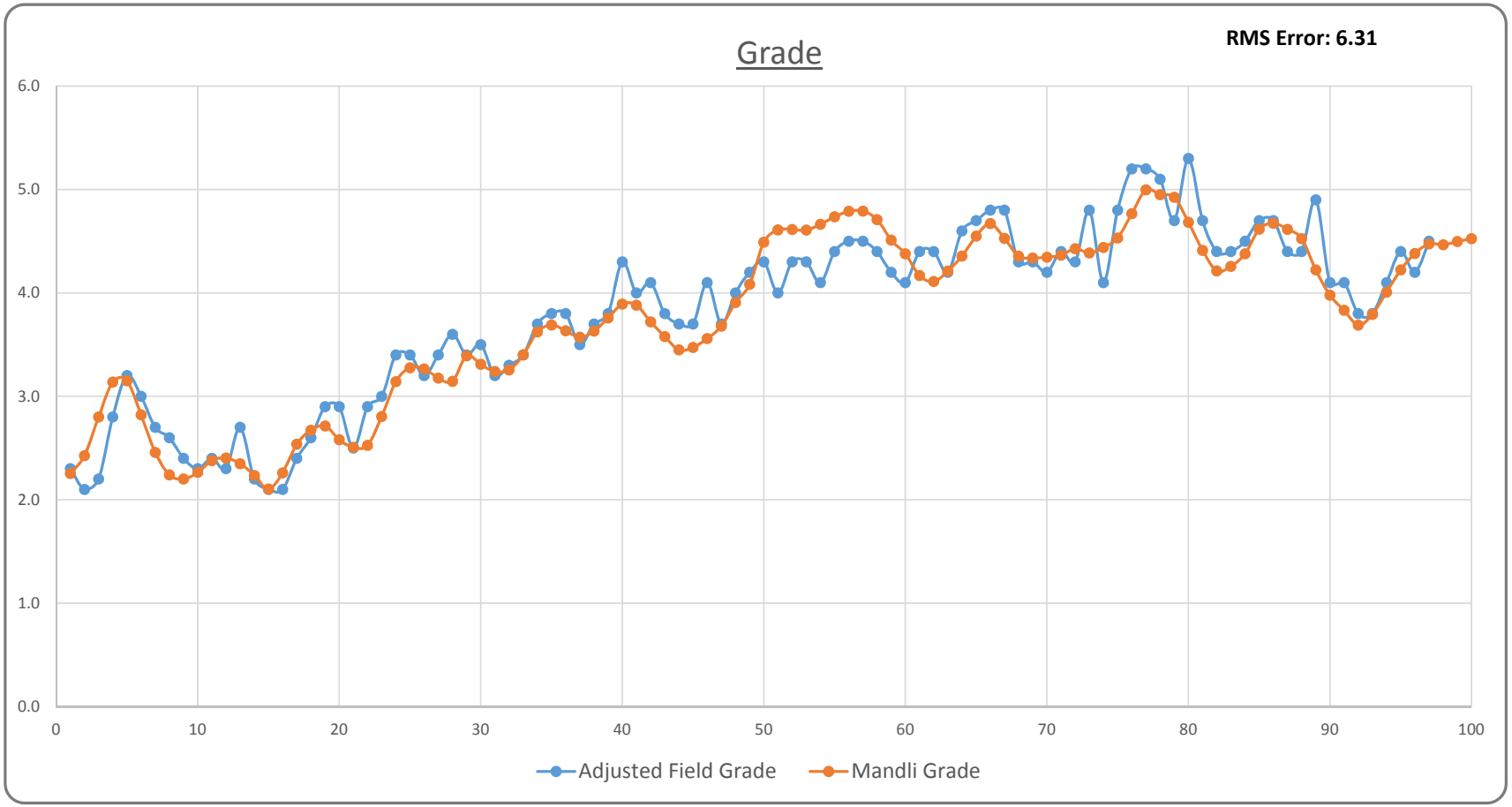
Catnip Hill: Milepoint 2.6-2.8 (Vertical Curve - Eastbound)



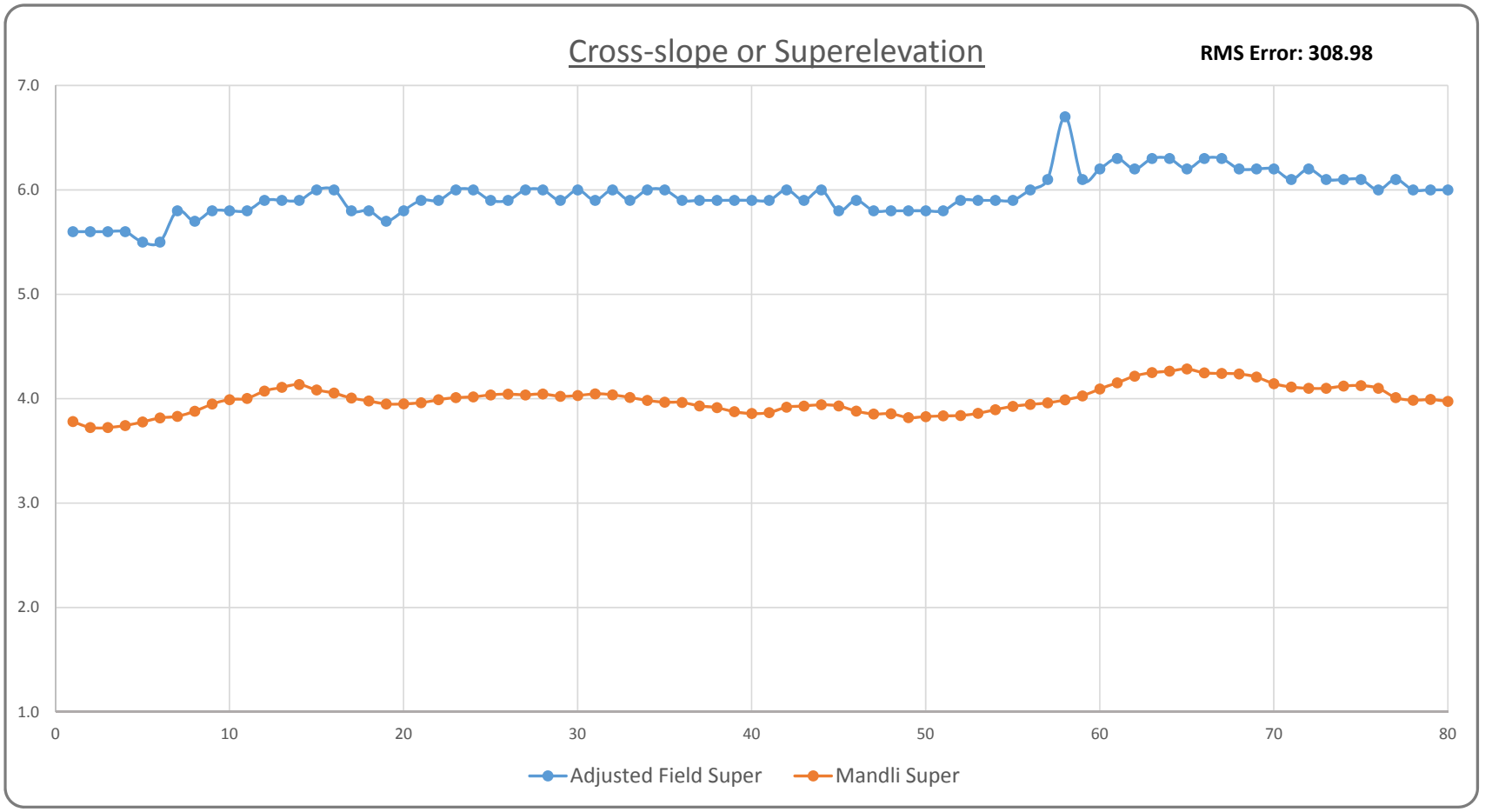
Catnip Hill: Milepoint 2.6-2.8 (Vertical Curve - Westbound)



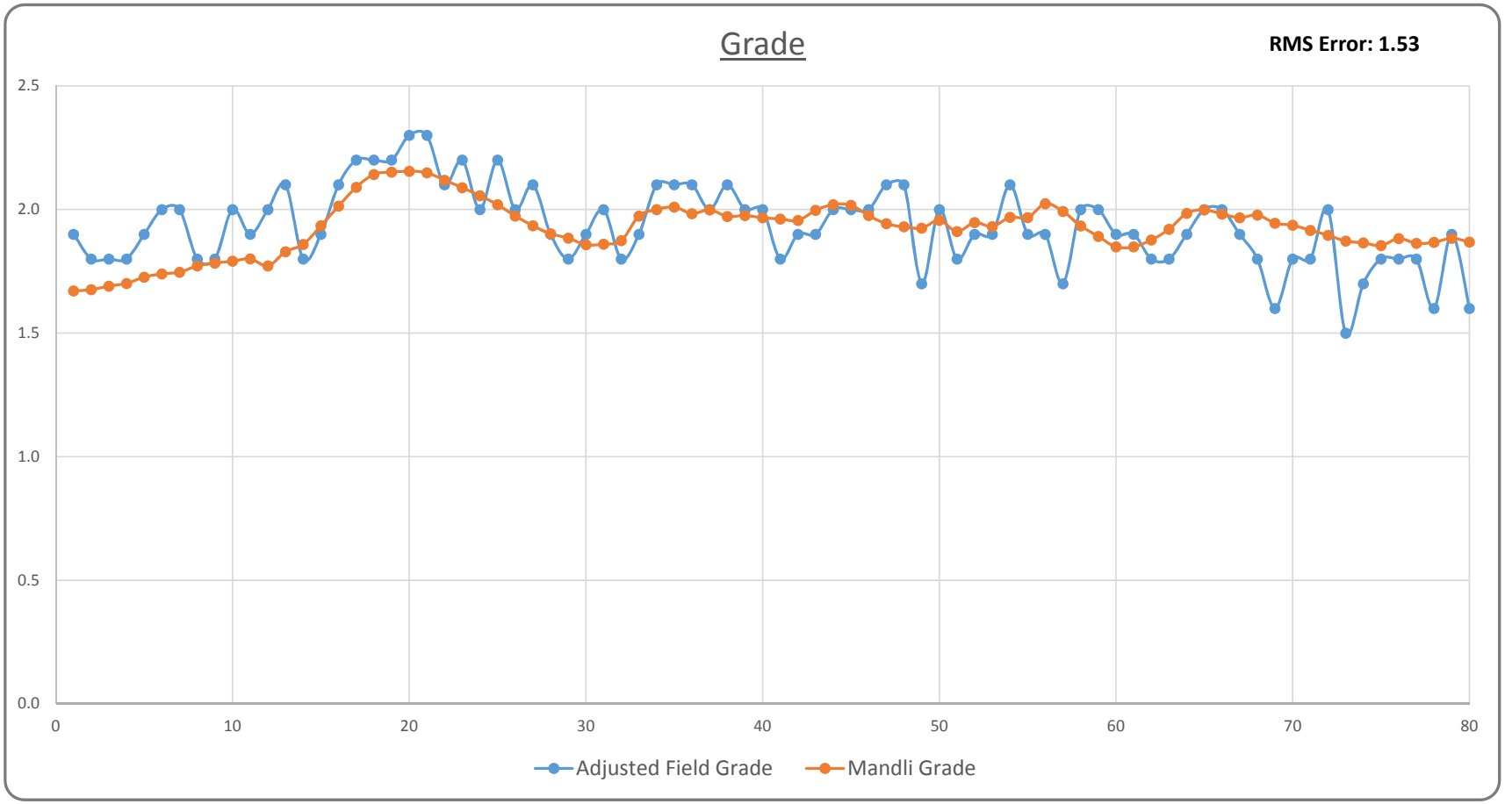
Catnip Hill: Milepoint 2.6-2.8 (Vertical Curve - Westbound)



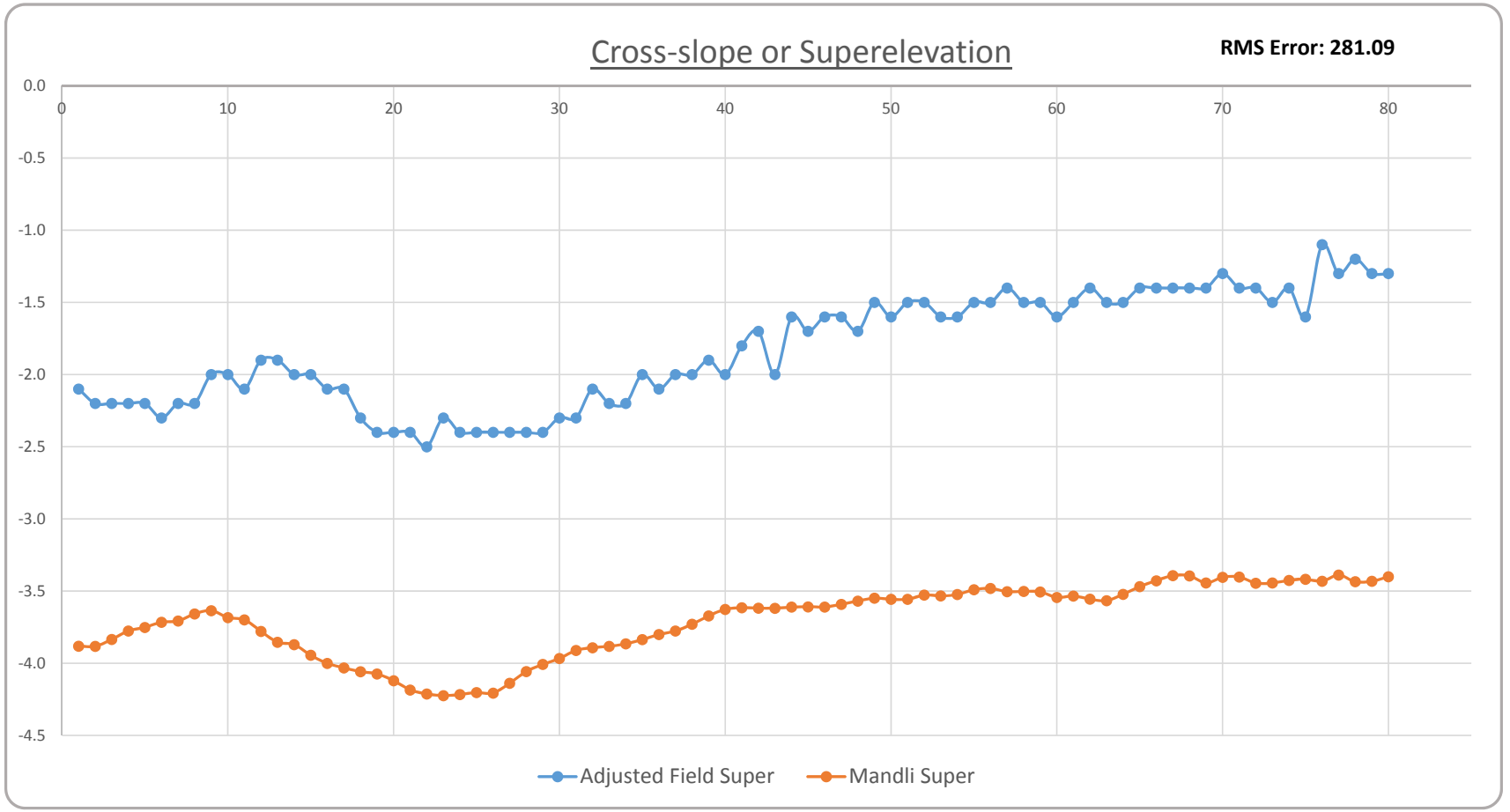
I-75: Milepoint 103.1-103.3 (Horizontal Curve - Northbound)



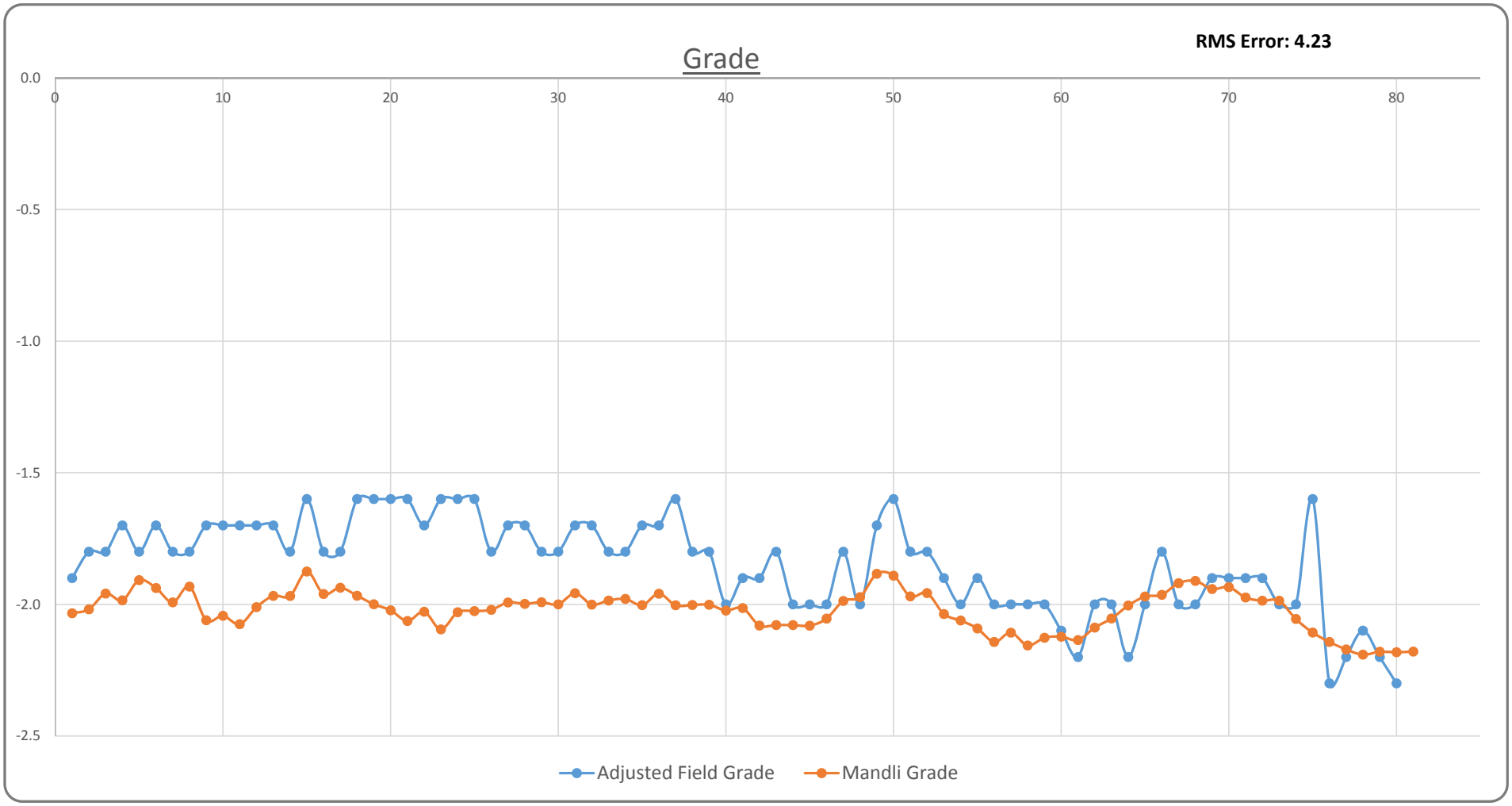
I-75: Milepoint 103.1-103.3 (Horizontal Curve - Northbound)



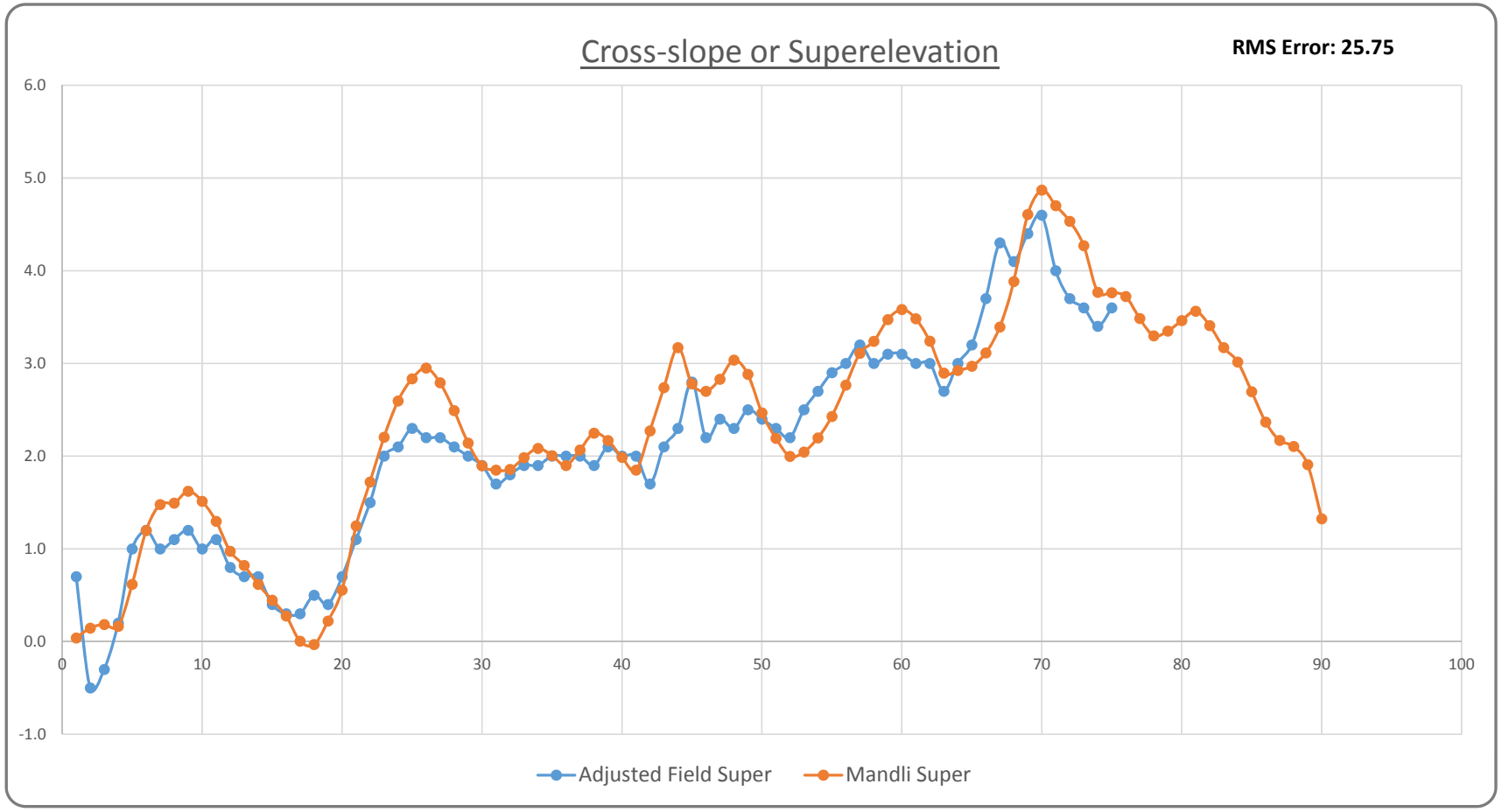
I-75: Milepoint 103.1-103.3 (Horizontal Curve - Southbound)



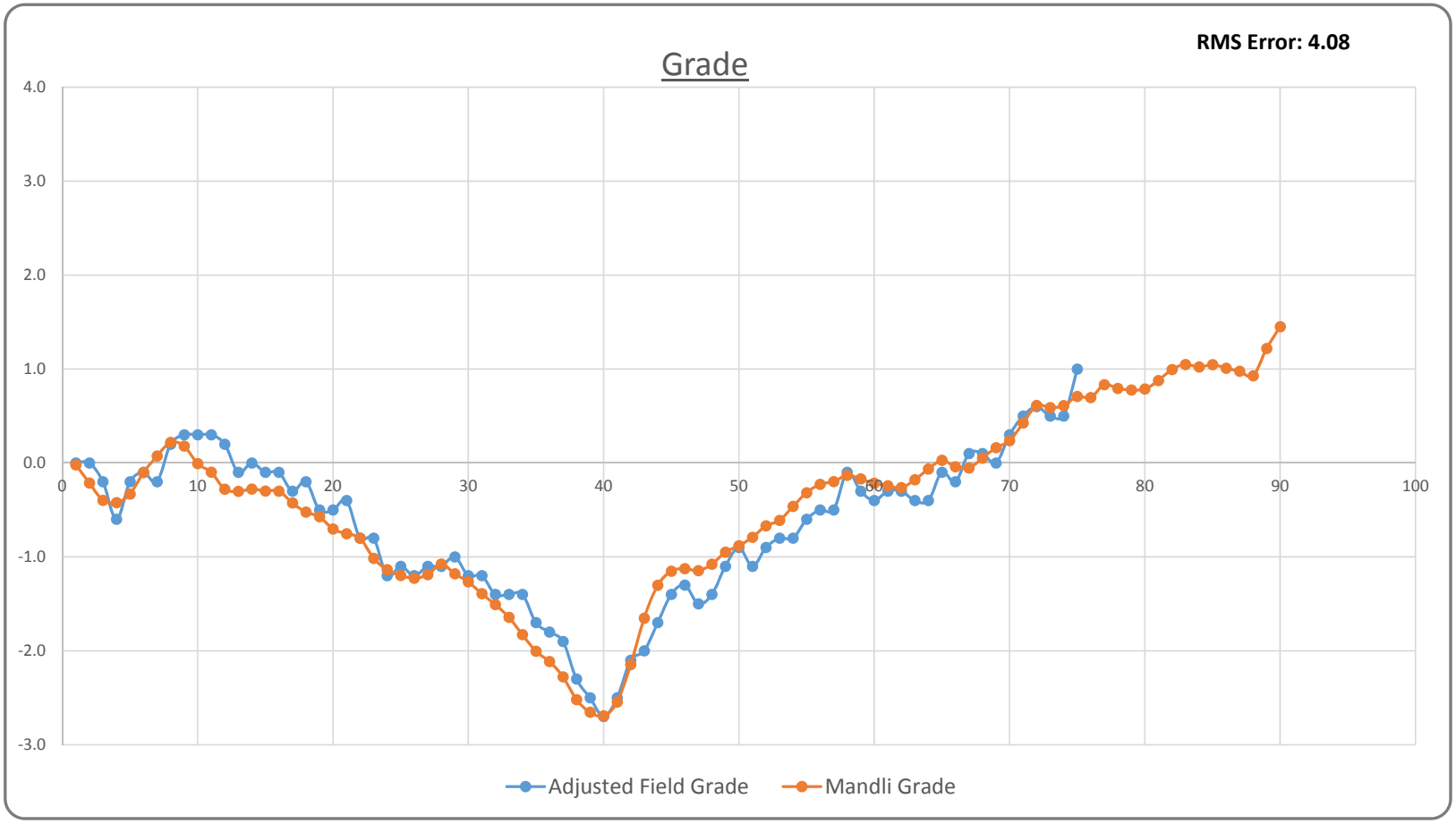
I-75: Milepoint 103.1-103.3 (Horizontal Curve - Southbound)



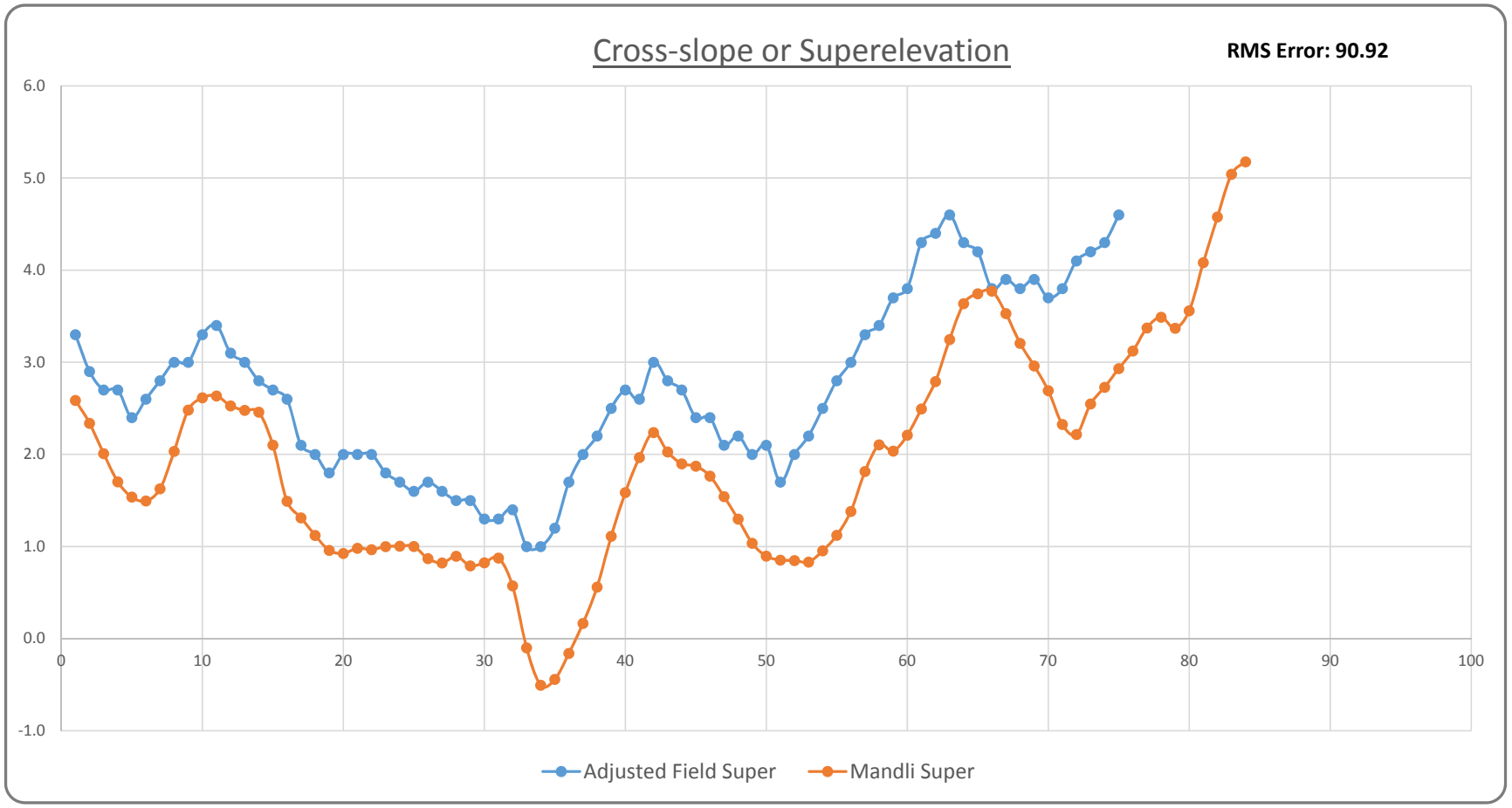
Tates Creek Rd: Milepoint 0-.2 (Vertical Curve - Northbound)



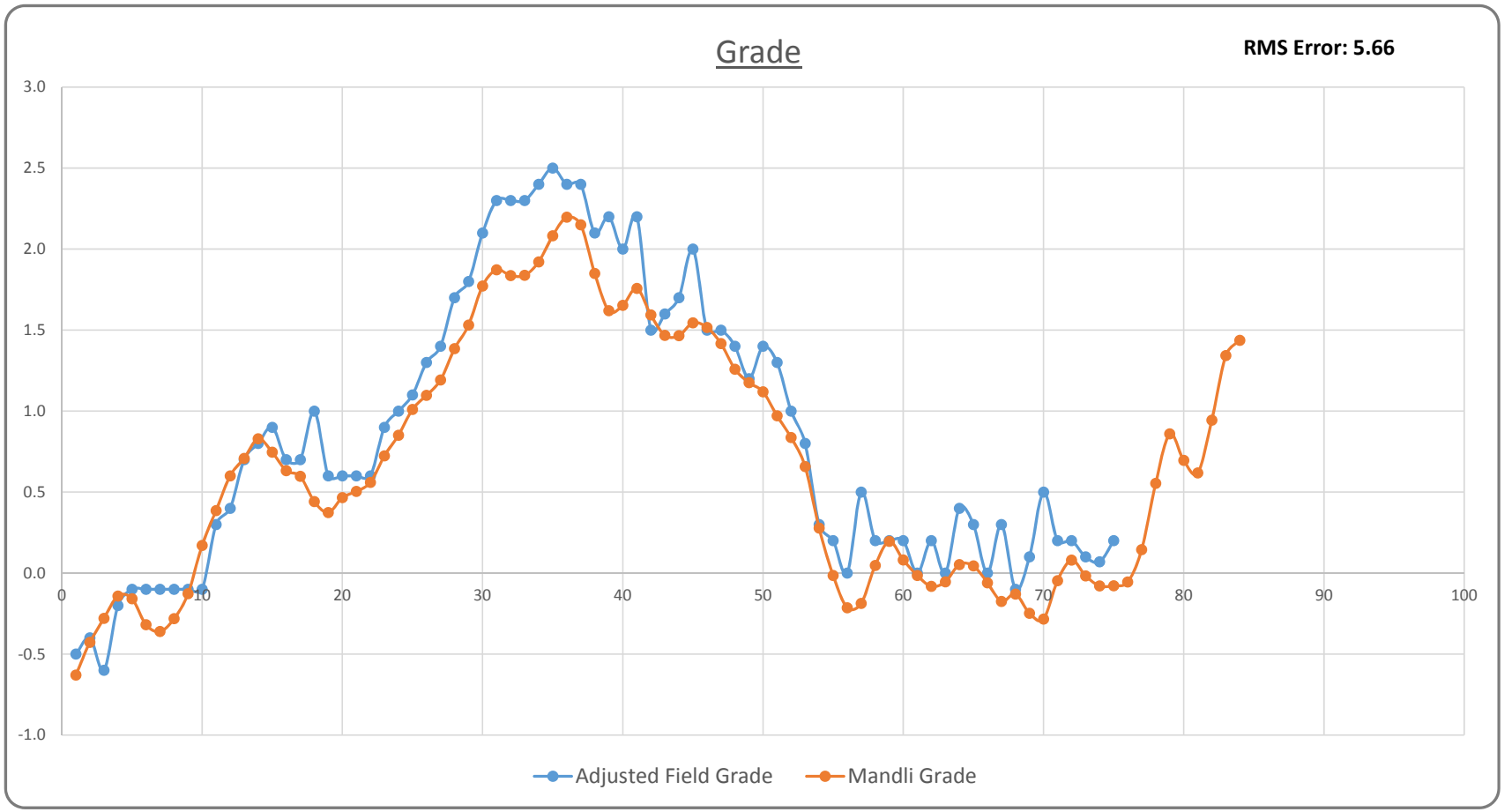
Tates Creek Rd: Milepoint 0-.2 (Vertical Curve - Northbound)



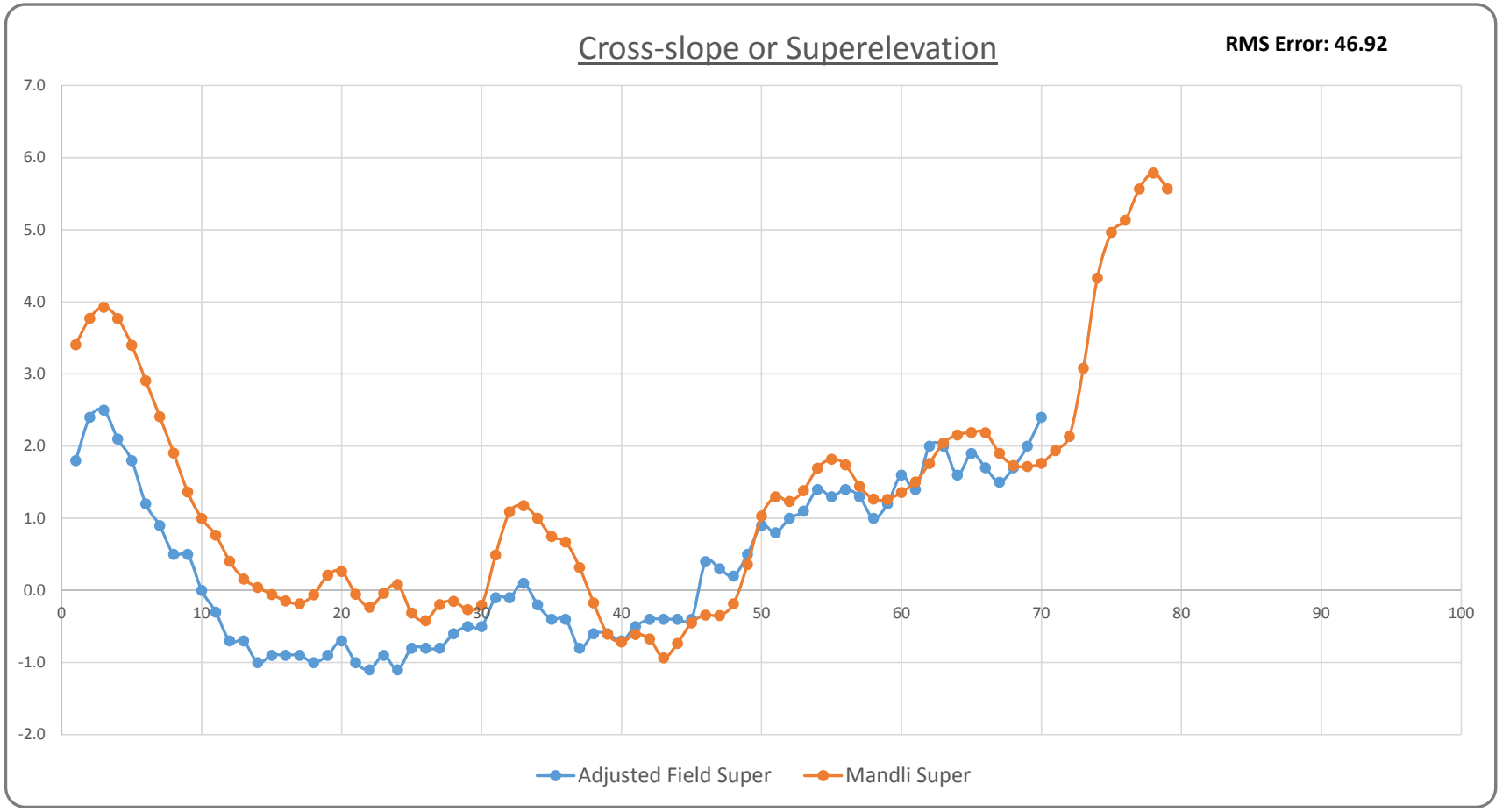
Tates Creek Rd: Milepoint 0-.2 (Vertical Curve - Southbound)



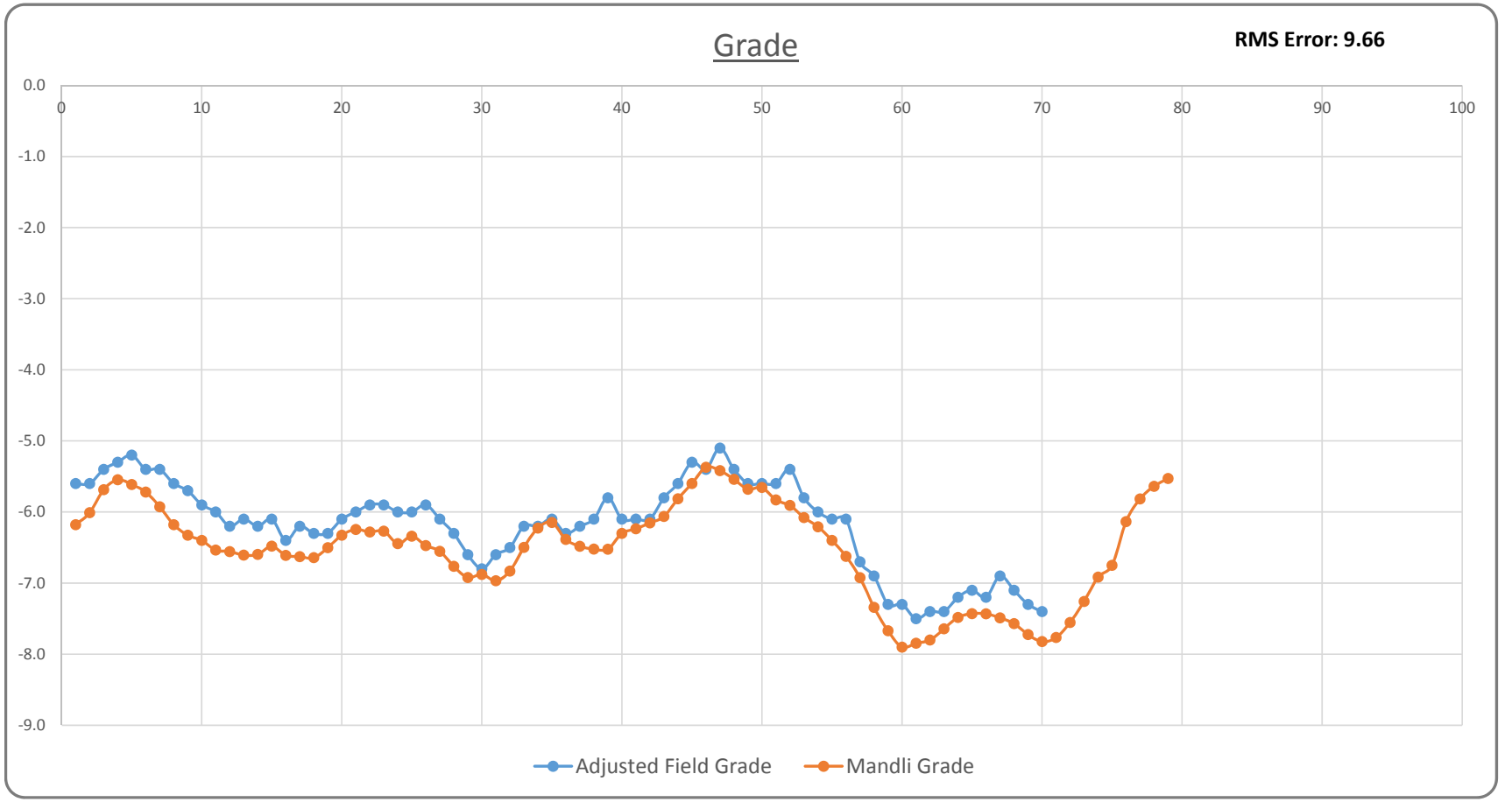
Tates Creek Rd: Milepoint 0-.2 (Vertical Curve - Southbound)



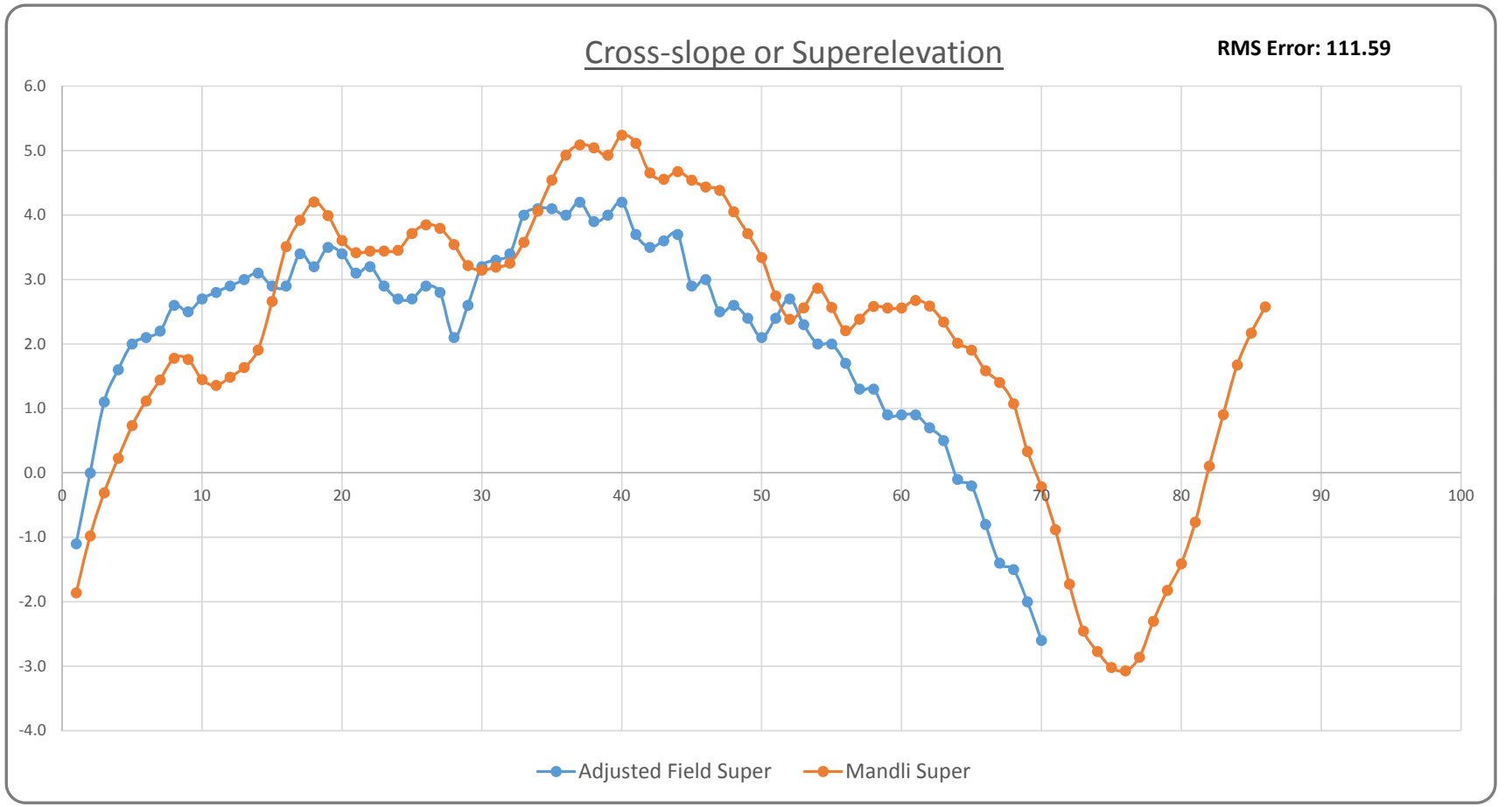
Tates Creek Rd: Milepoint .4-.5 (Horizontal Curve - Northbound)



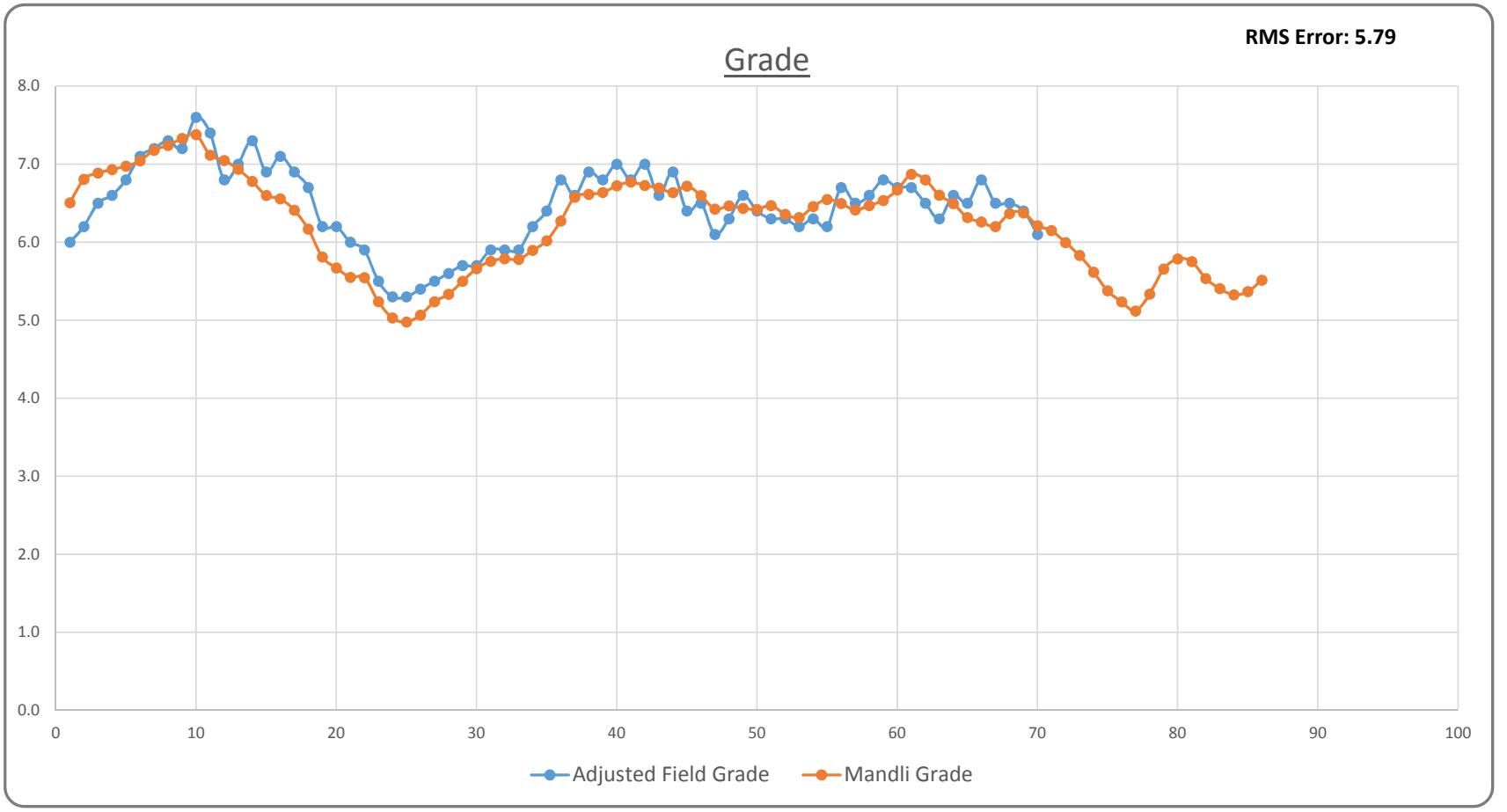
Tates Creek Rd: Milepoint .4-.5 (Horizontal Curve - Northbound)



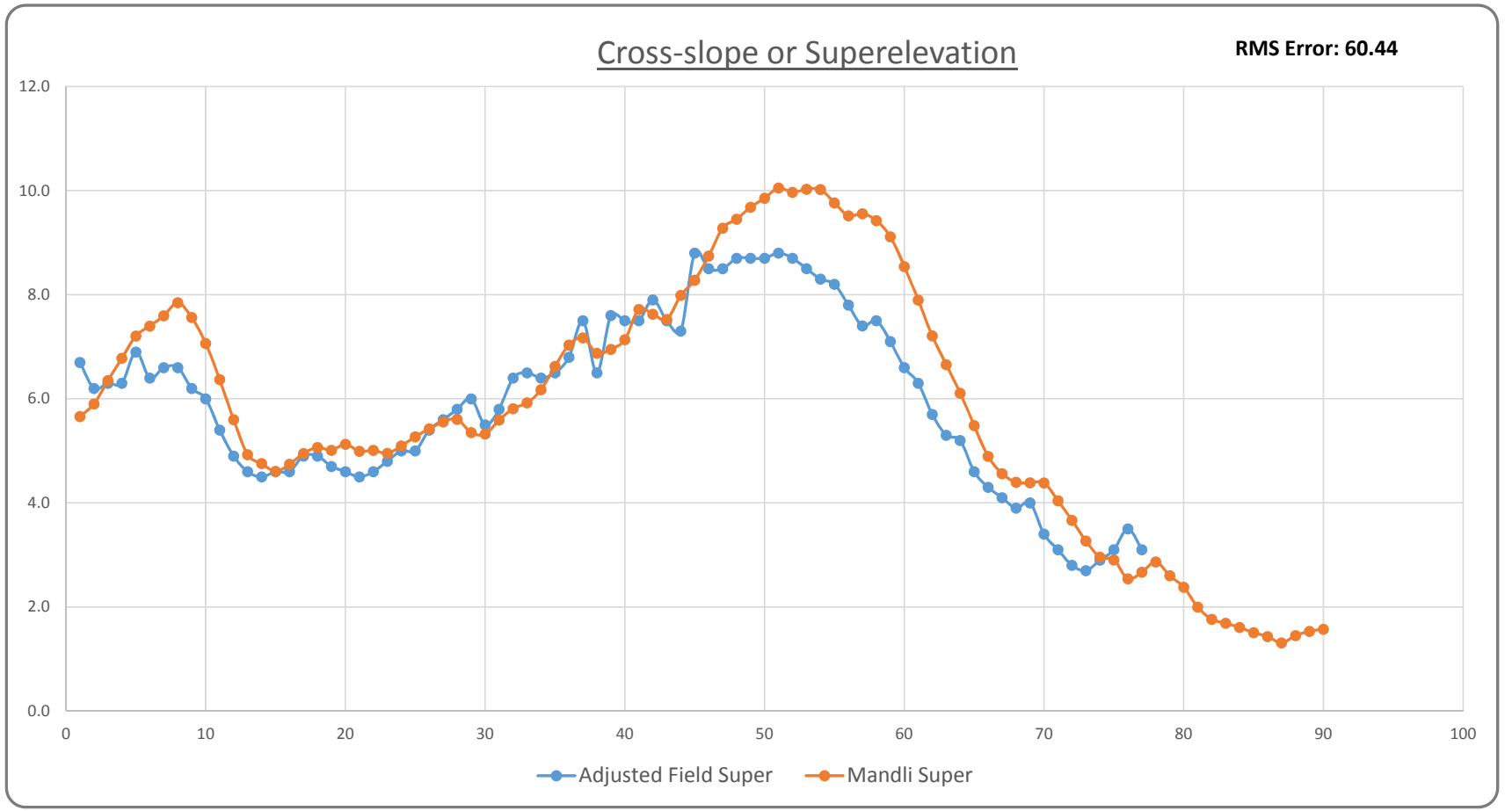
Tates Creek Rd: Milepoint .4-.5 (Horizontal Curve - Southbound)



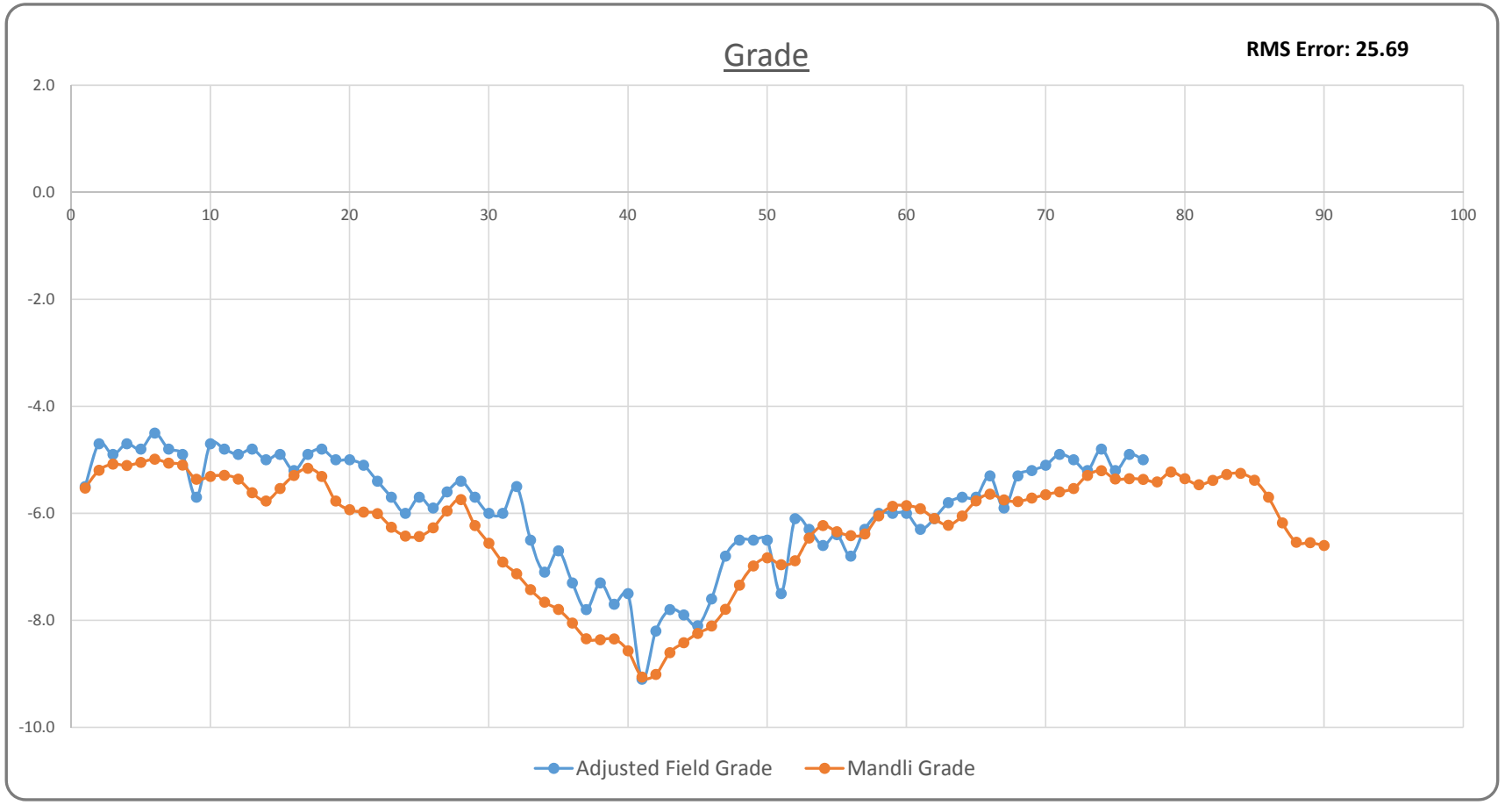
Tates Creek Rd: Milepoint .4-.5 (Horizontal Curve - Southbound)



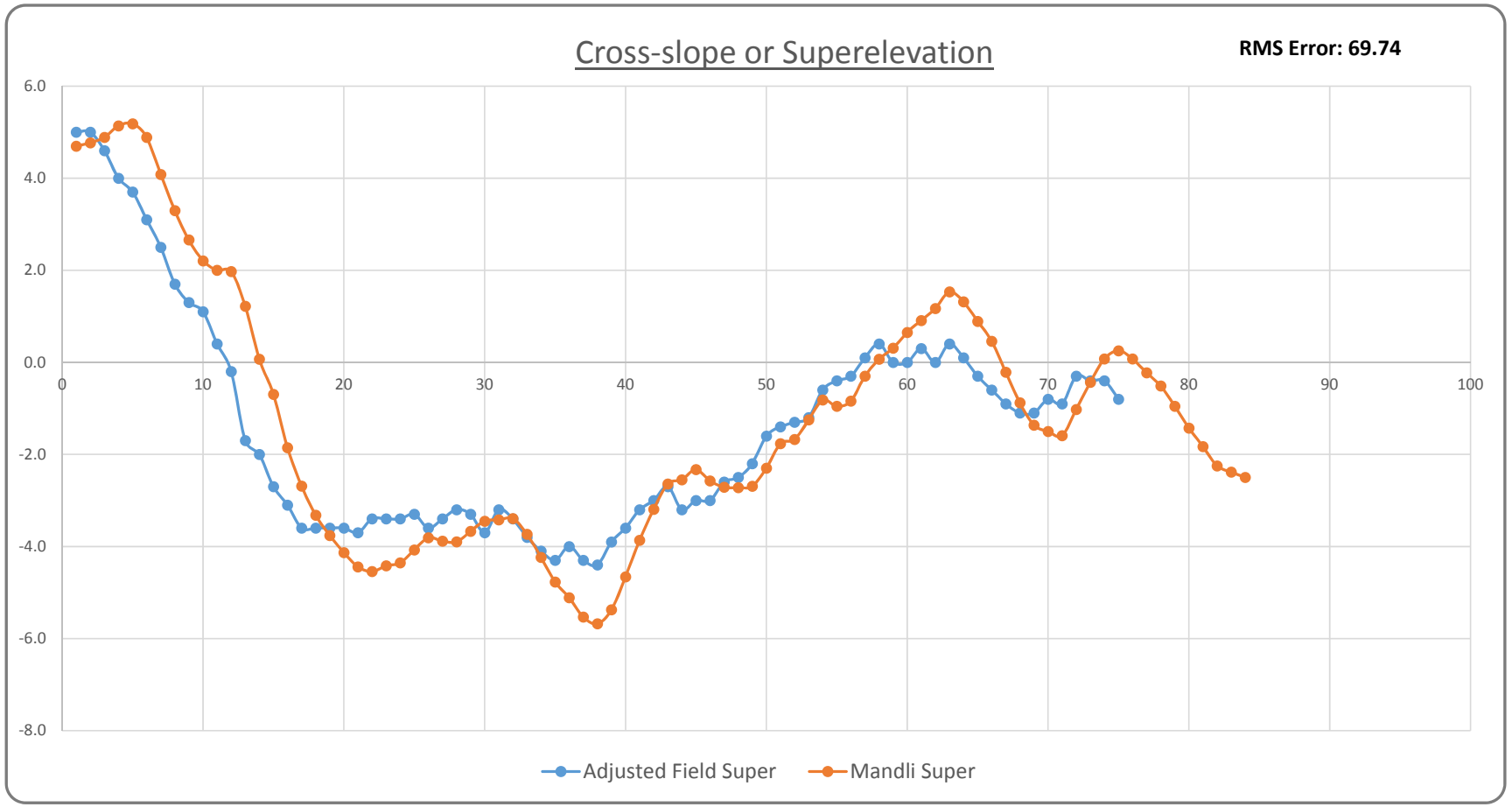
Tates Creek Rd: Milepoint .5-.6 (Horizontal Curve - Northbound)



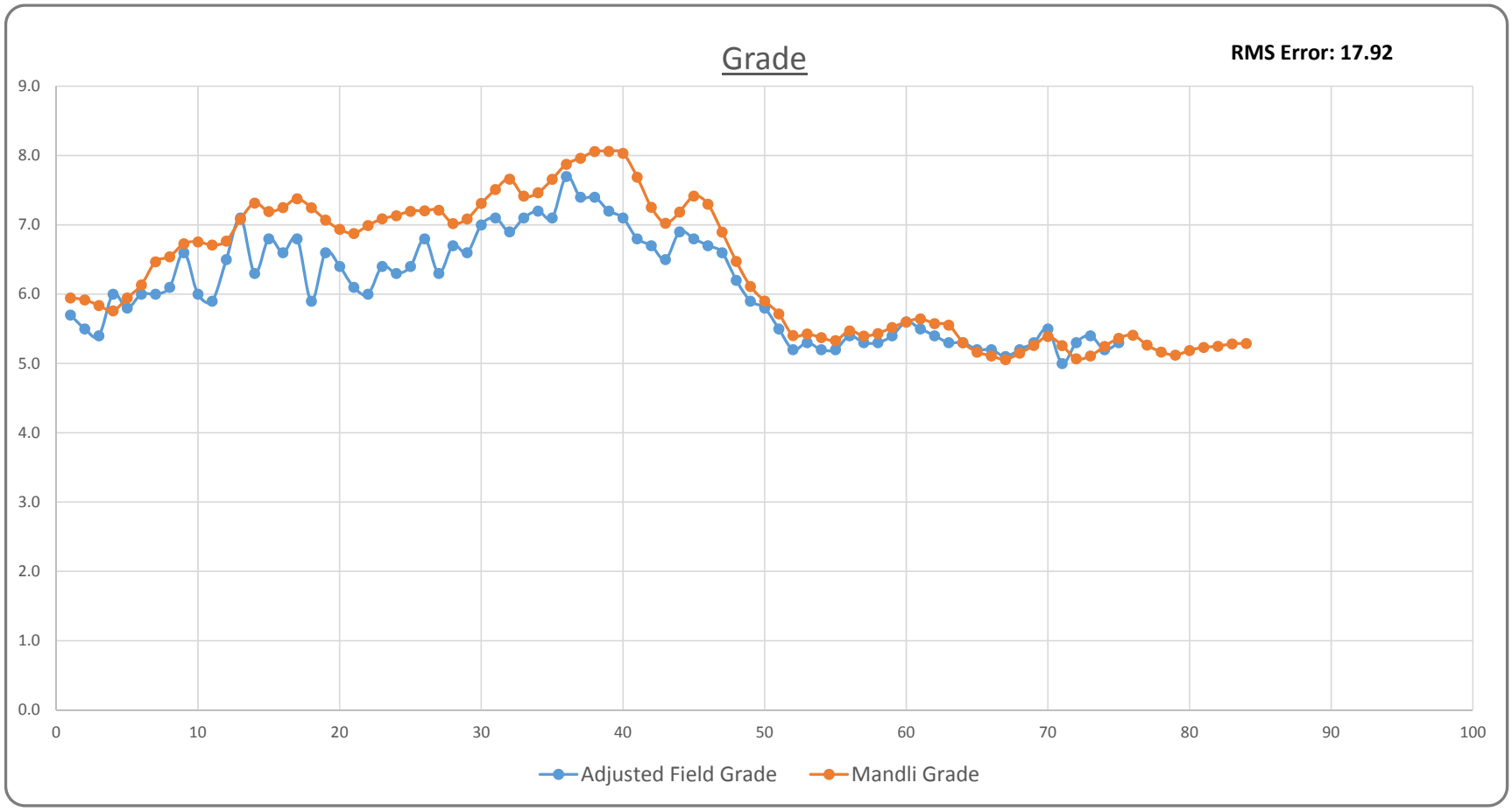
Tates Creek Rd: Milepoint .5-.6 (Horizontal Curve - Northbound)



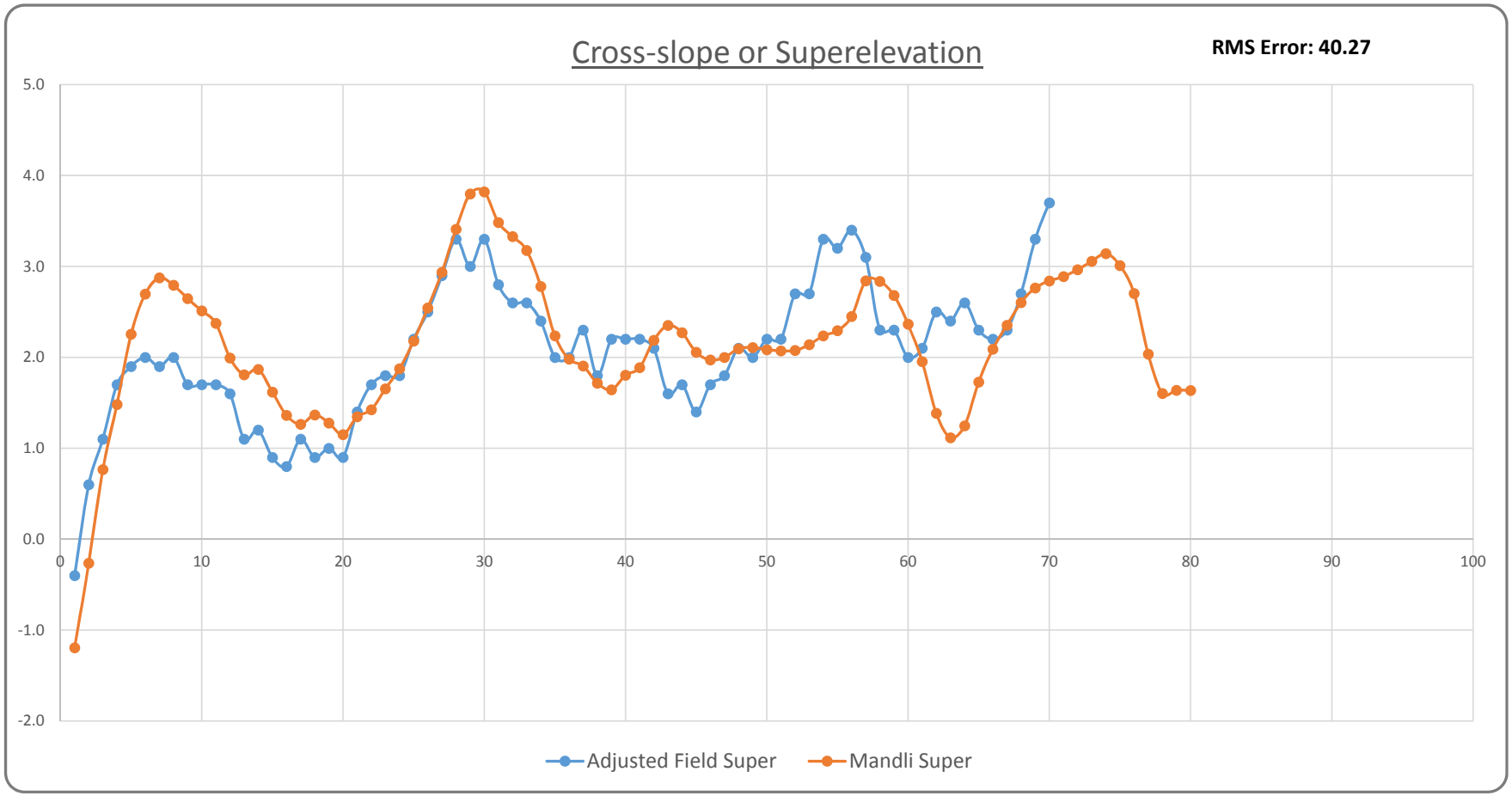
Tates Creek Rd: Milepoint .5-.6 (Horizontal Curve - Southbound)



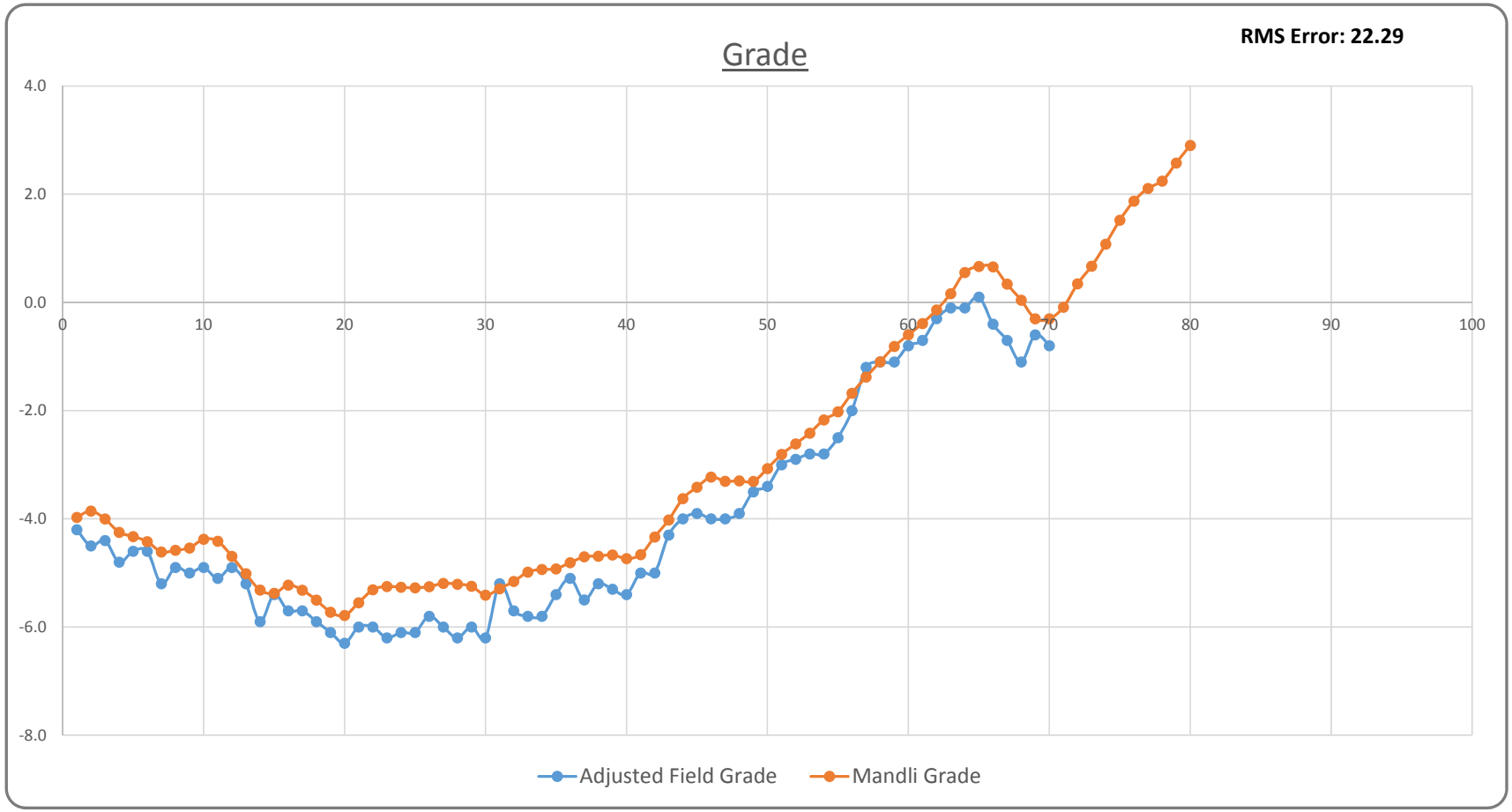
Tates Creek Rd: Milepoint .5-.6 (Horizontal Curve - Southbound)



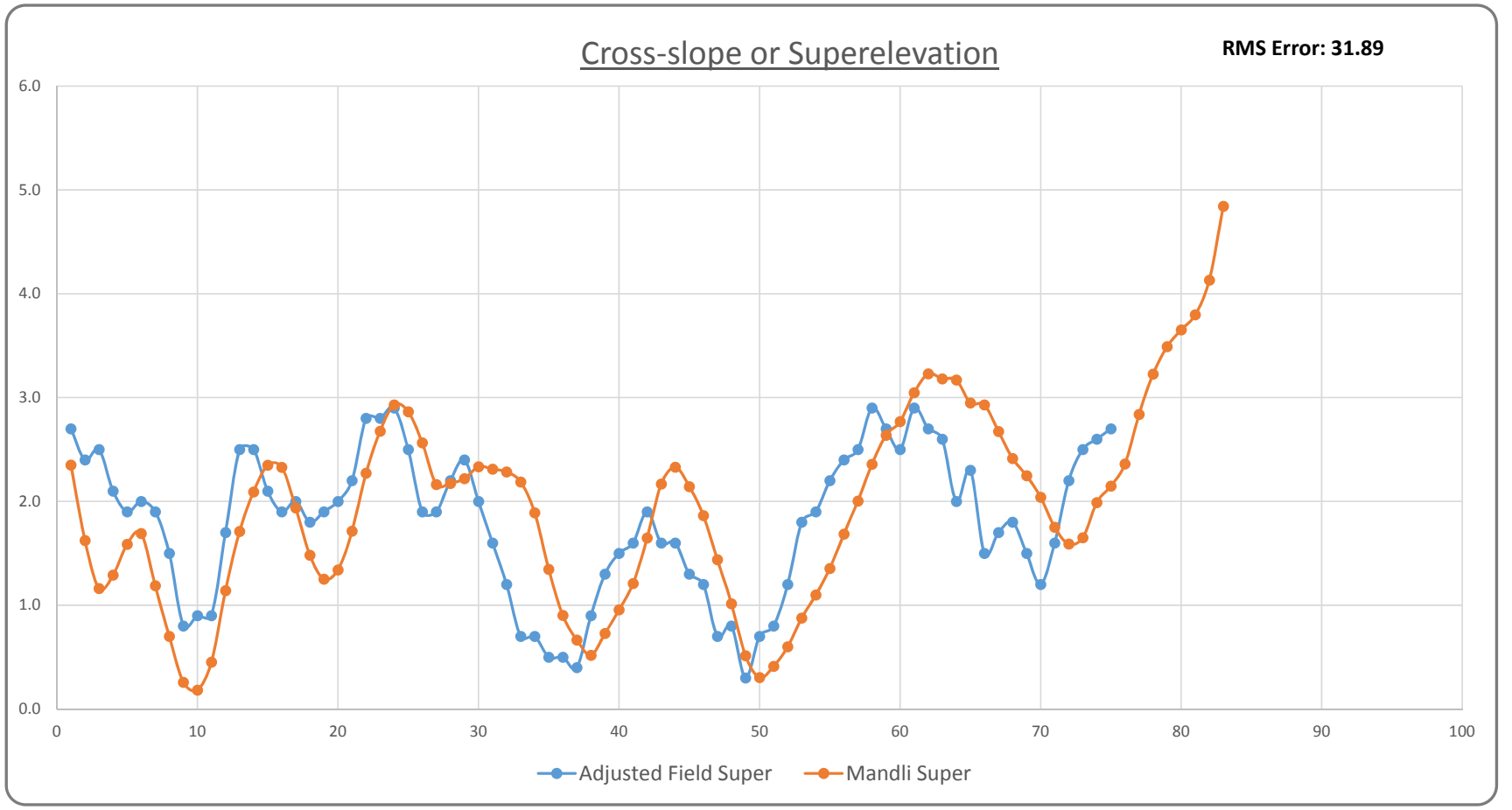
Tates Creek Rd: Milepoint .75-.85 (Vertical Curve - Northbound)



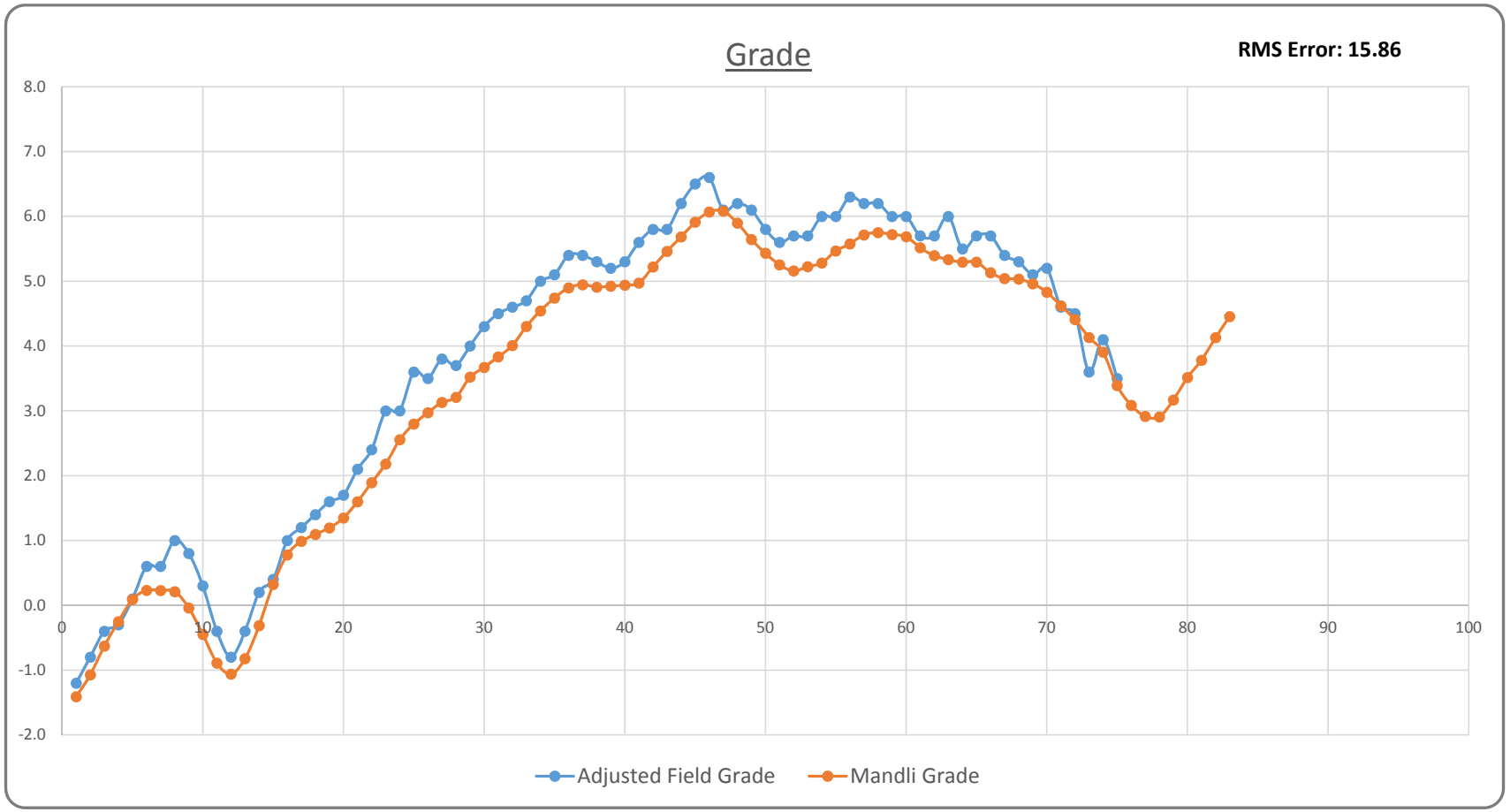
Tates Creek Rd: Milepoint .75-.85 (Vertical Curve - Northbound)



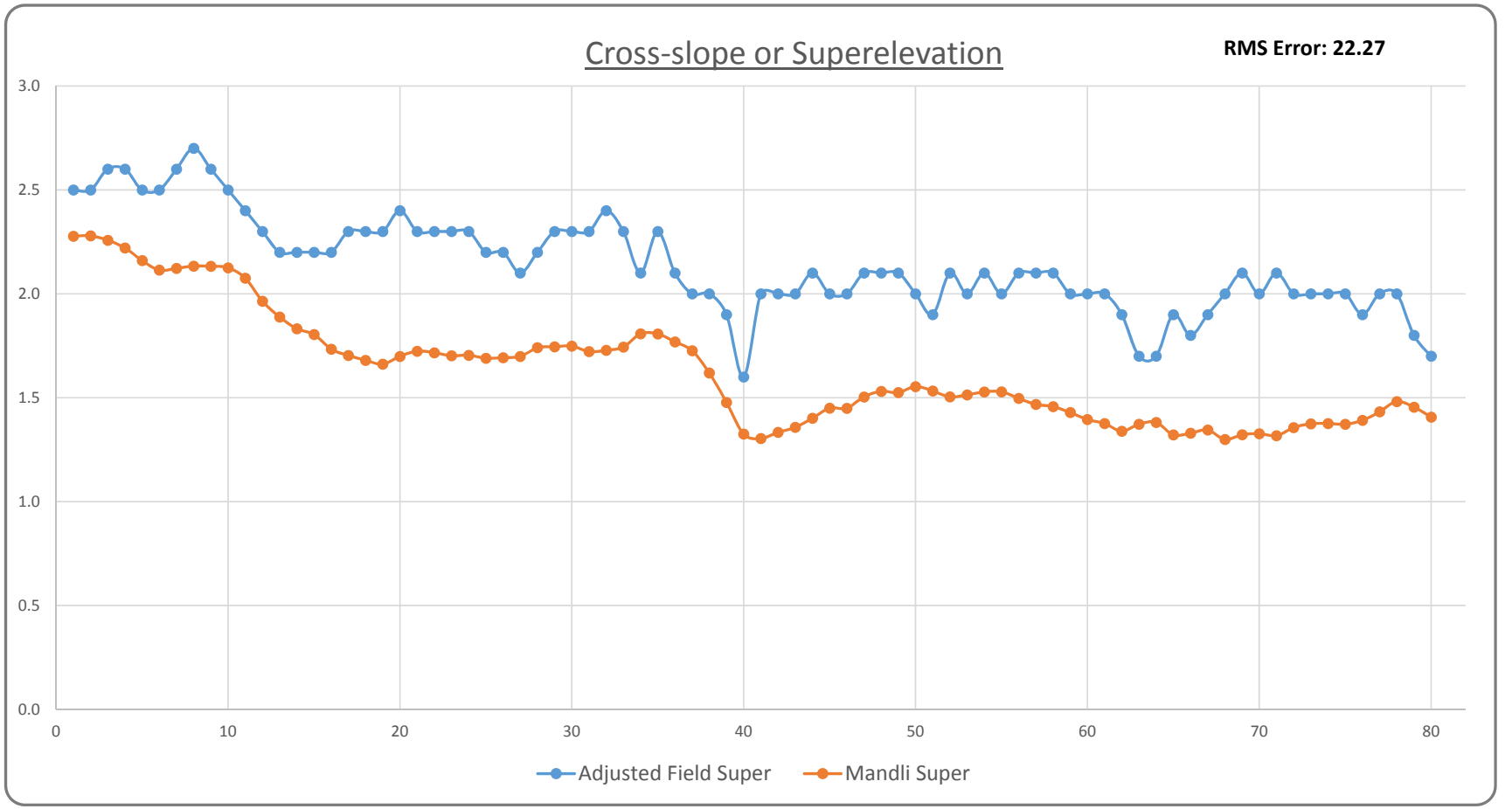
Tates Creek Rd: Milepoint .75-.85 (Vertical Curve - Southbound)



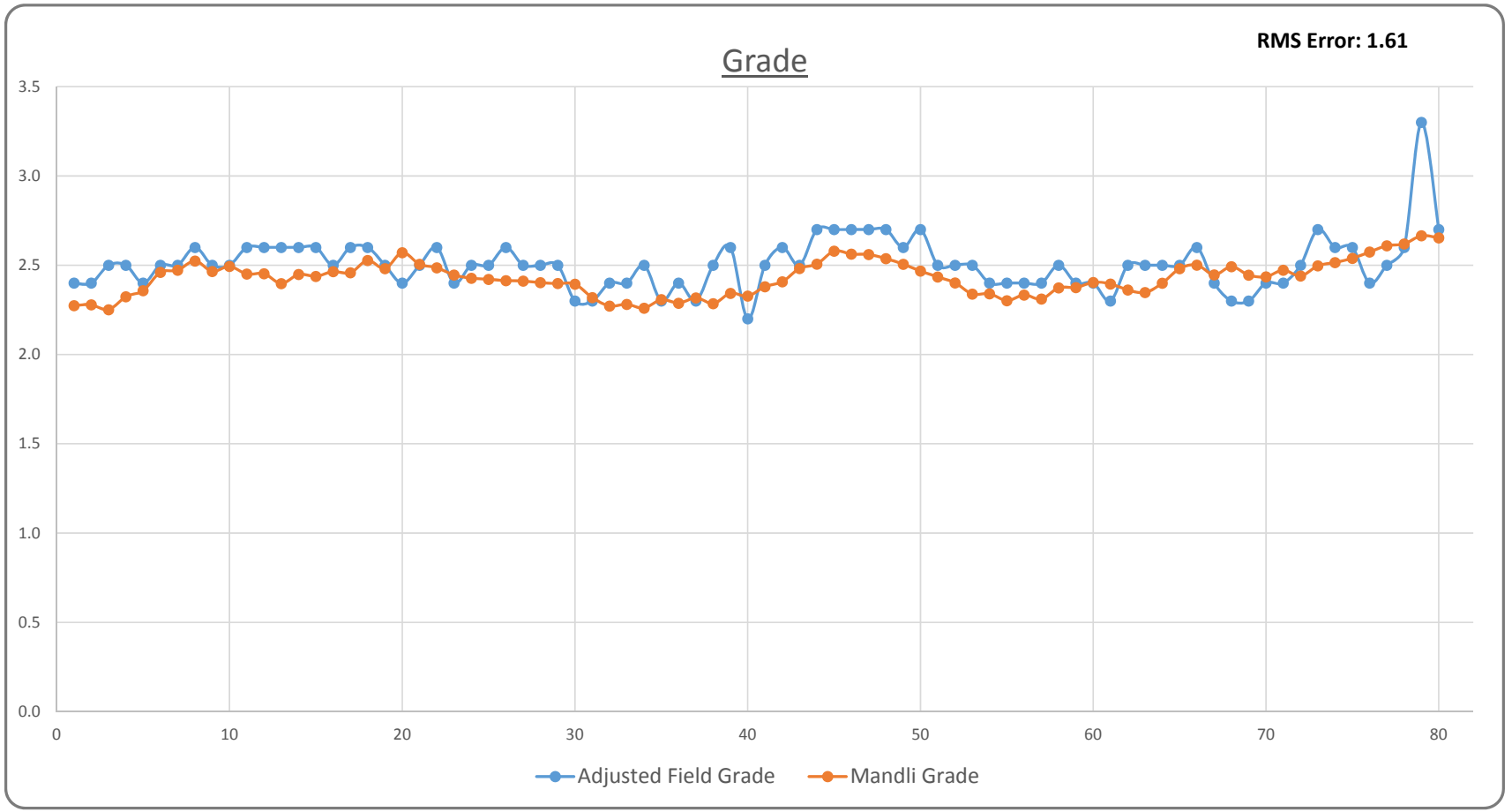
Tates Creek Rd: Milepoint .75-.85 (Vertical Curve - Southbound)



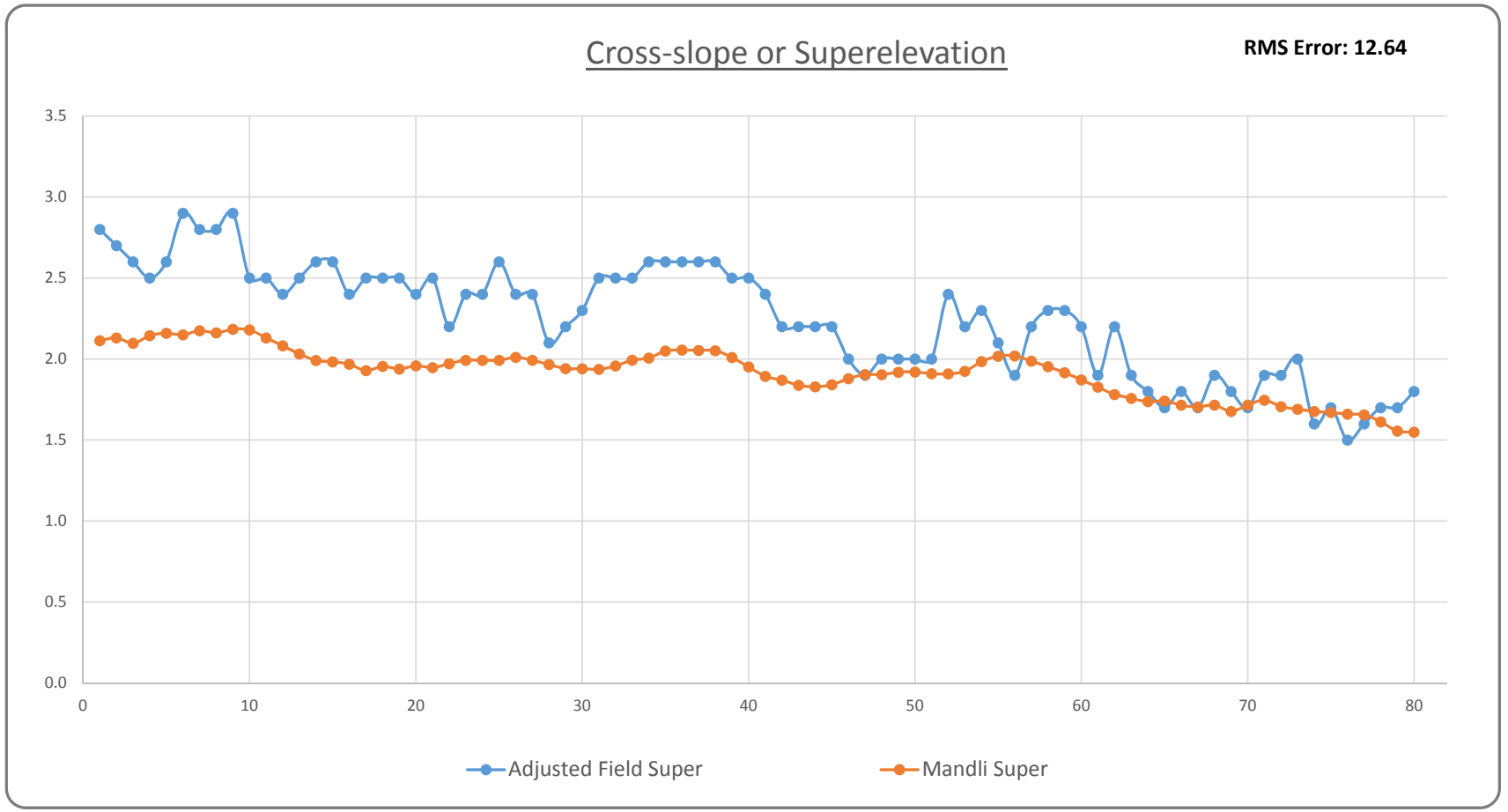
I-75: Milepoint 104.4-104.6 (Vertical Curve - Northbound)



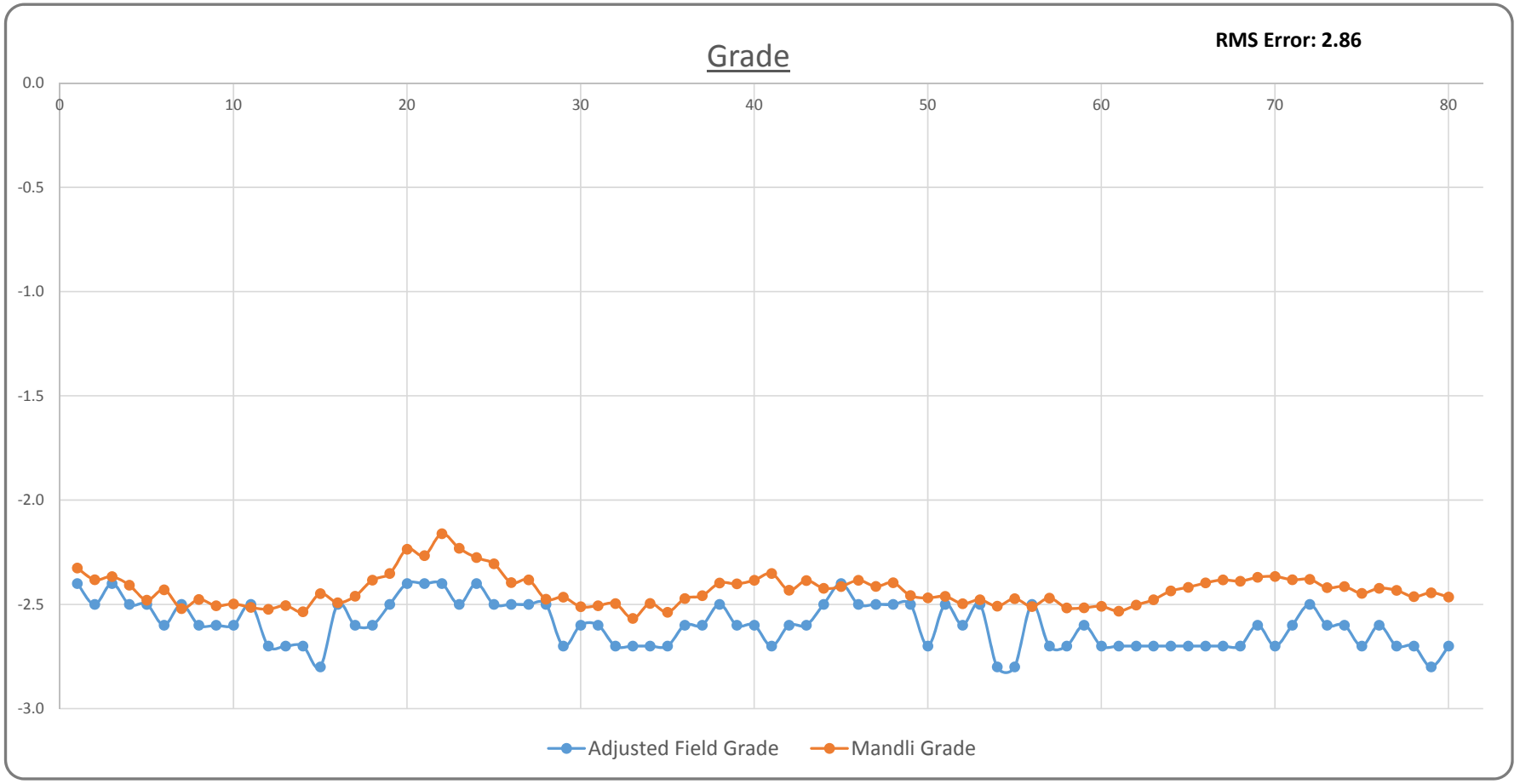
I-75: Milepoint 104.4-104.6 (Vertical Curve - Northbound)



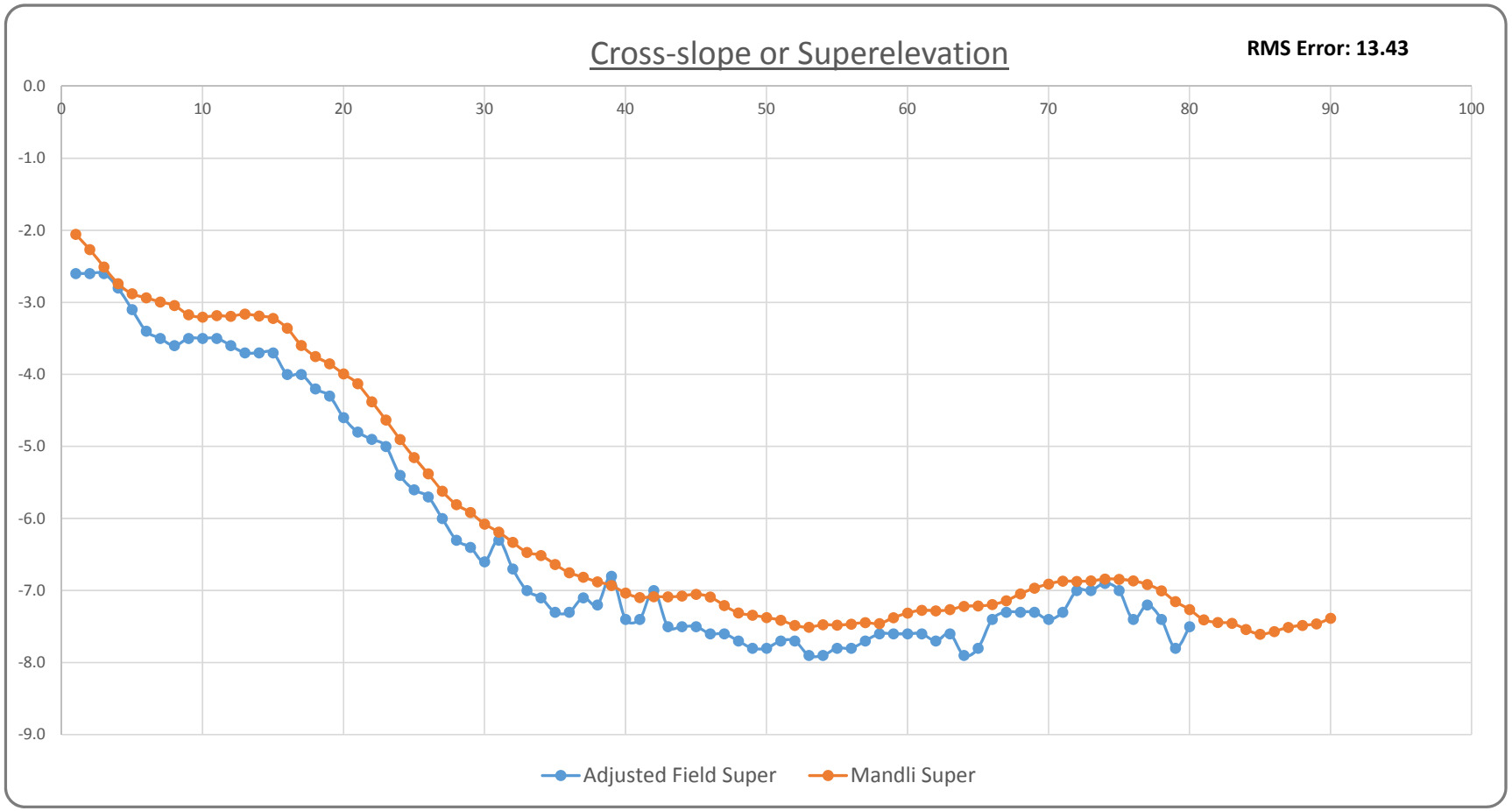
I-75: Milepoint 104.4-104.6 (Vertical Curve - Southbound)



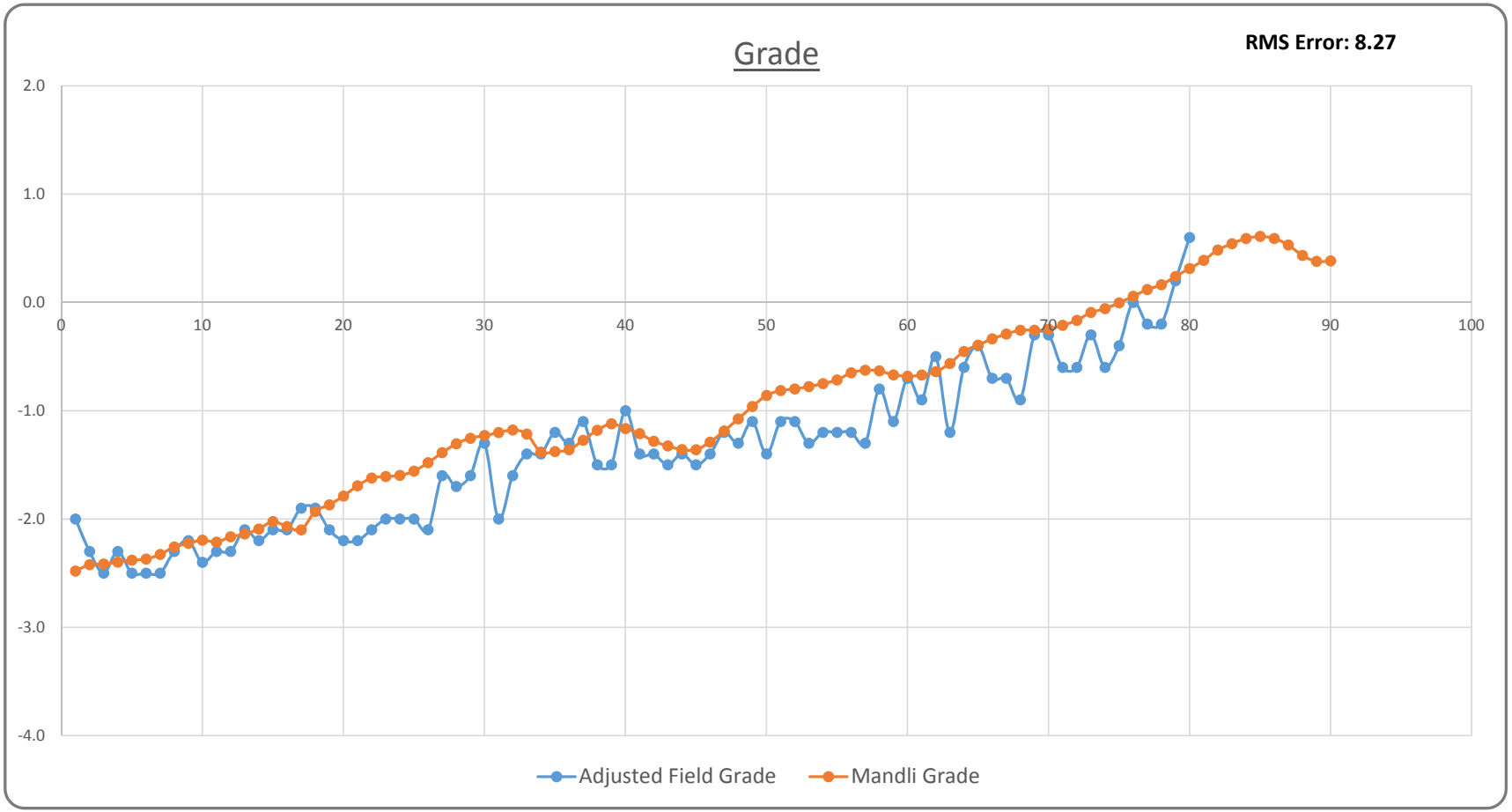
I-75: Milepoint 104.4-104.6 (Vertical Curve - Southbound)



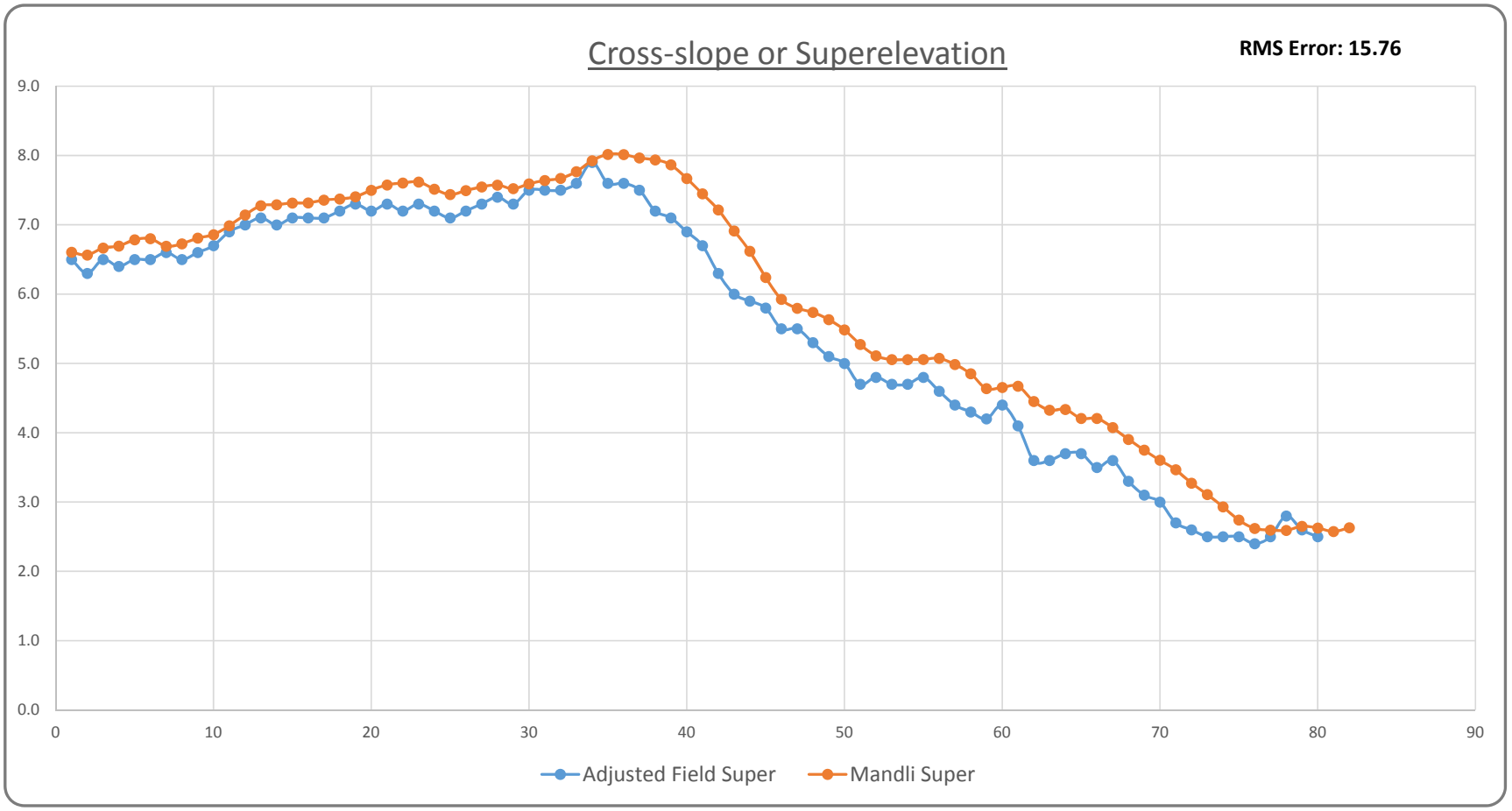
KY 1143: Milepoint 1.1-1.4 (Horizontal Curve - Northbound)



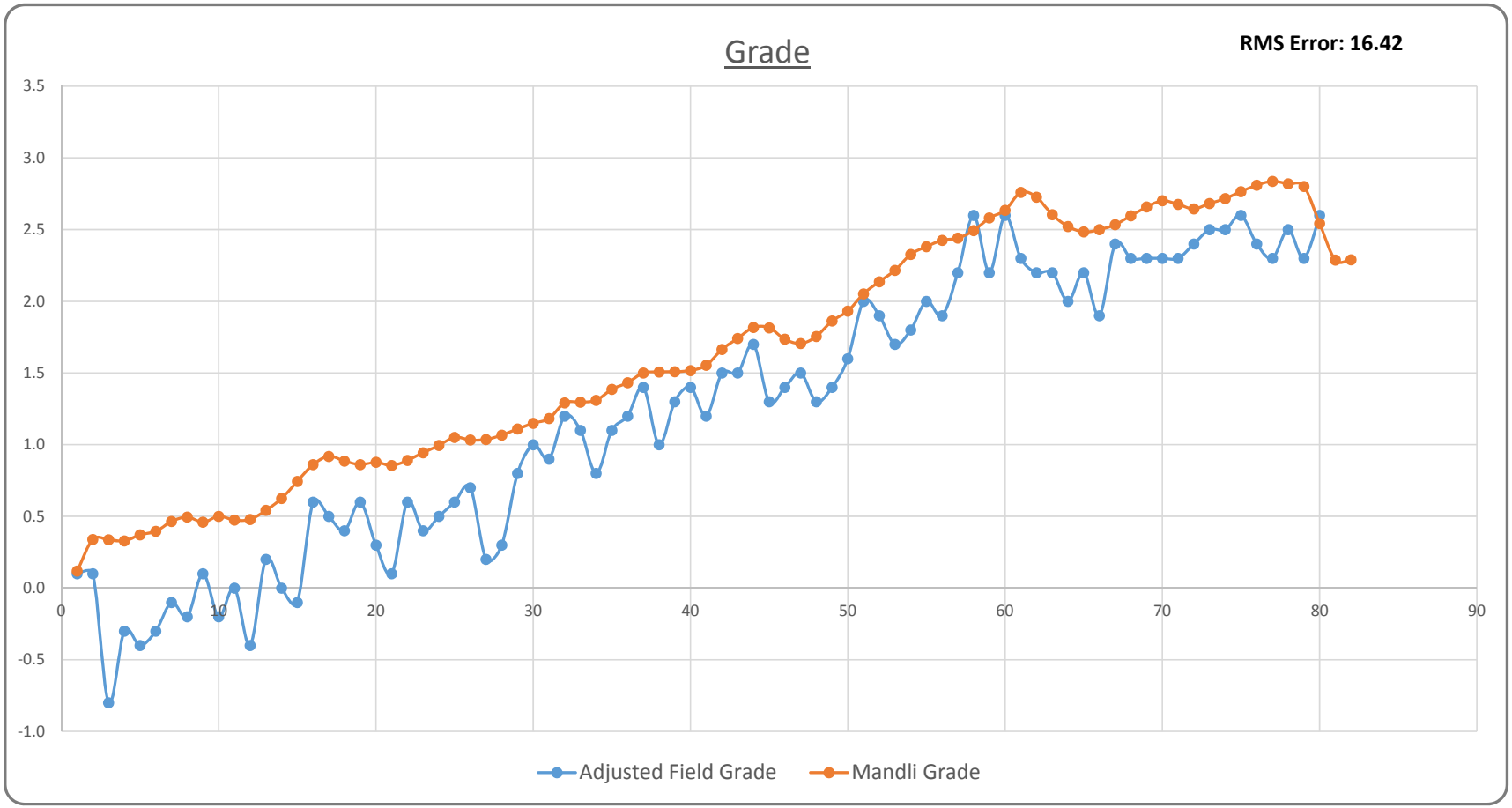
KY 1143: Milepoint 1.1-1.4 (Horizontal Curve - Northbound)



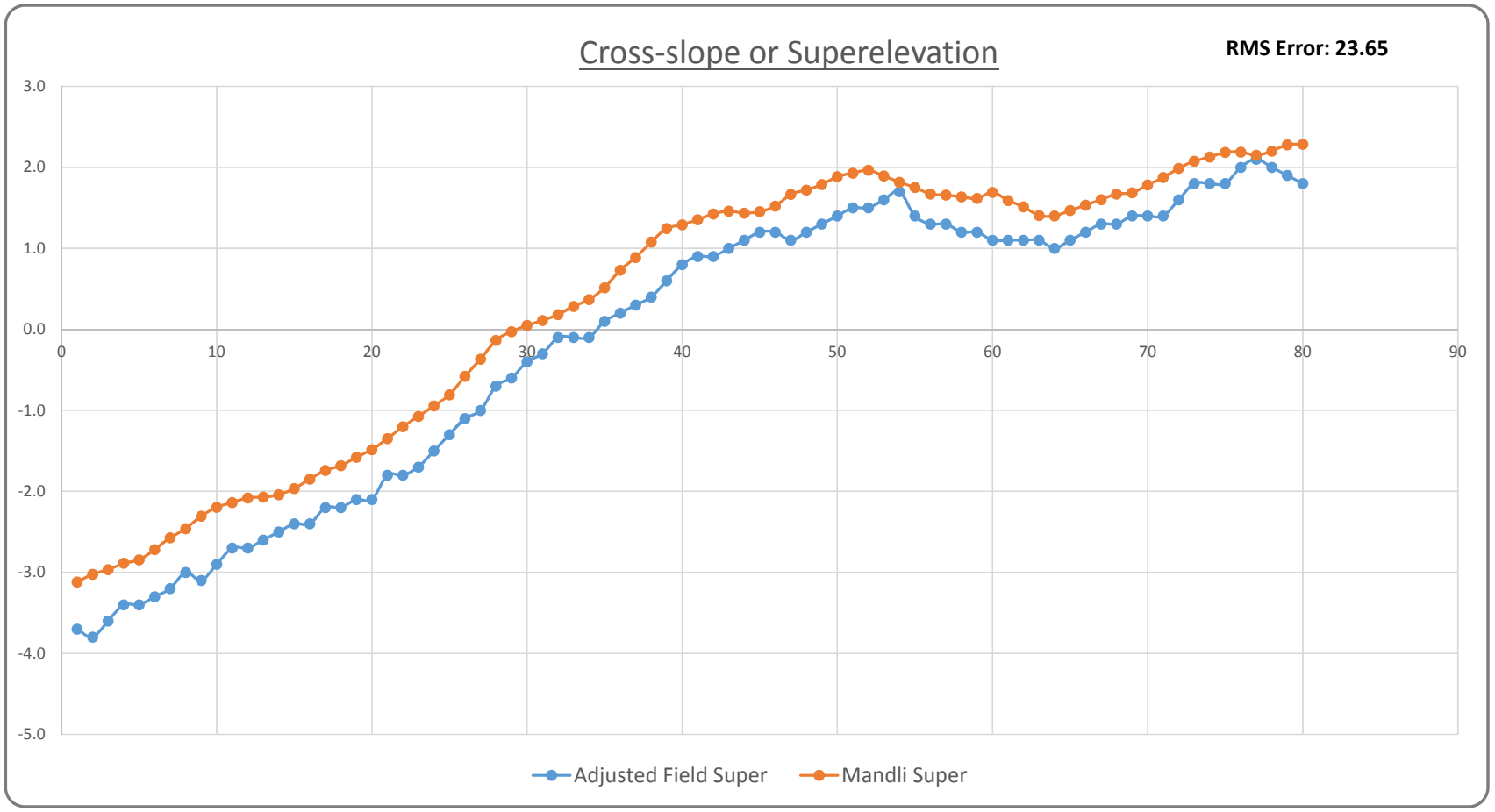
KY 1143: Milepoint 1.1-1.4 (Horizontal Curve - Southbound)



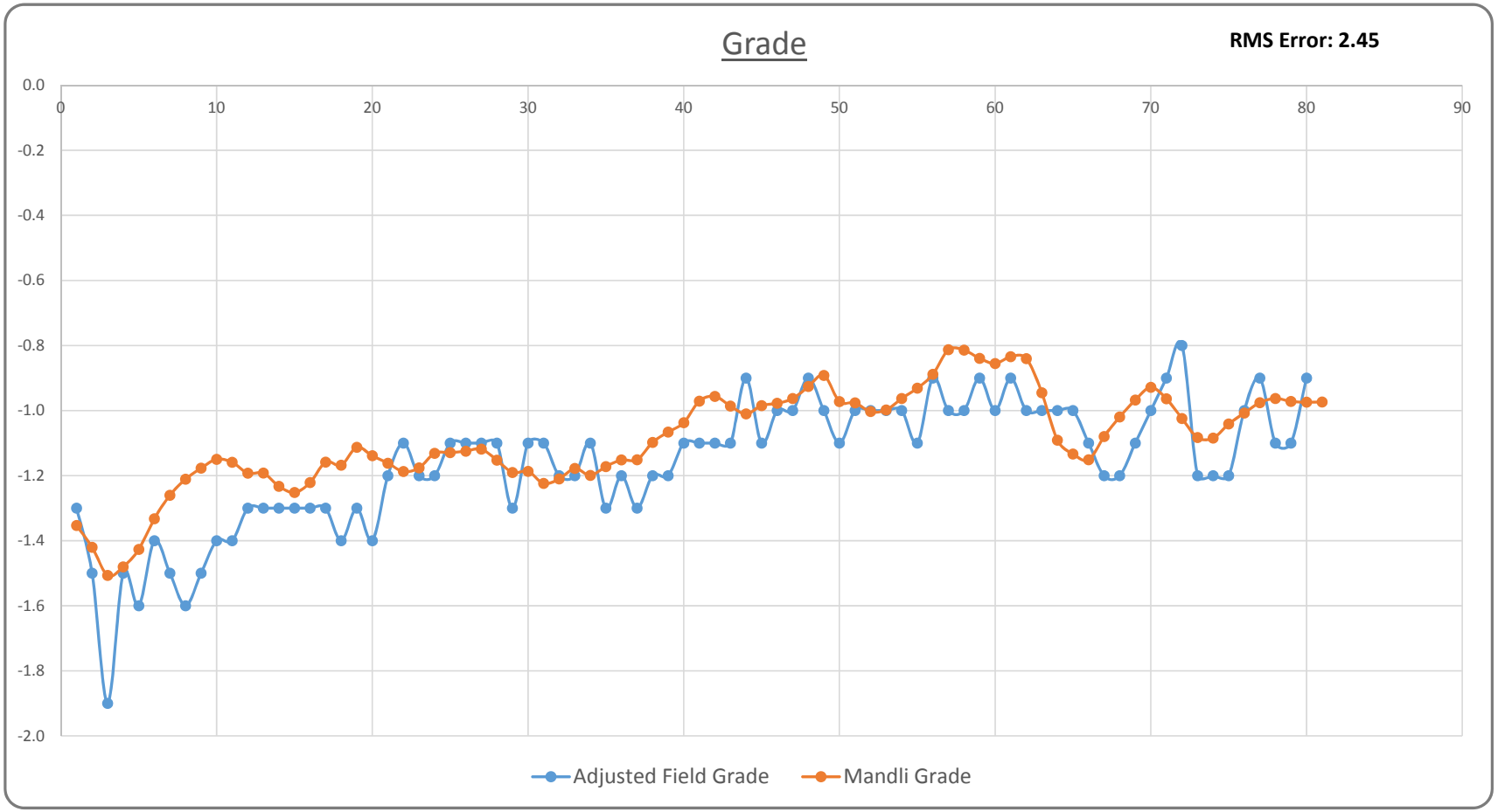
KY 1143: Milepoint 1.1-1.4 (Horizontal Curve - Southbound)



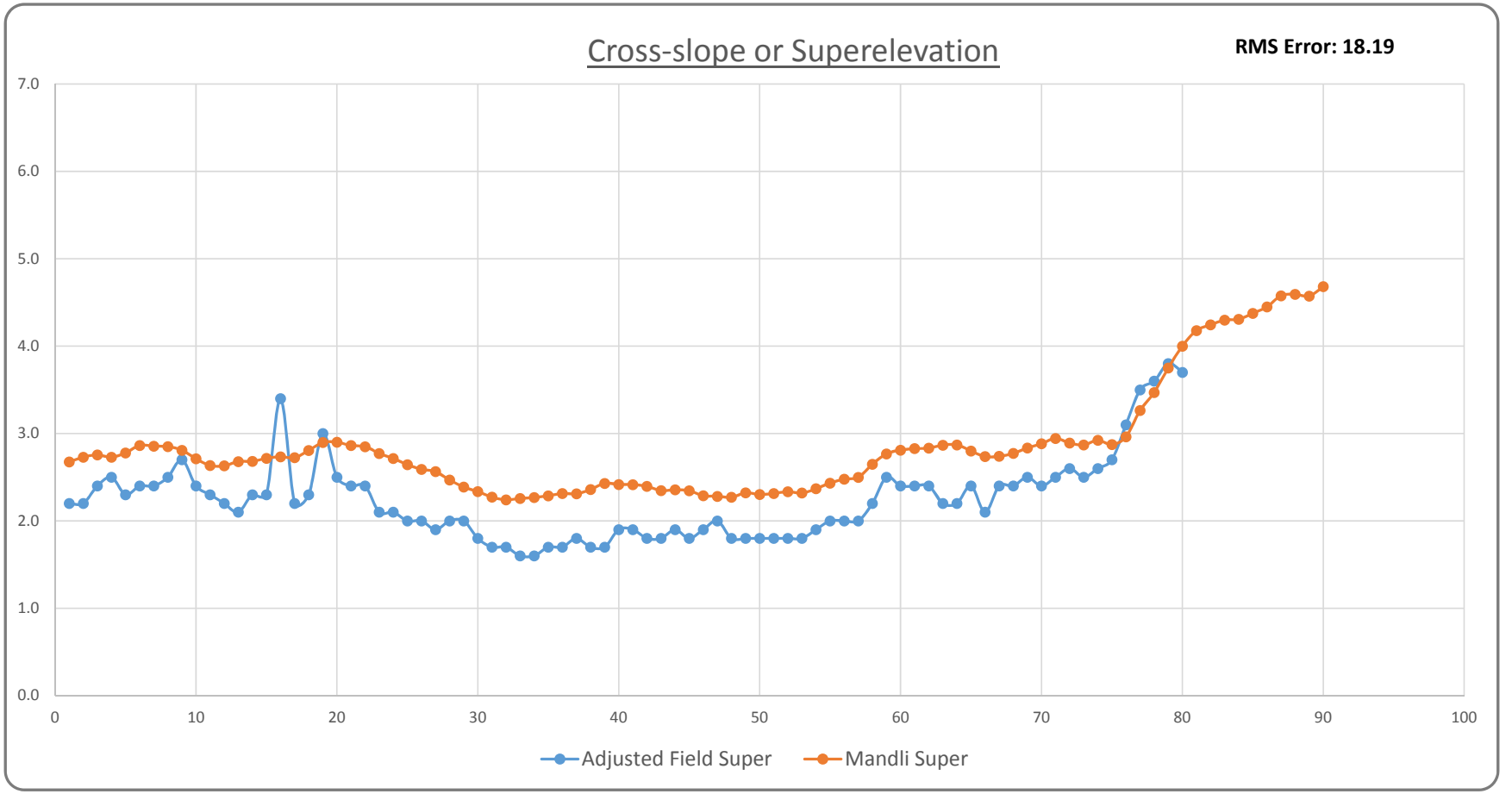
KY 1143: Milepoint 1.4-1.7 (Vertical Curve - Northbound)



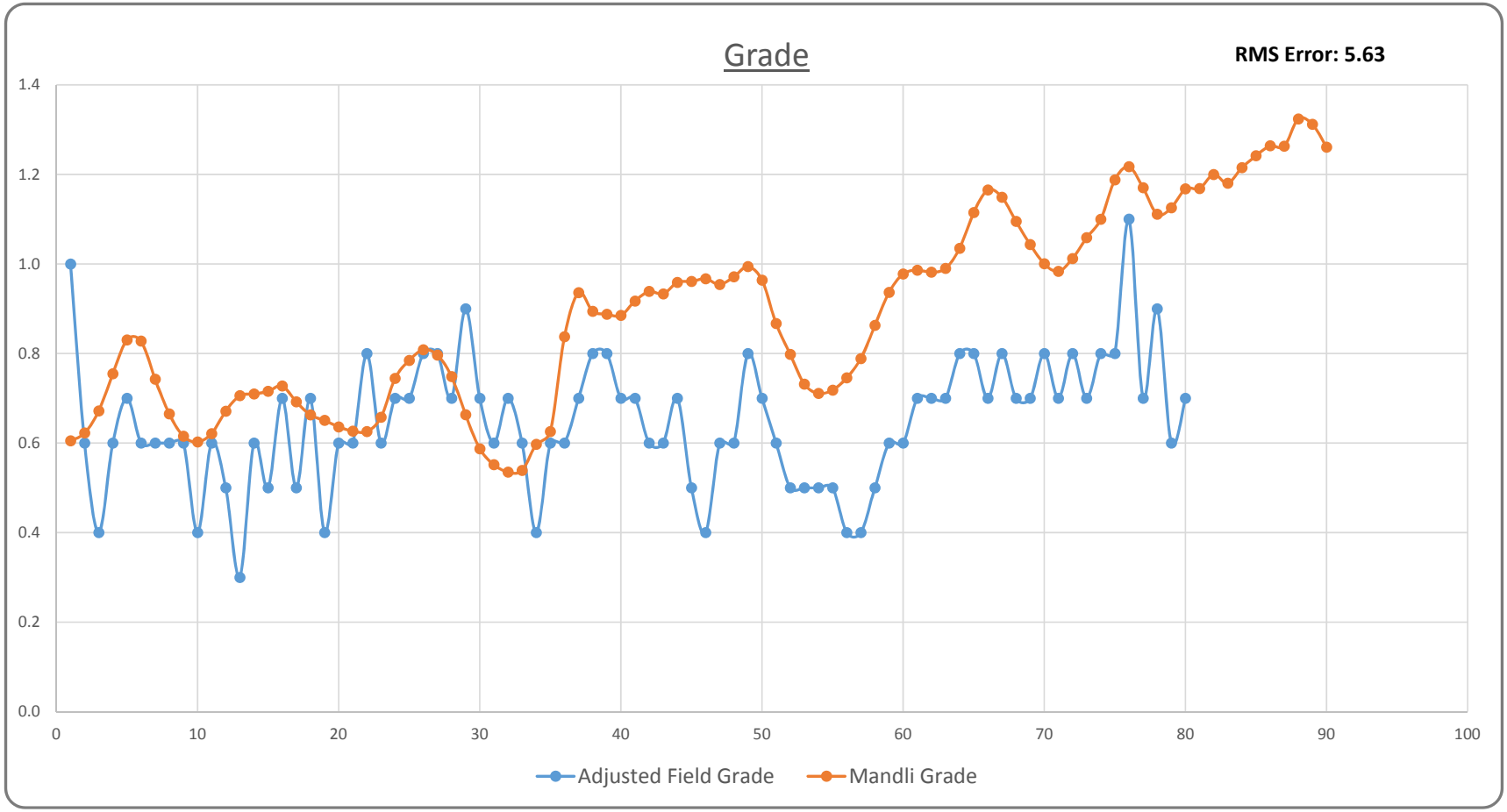
KY 1143: Milepoint 1.4-1.7 (Vertical Curve - Northbound)



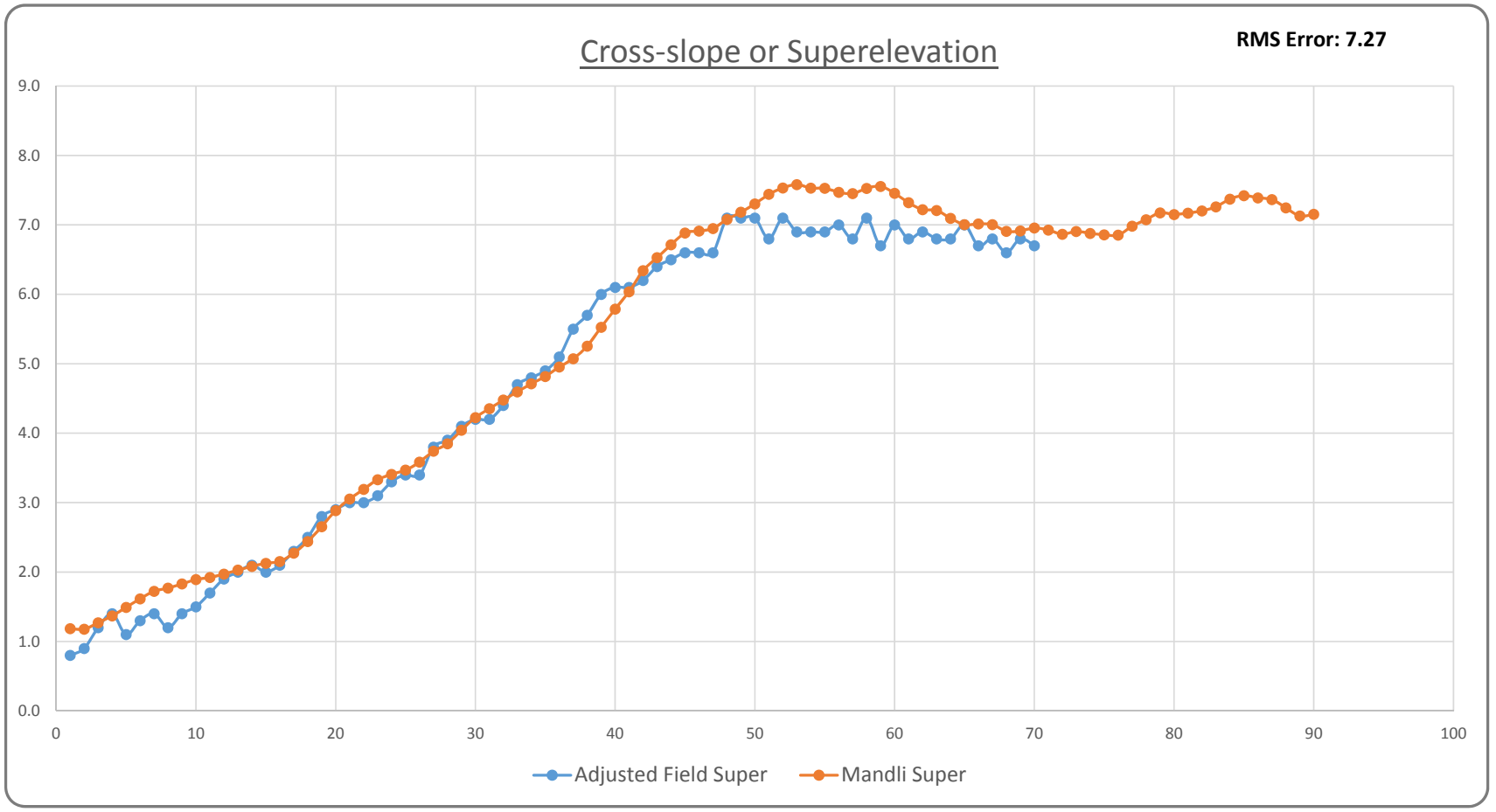
KY 1143: Milepoint 1.4-1.7 (Vertical Curve - Southbound)



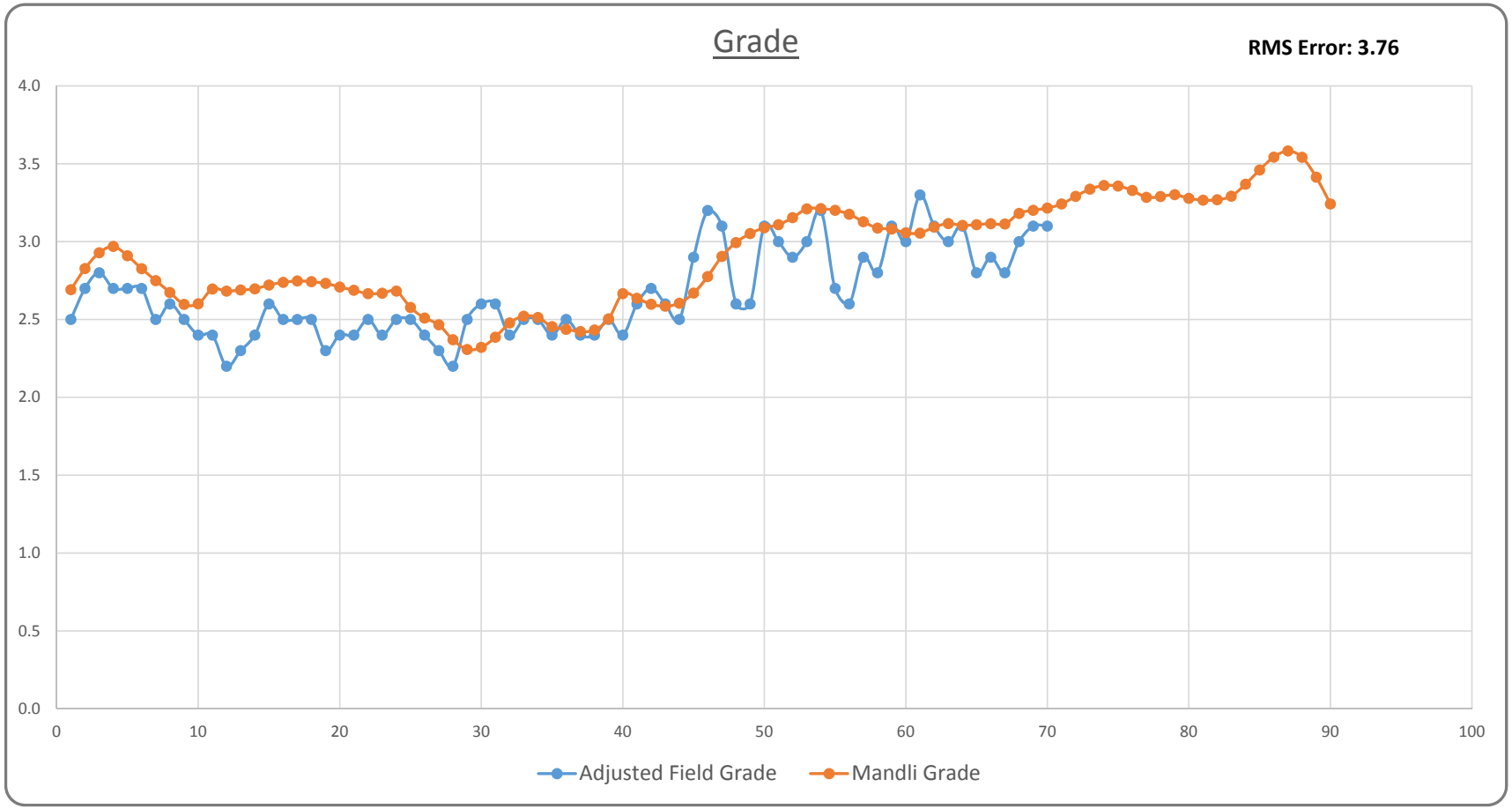
KY 1143: Milepoint 1.4-1.7 (Vertical Curve - Southbound)



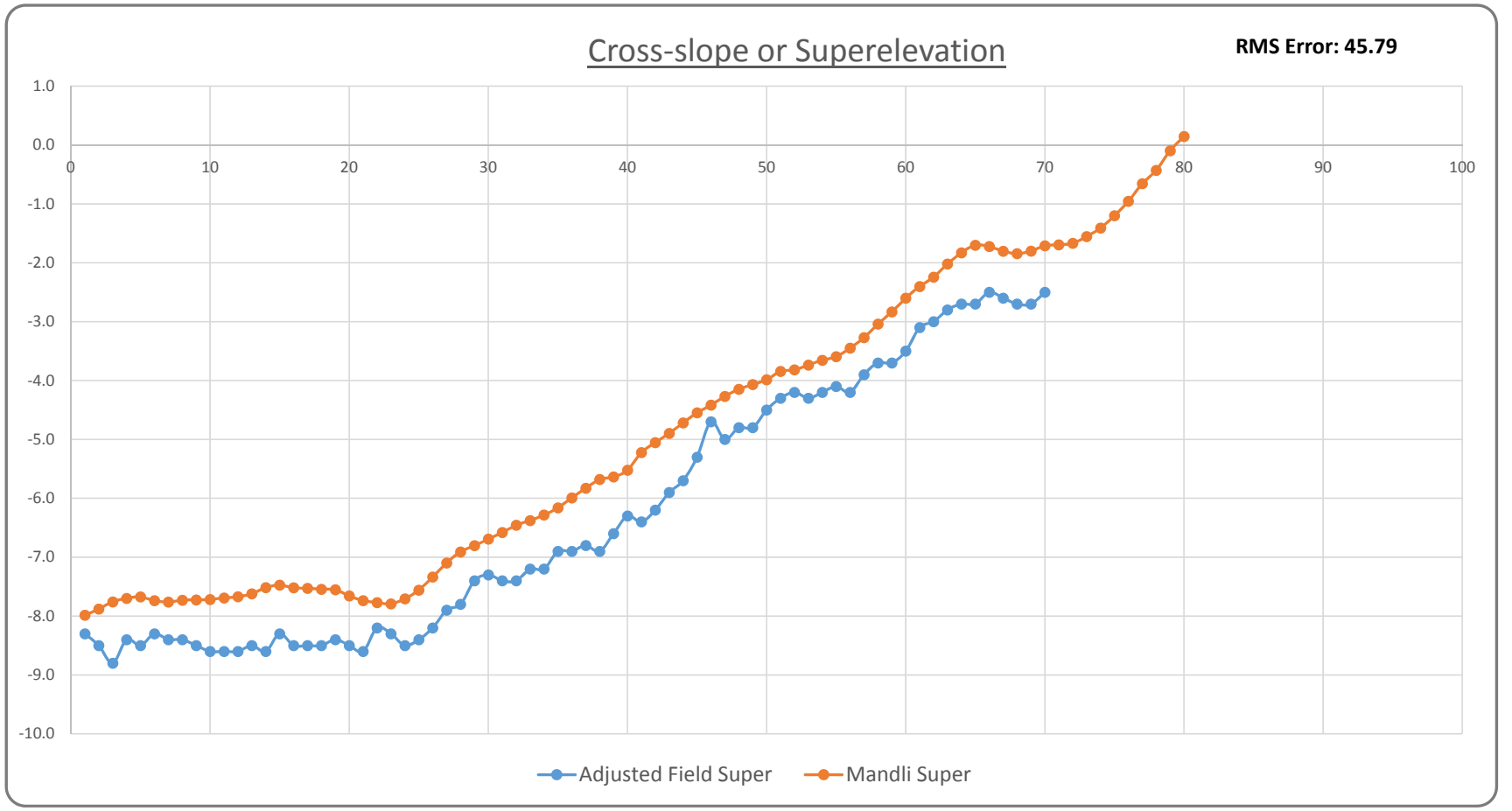
KY 1143: Milepoint 1.7-2.0 (Horizontal Curve - Northbound)



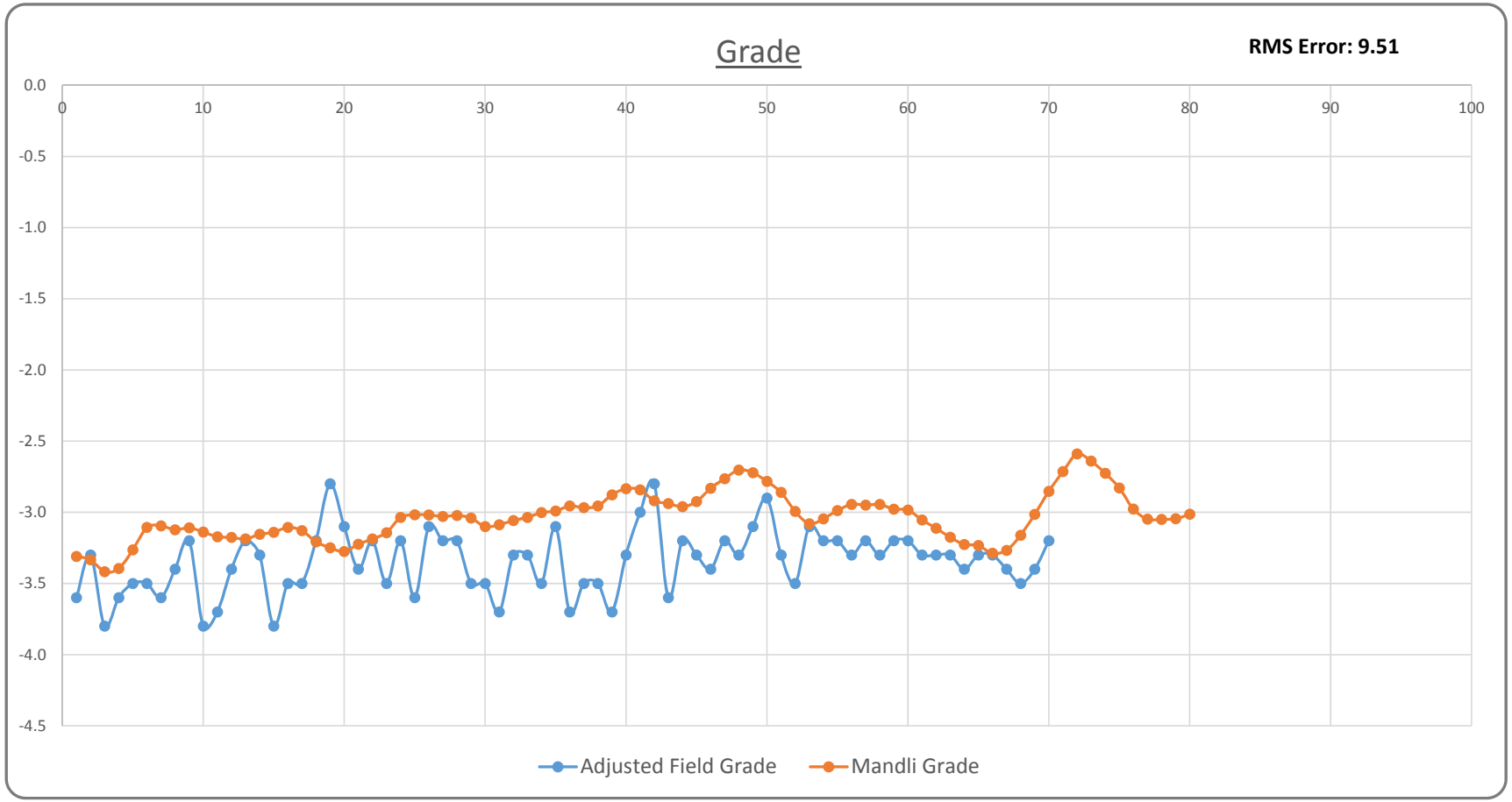
KY 1143: Milepoint 1.7-2.0 (Horizontal Curve - Northbound)



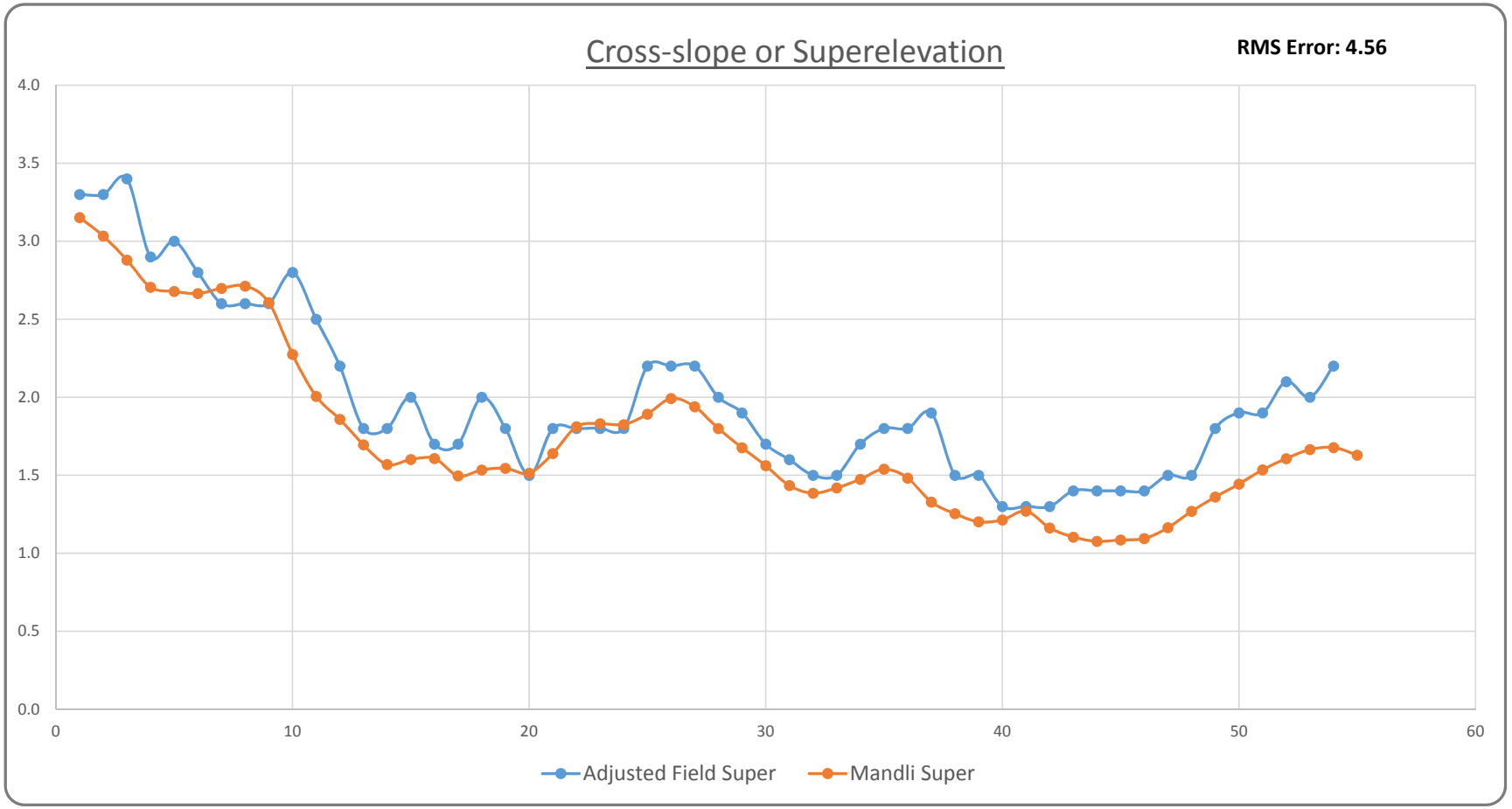
KY 1143: Milepoint 1.7-2.0 (Horizontal Curve - Southbound)



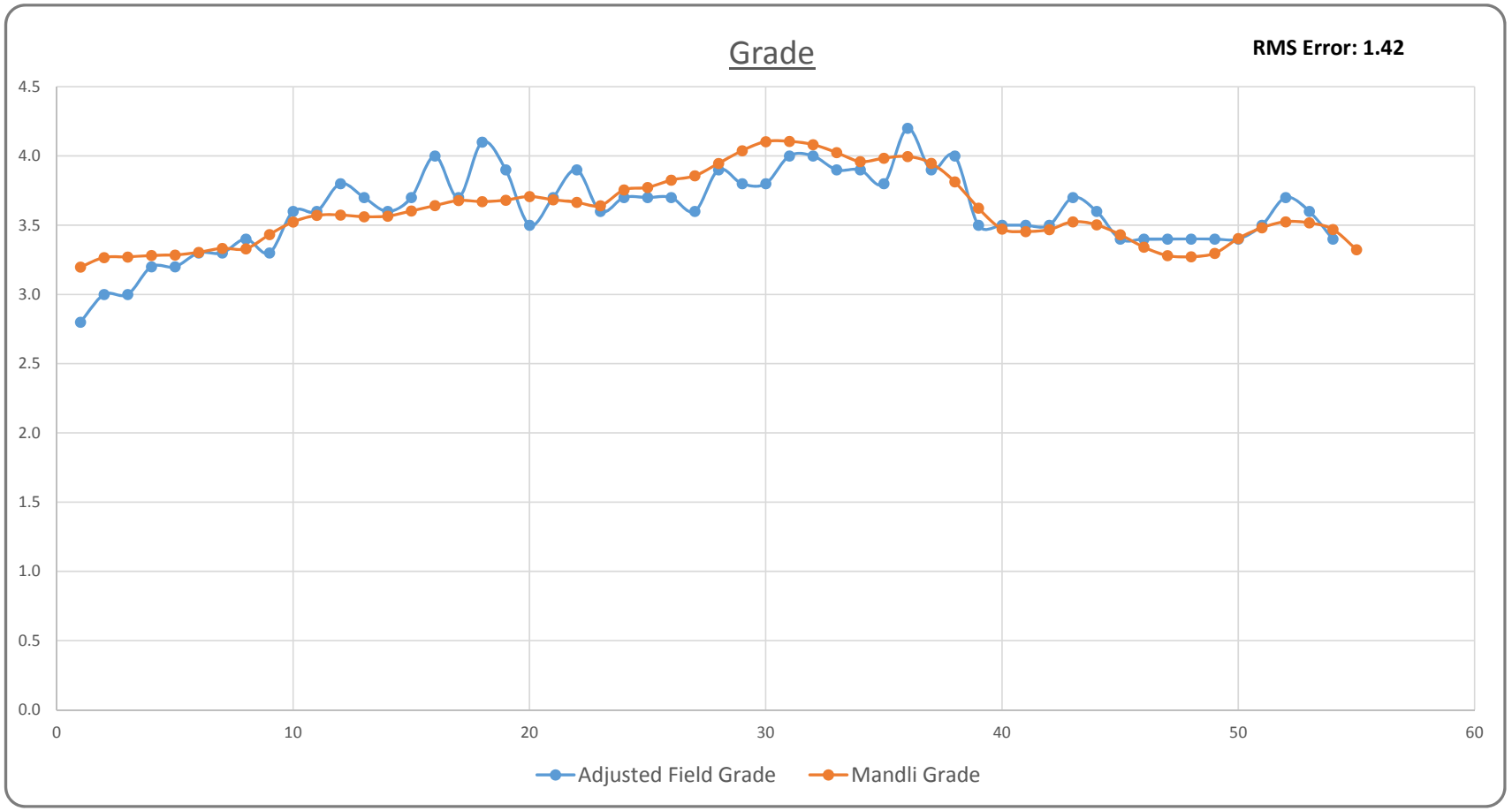
KY 1143: Milepoint 1.7-2.0 (Horizontal Curve - Southbound)



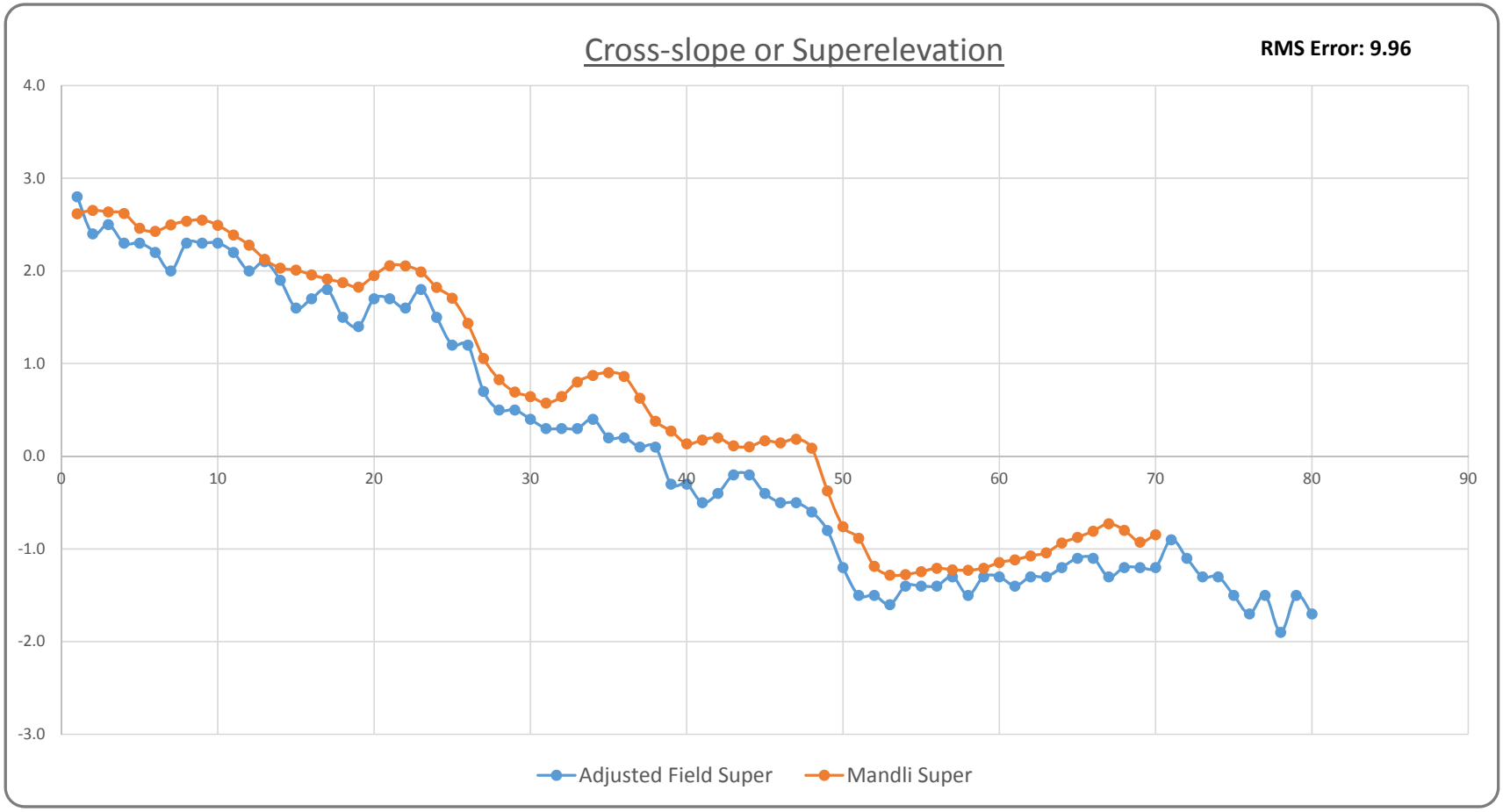
KY 1143: Milepoint .9-1.1 (Vertical Curve - Northbound)



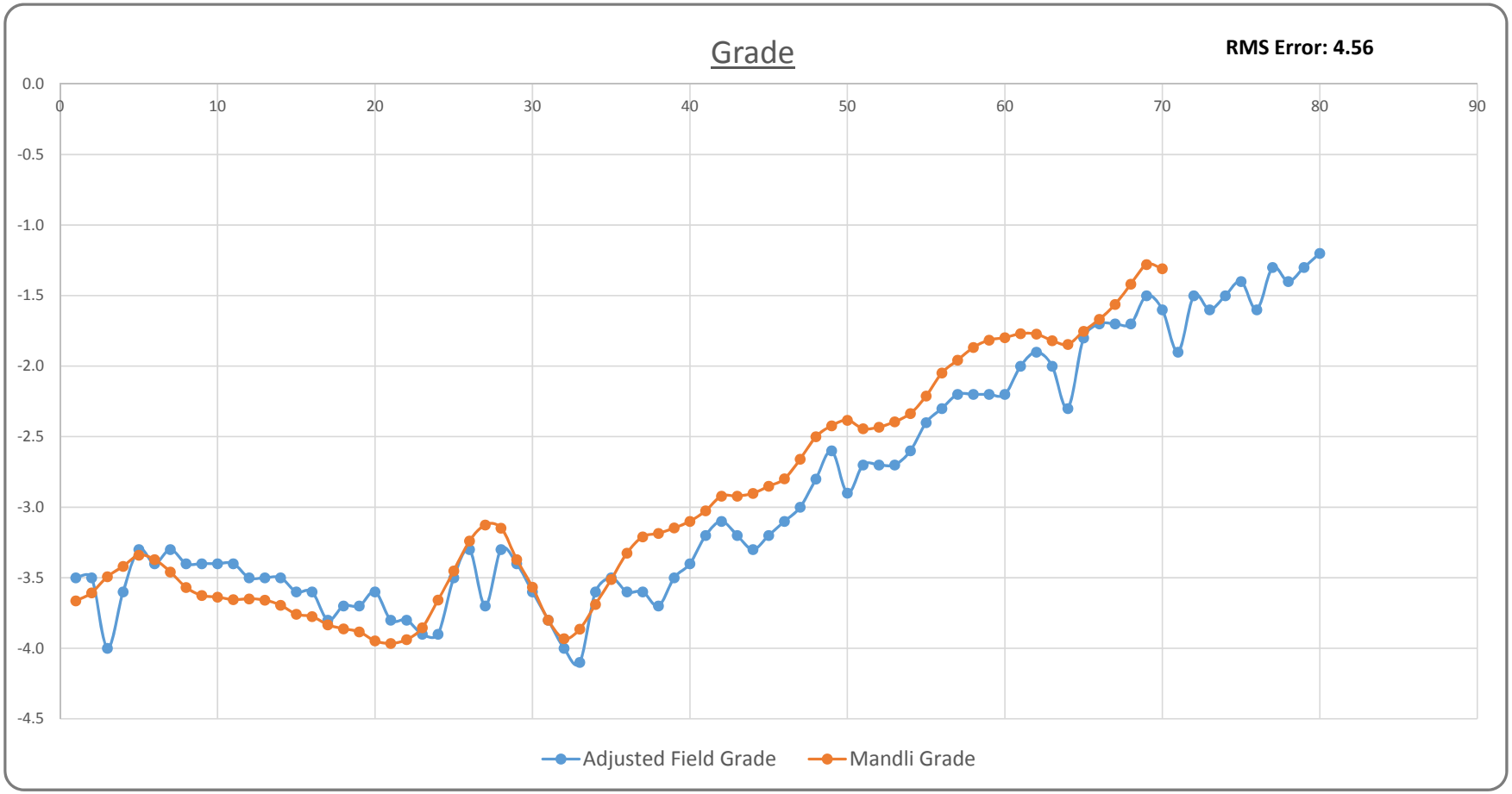
KY 1143: Milepoint .9-1.1 (Vertical Curve - Northbound)



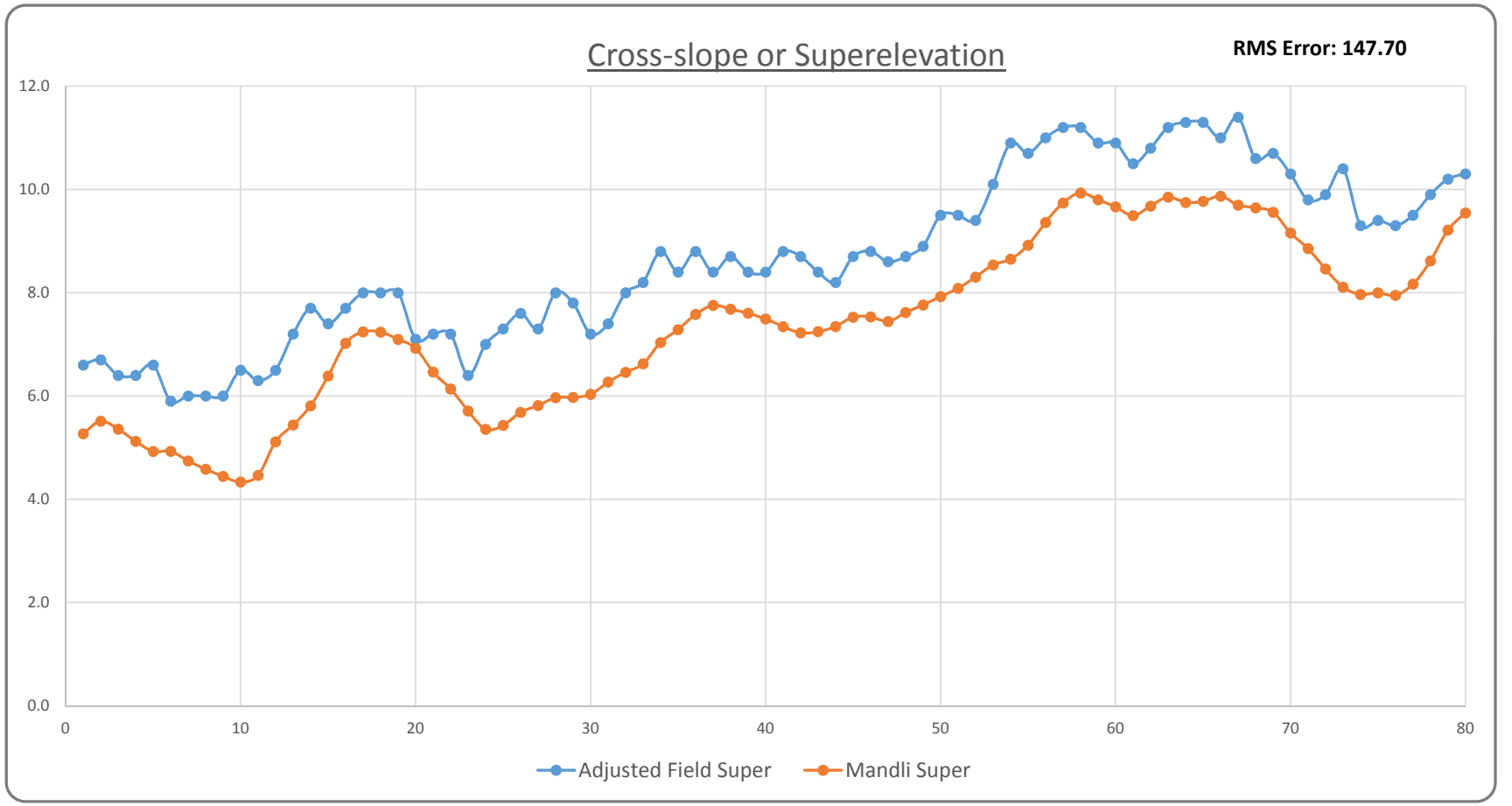
KY 1143: Milepoint .9-1.1 (Vertical Curve - Southbound)



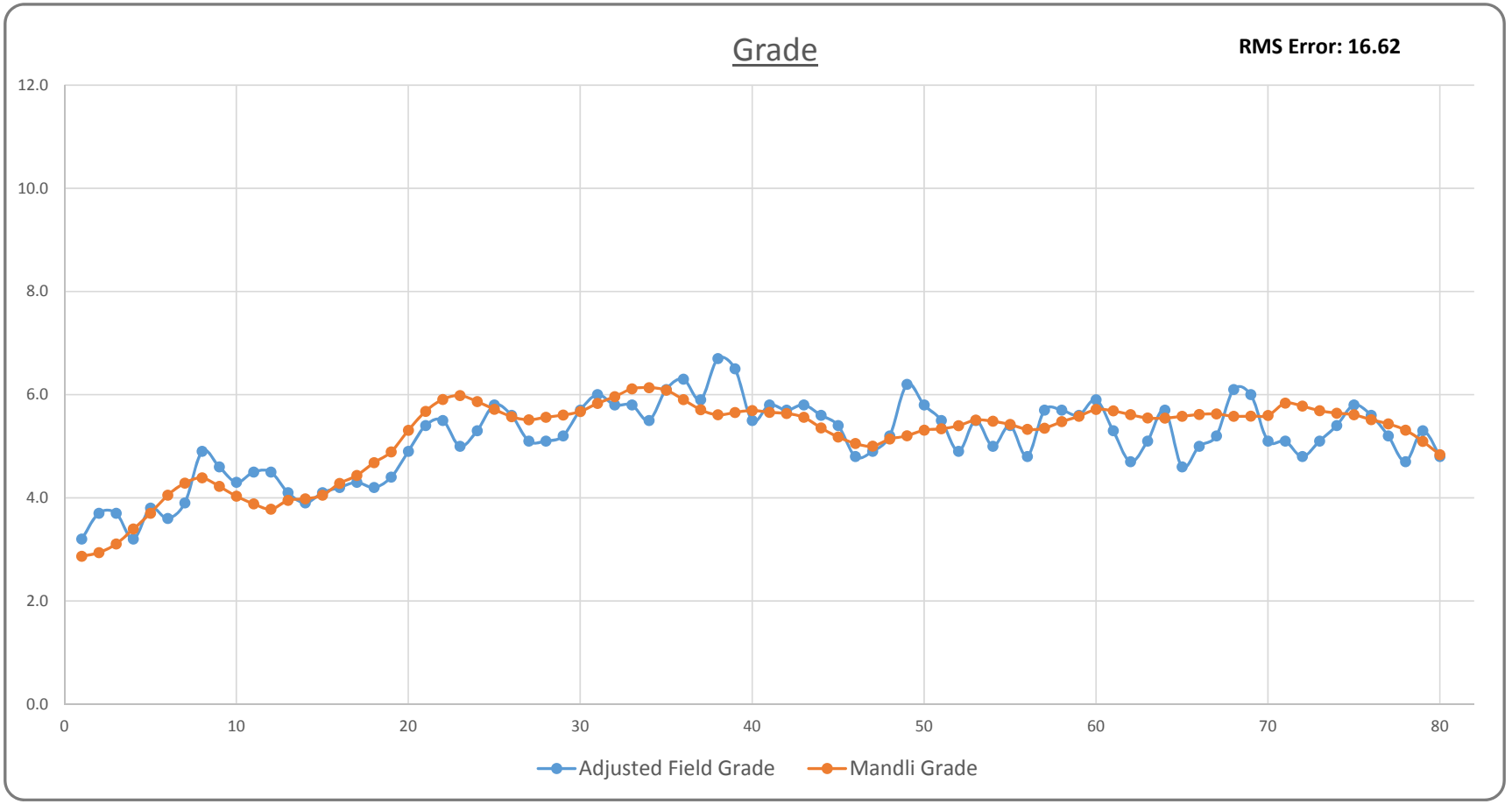
KY 1143: Milepoint .9-1.1 (Vertical Curve - Southbound)



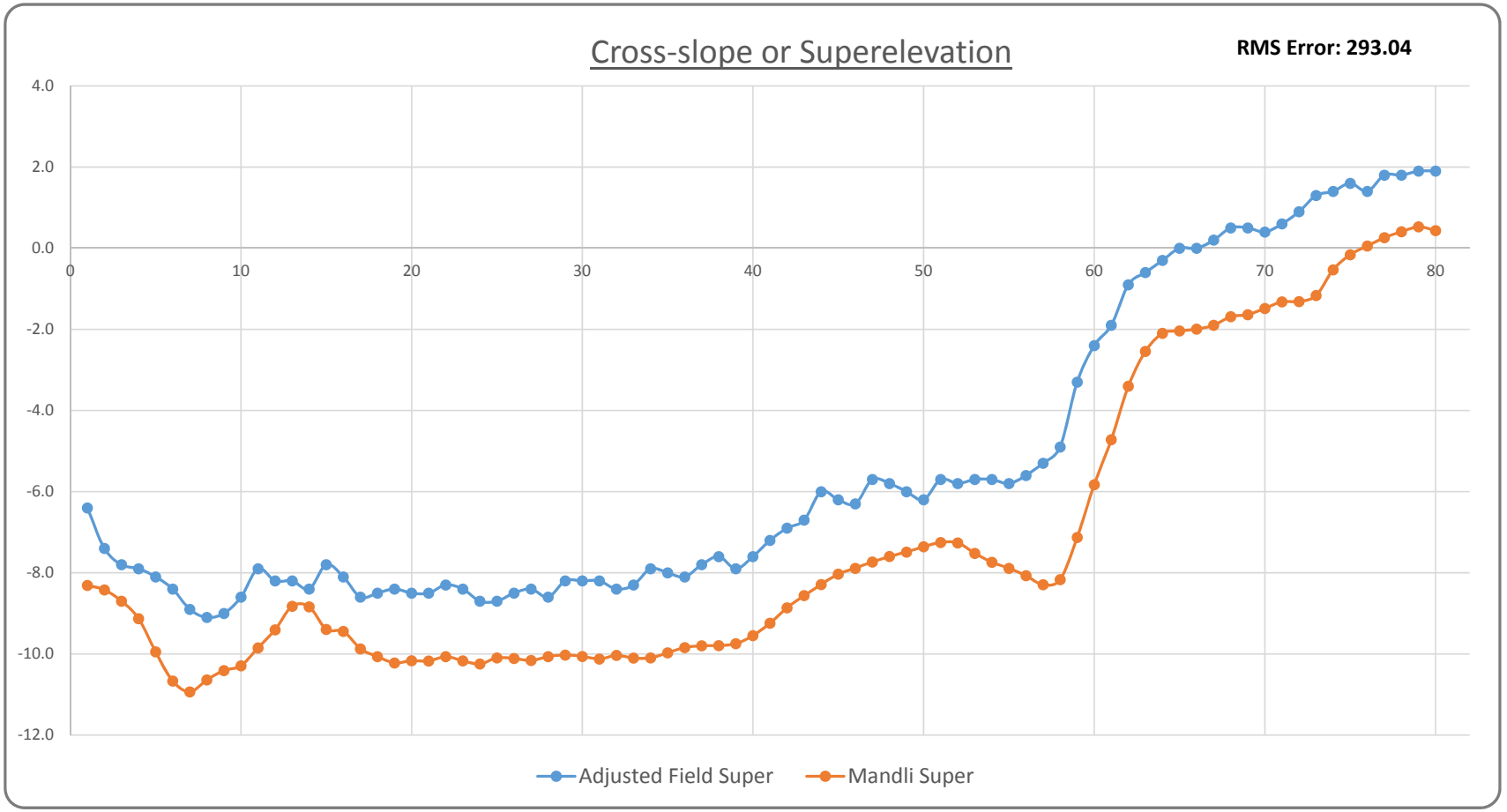
Newtown Pike: Milepoint .5-.65 (Horizontal Curve - Northbound)



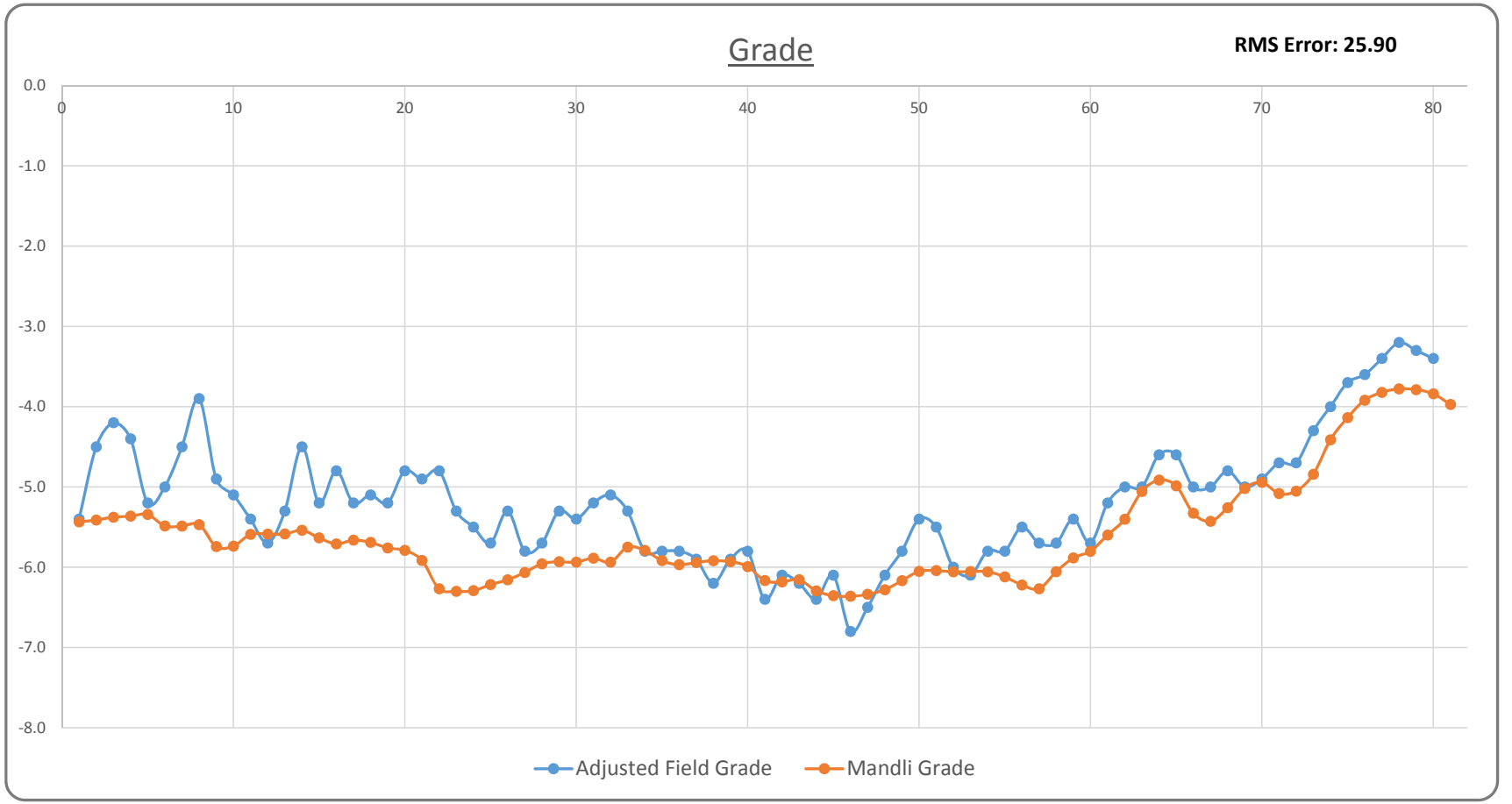
Newtown Pike: Milepoint .5-.65 (Horizontal Curve - Northbound)



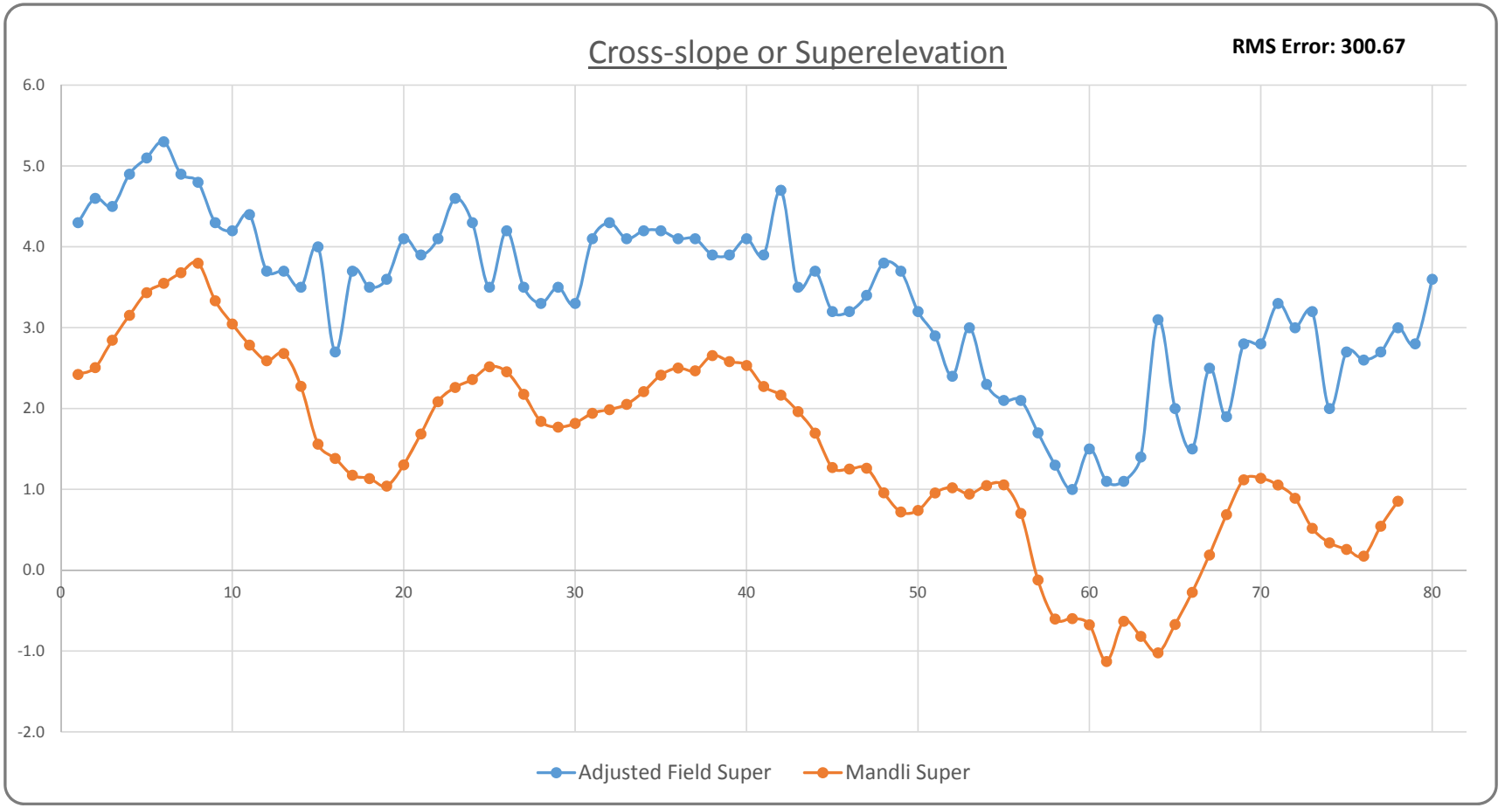
Newtown Pike: Milepoint .5-.65 (Horizontal Curve - Southbound)



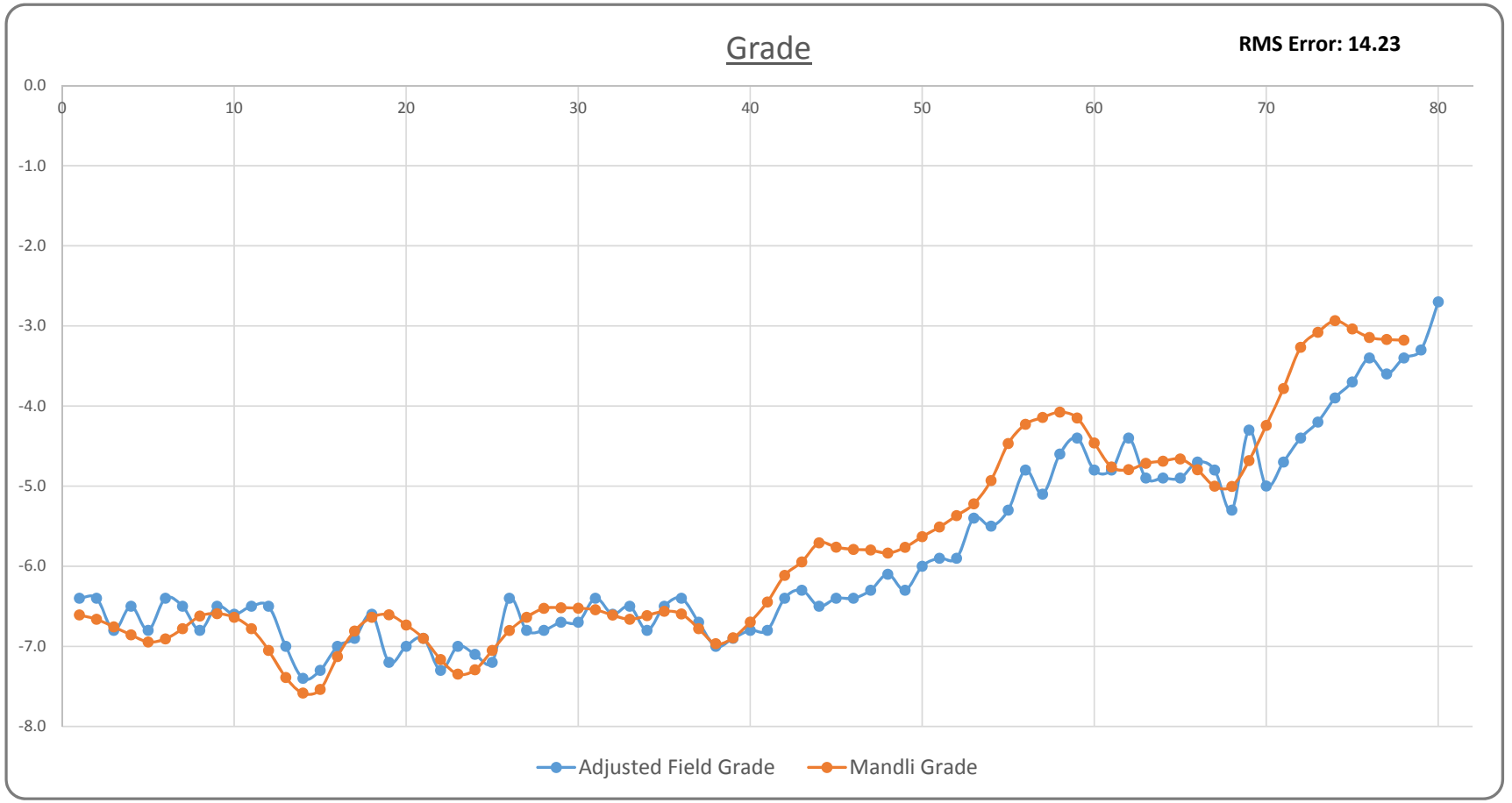
Newtown Pike: Milepoint .5-.65 (Horizontal Curve - Southbound)



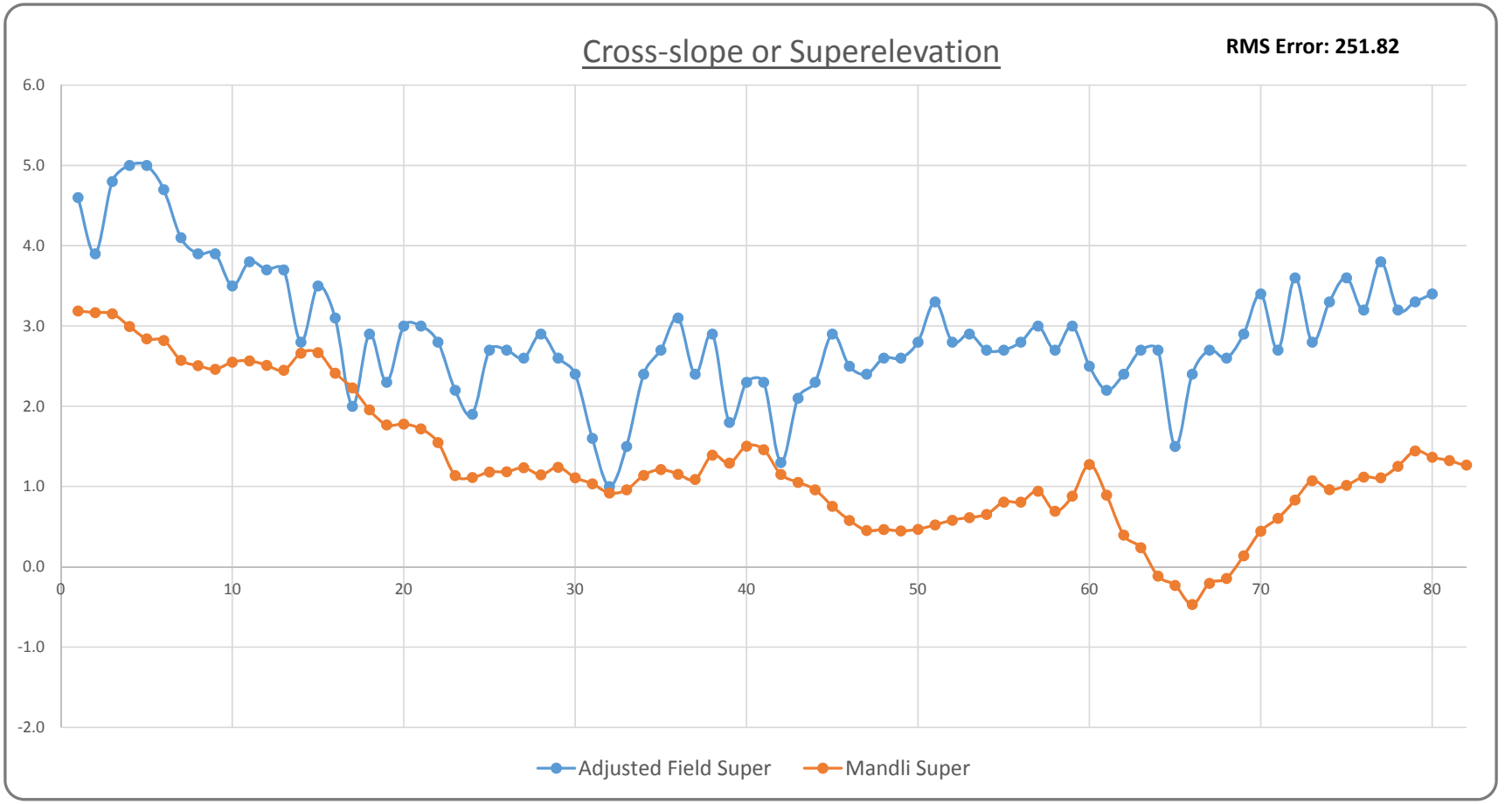
Newtown Pike: Milepoint .2-.4 (Vertical Curve - Northbound)



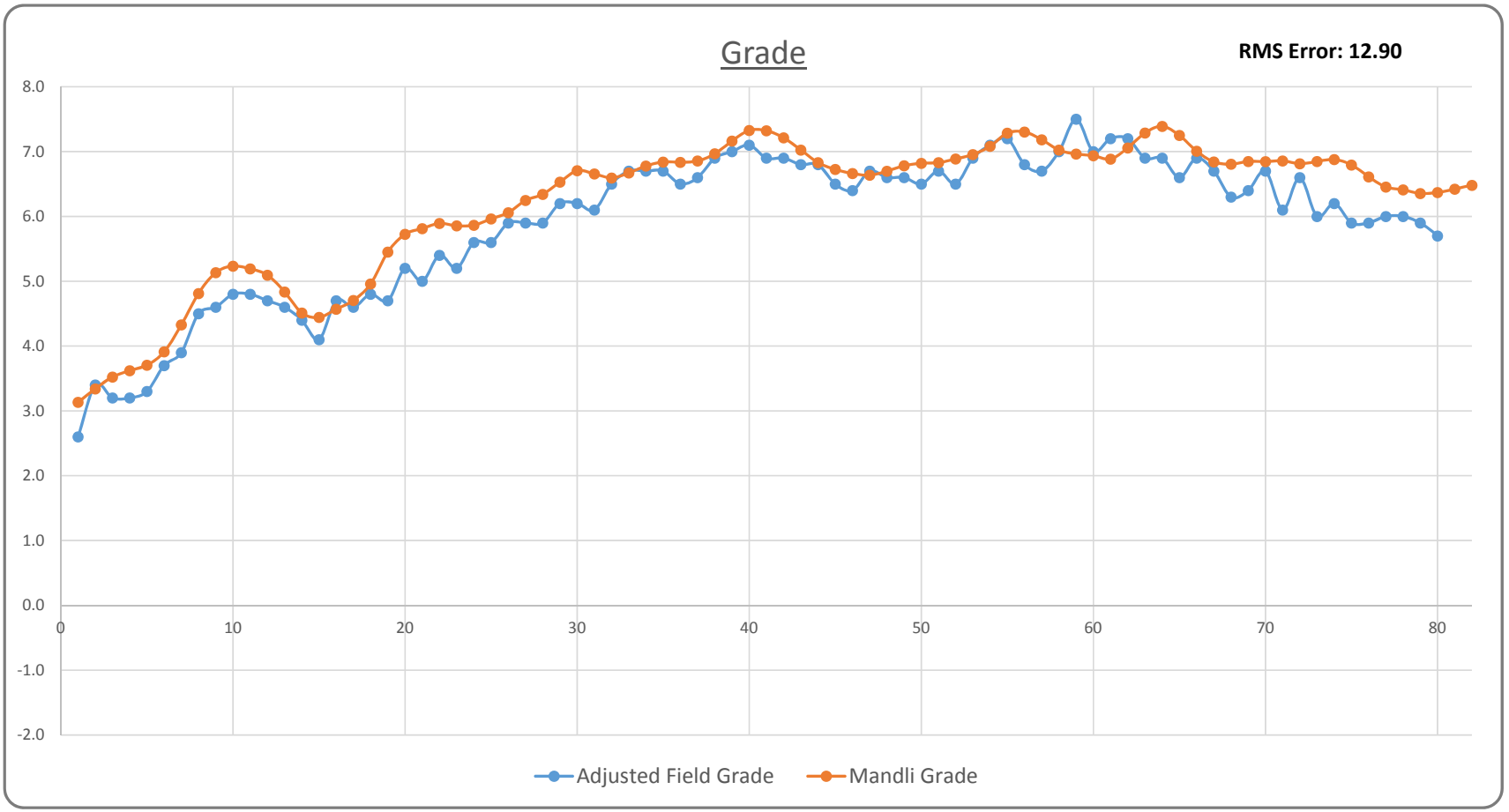
Newtown Pike: Milepoint .2-.4 (Vertical Curve - Northbound)



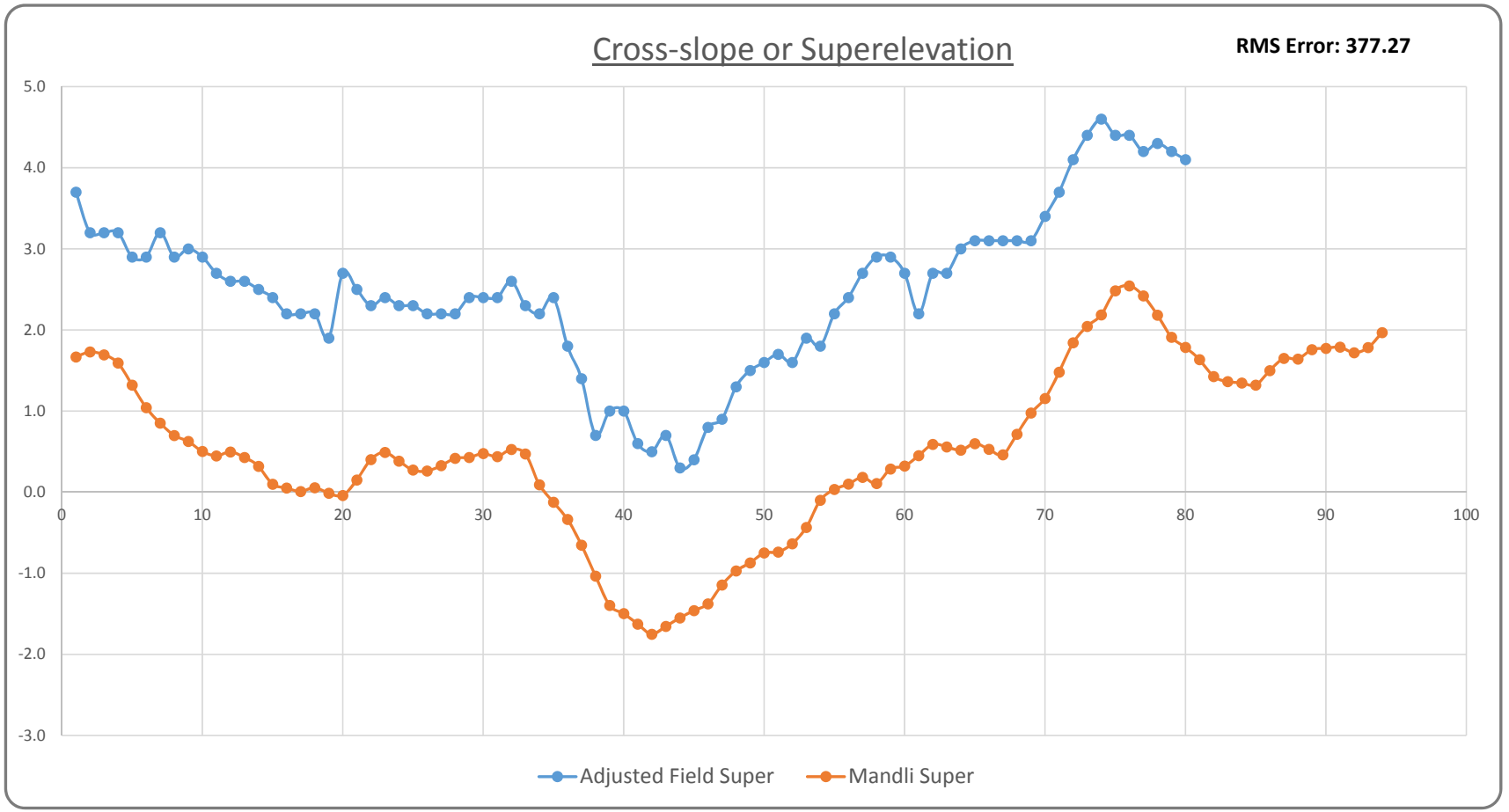
Newtown Pike: Milepoint .2-.4 (Vertical Curve – Southbound)



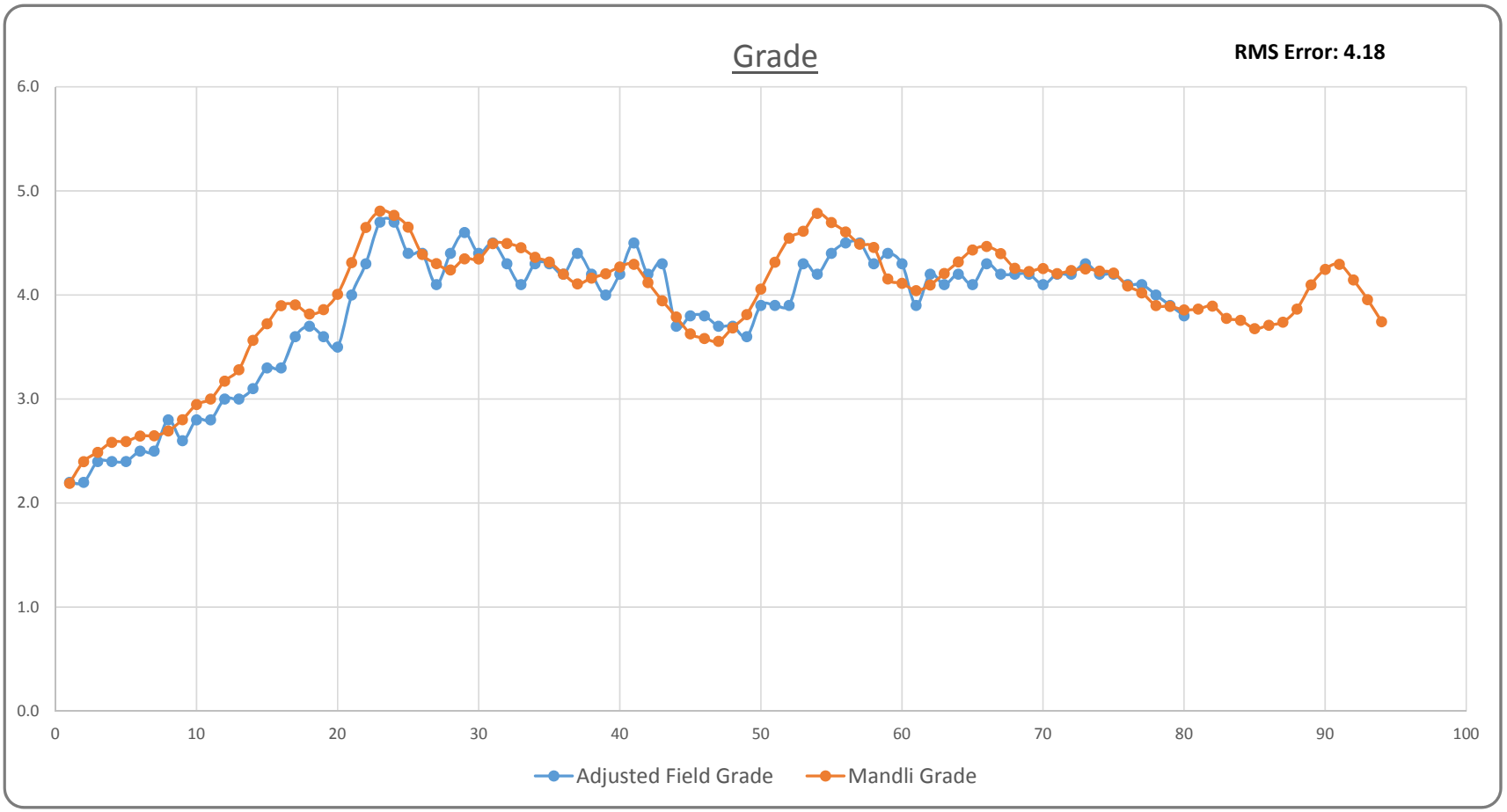
Newtown Pike: Milepoint .2-.4 (Vertical Curve – Southbound)



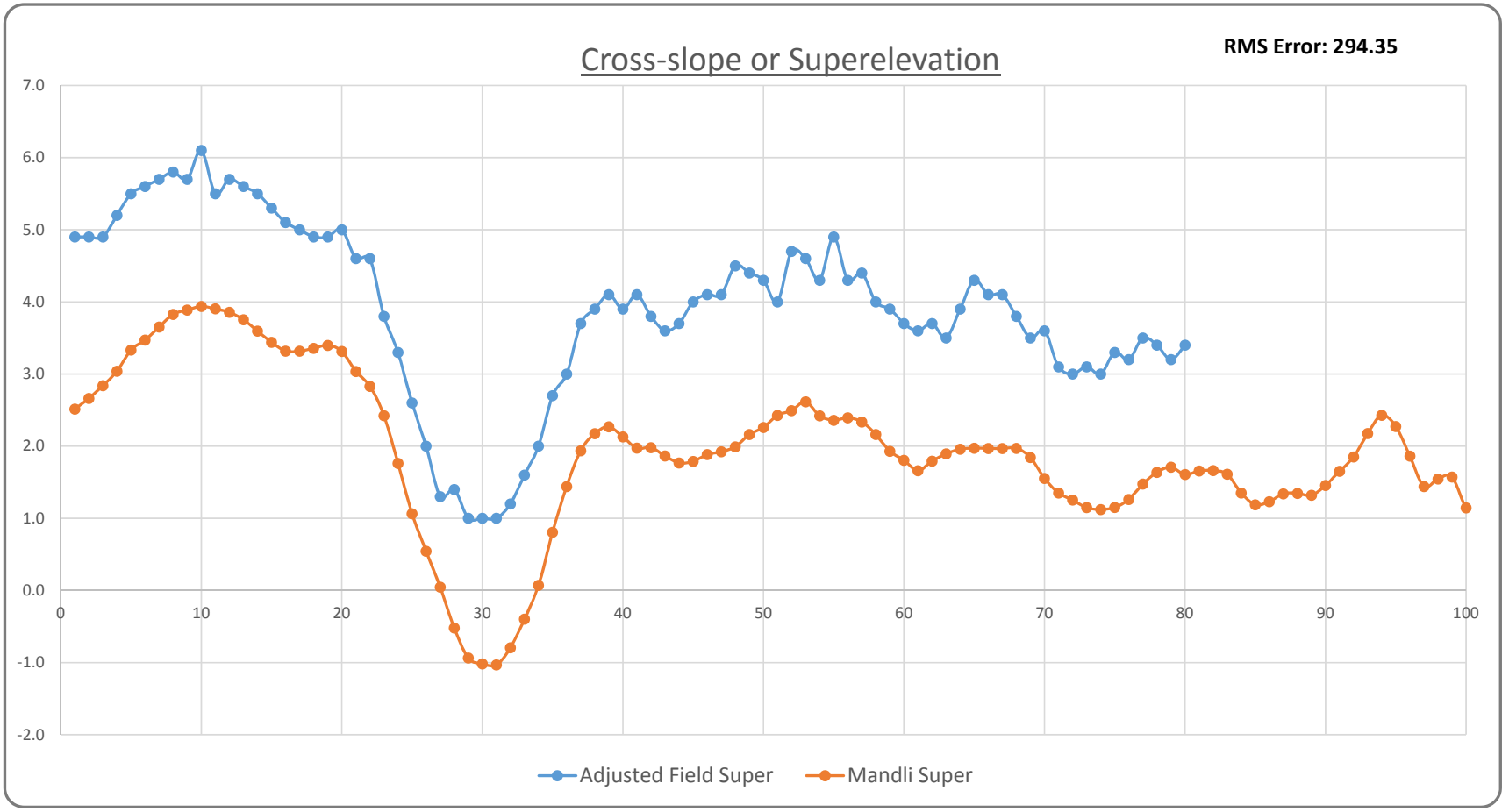
US 460: Milepoint 6.7-6.9 (Vertical Curve - Eastbound)



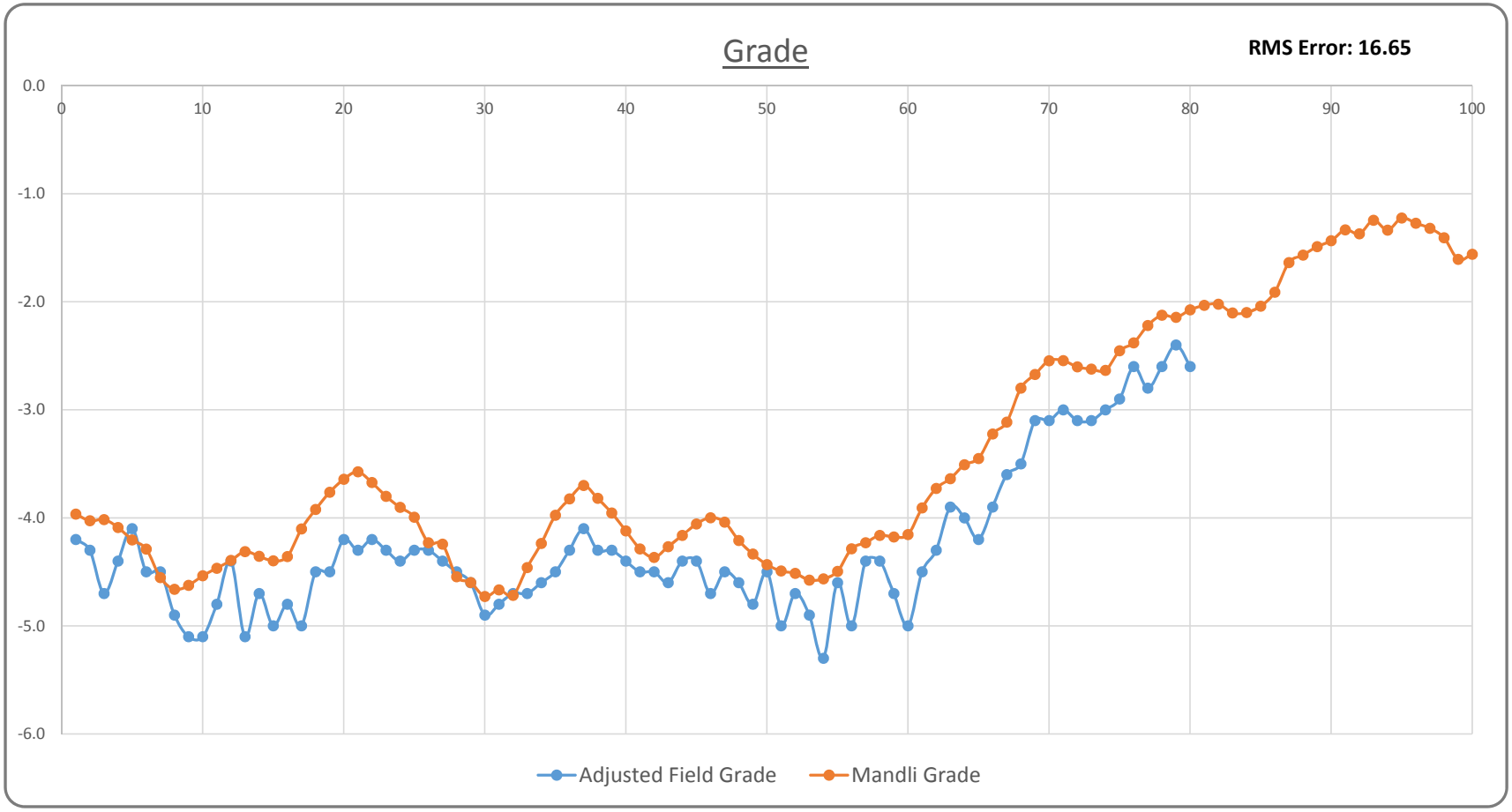
US 460: Milepoint 6.7-6.9 (Vertical Curve - Eastbound)



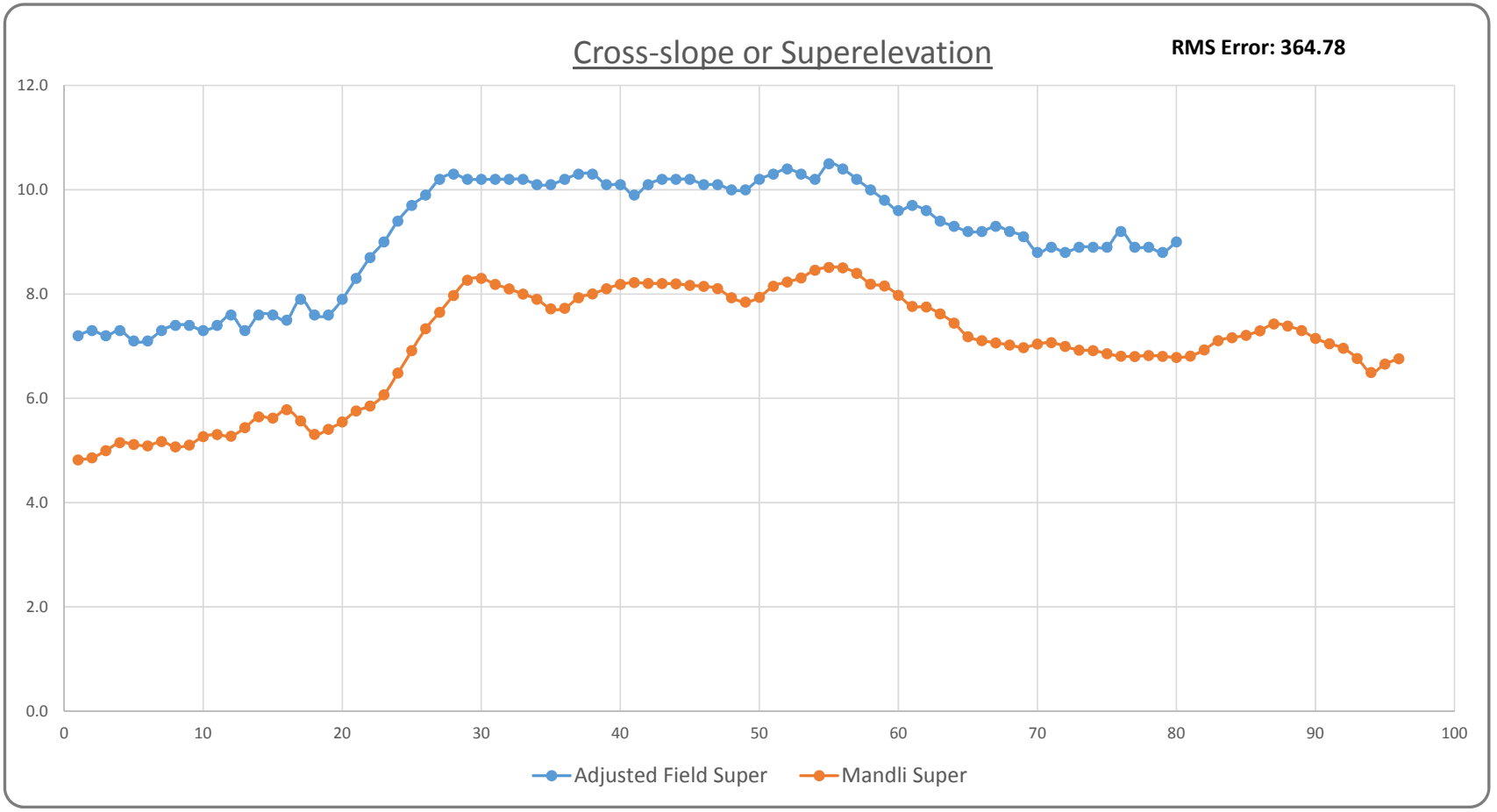
US 460: Milepoint 6.7-6.9 (Vertical Curve - Westbound)



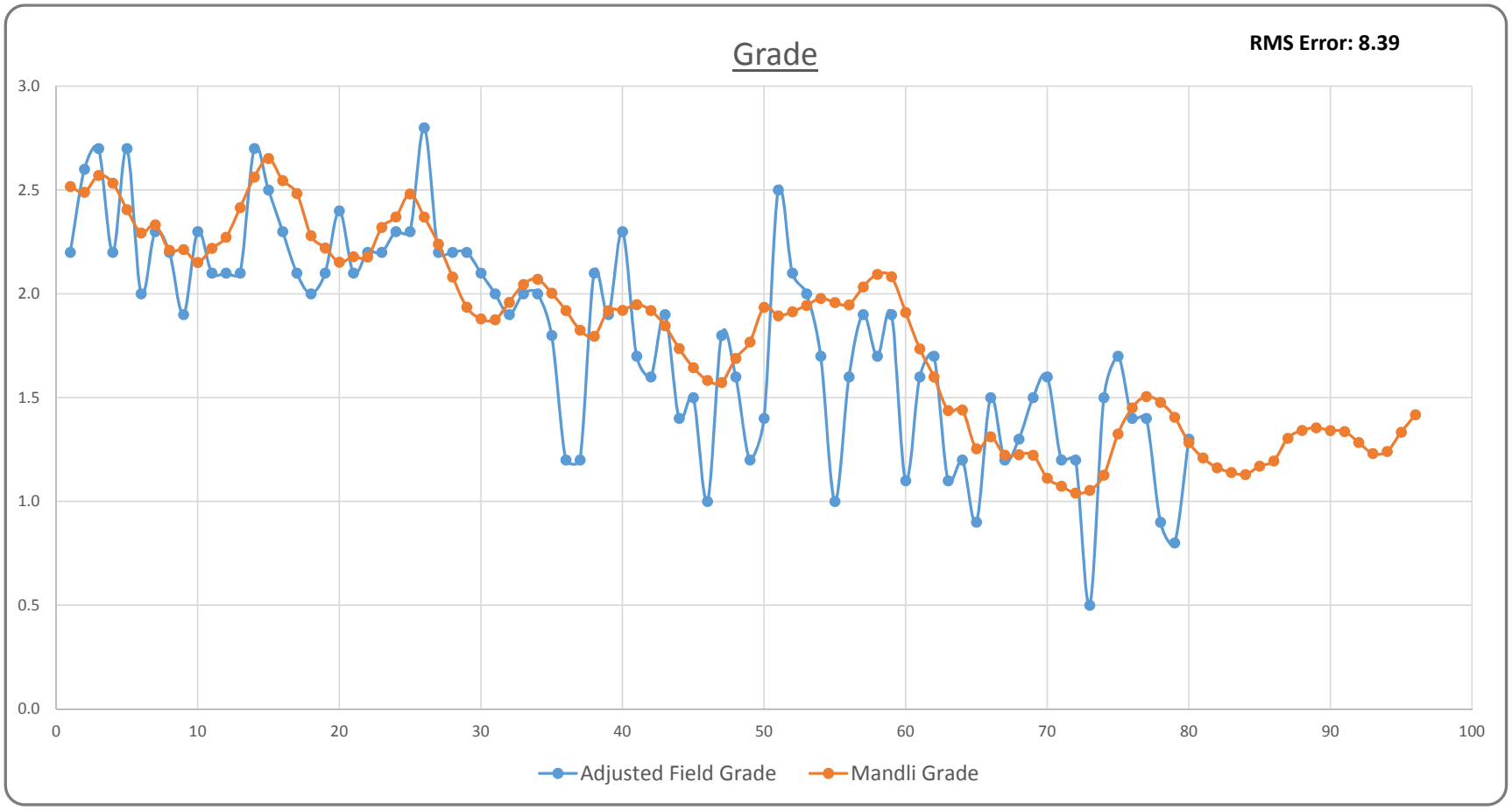
US 460: Milepoint 6.7-6.9 (Vertical Curve - Westbound)



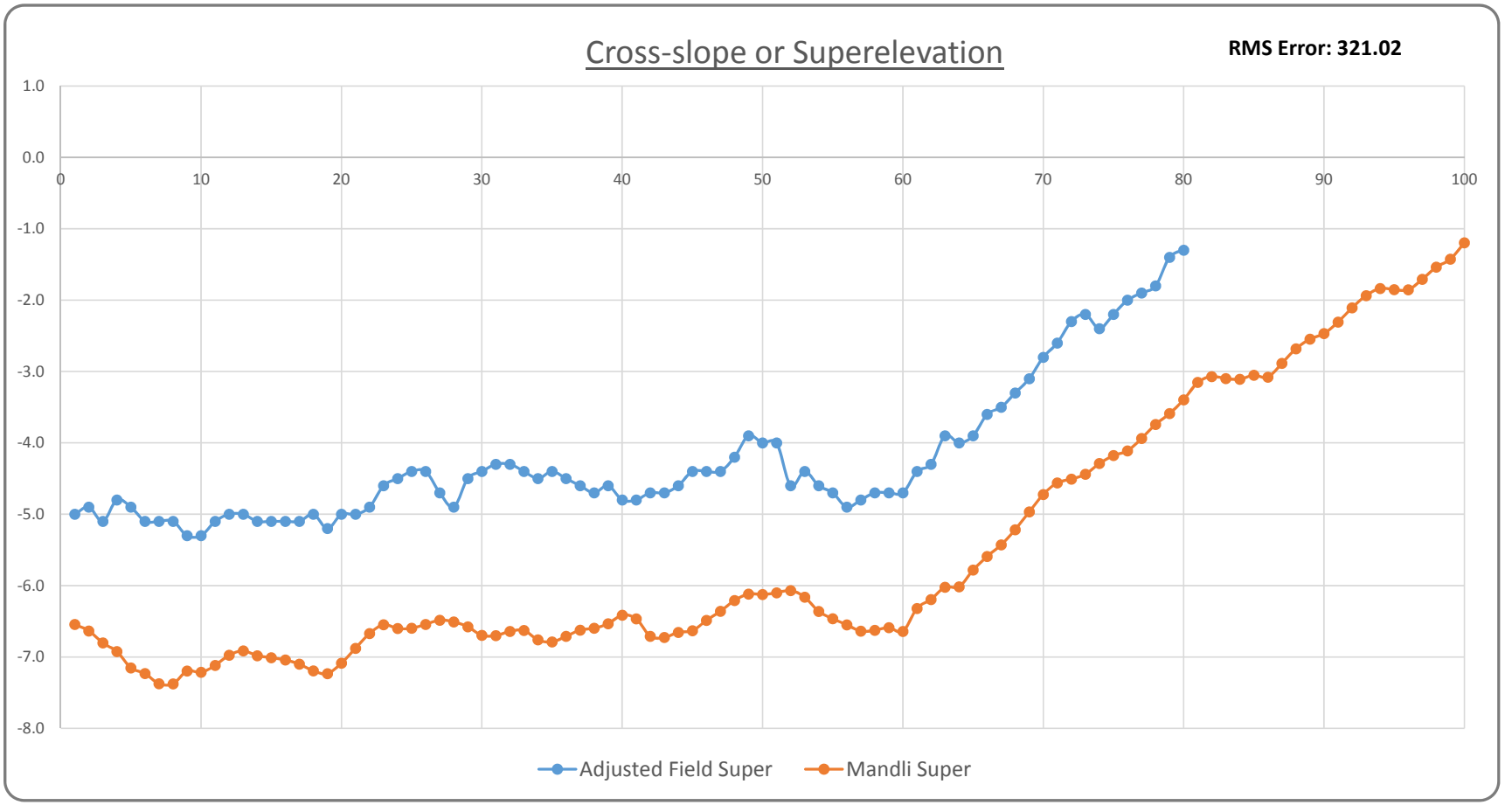
US 460: Milepoint 6.9-7.1 (Horizontal Curve - Eastbound)



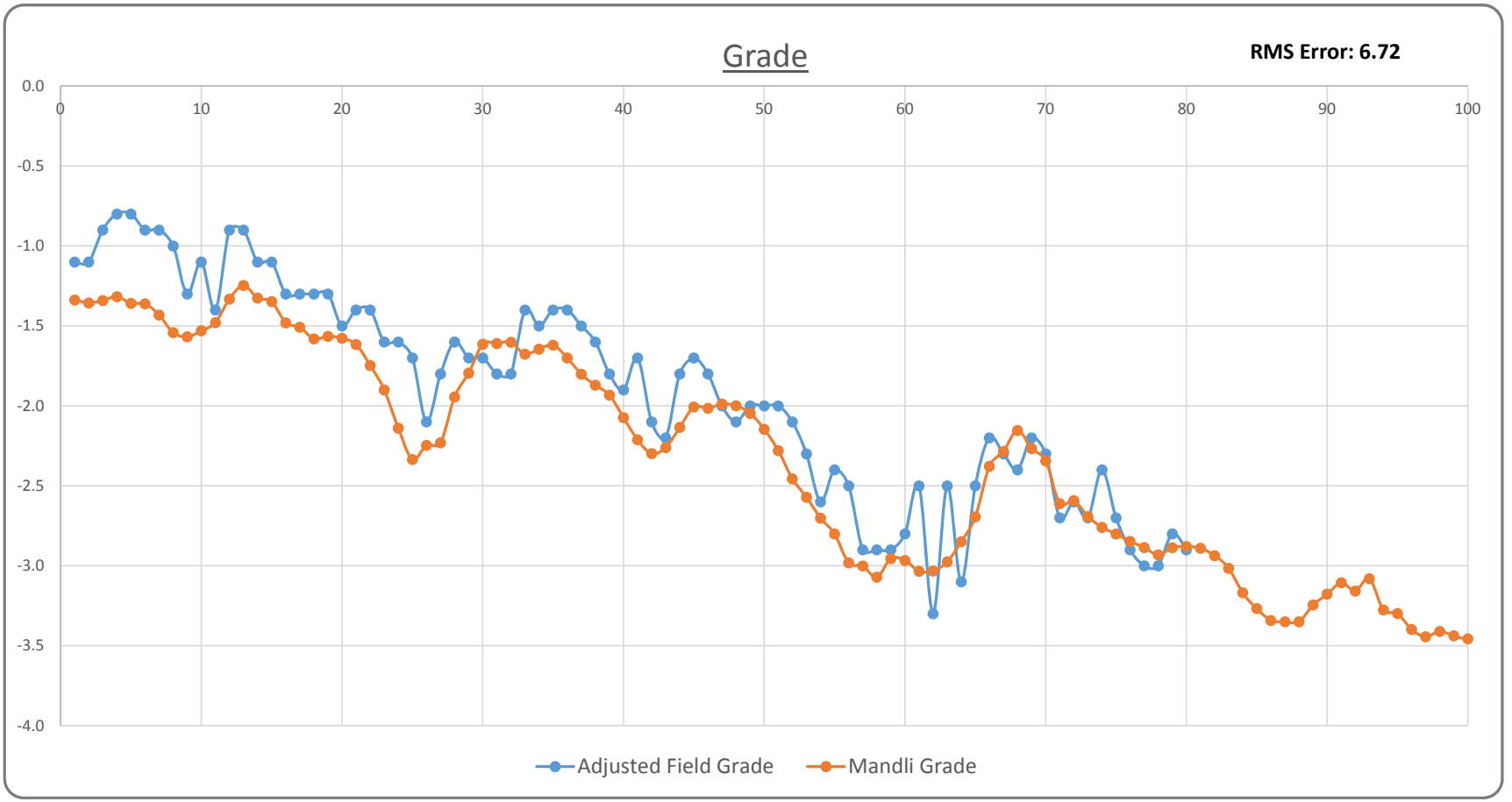
US 460: Milepoint 6.9-7.1 (Horizontal Curve - Eastbound)



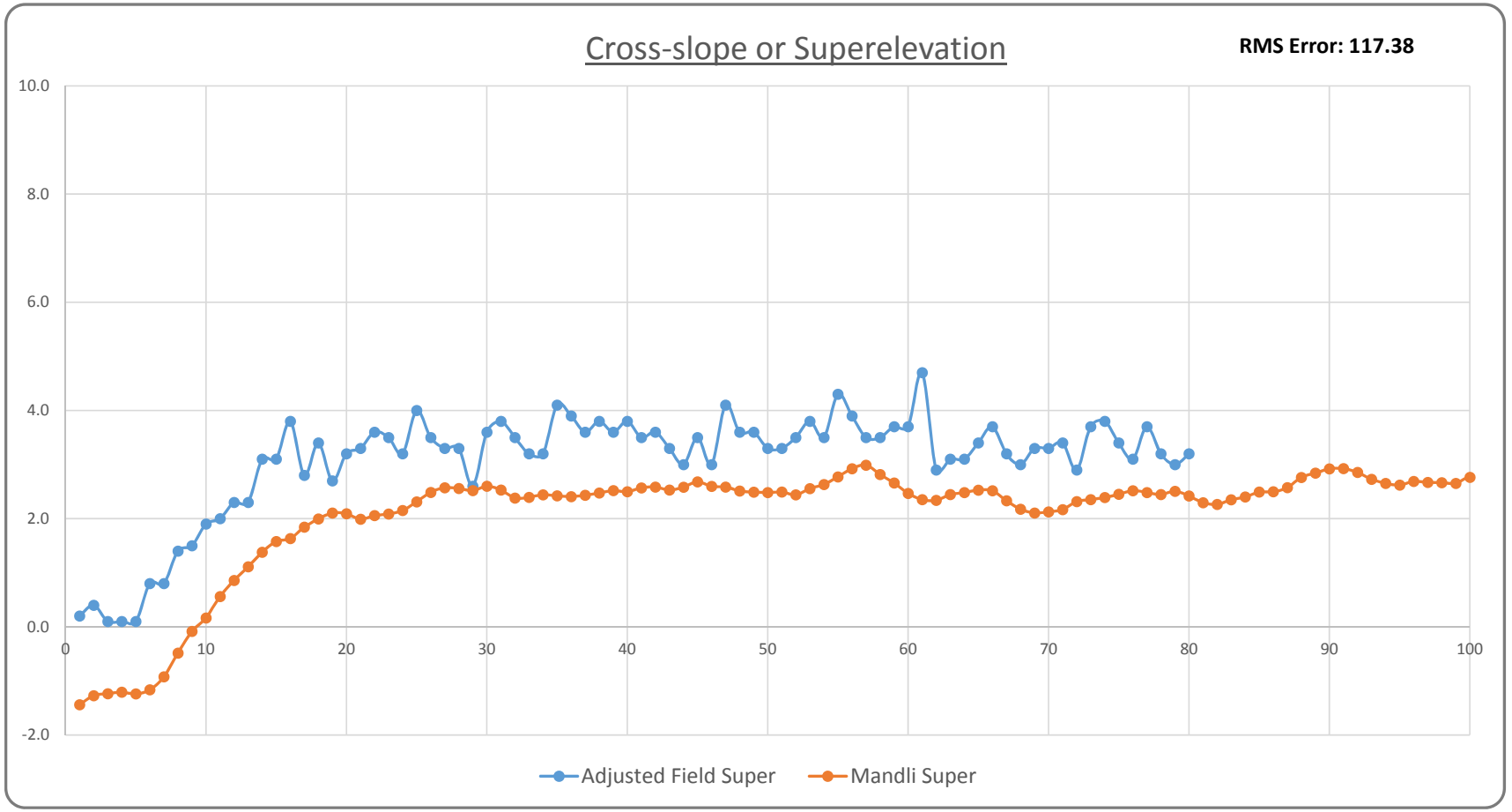
US 460: Milepoint 6.9-7.1 (Horizontal Curve - Westbound)



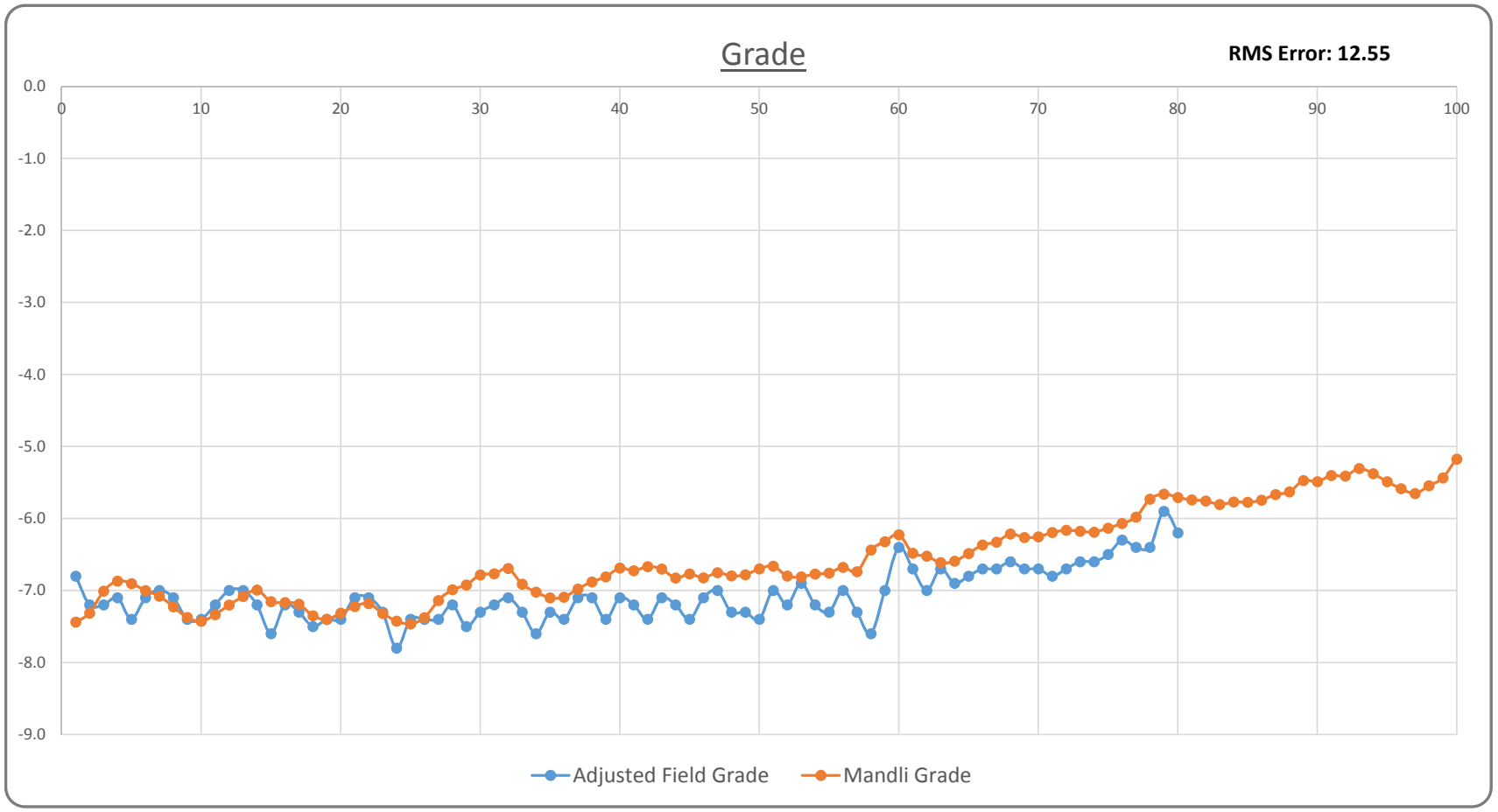
US 460: Milepoint 6.9-7.1 (Horizontal Curve - Westbound)



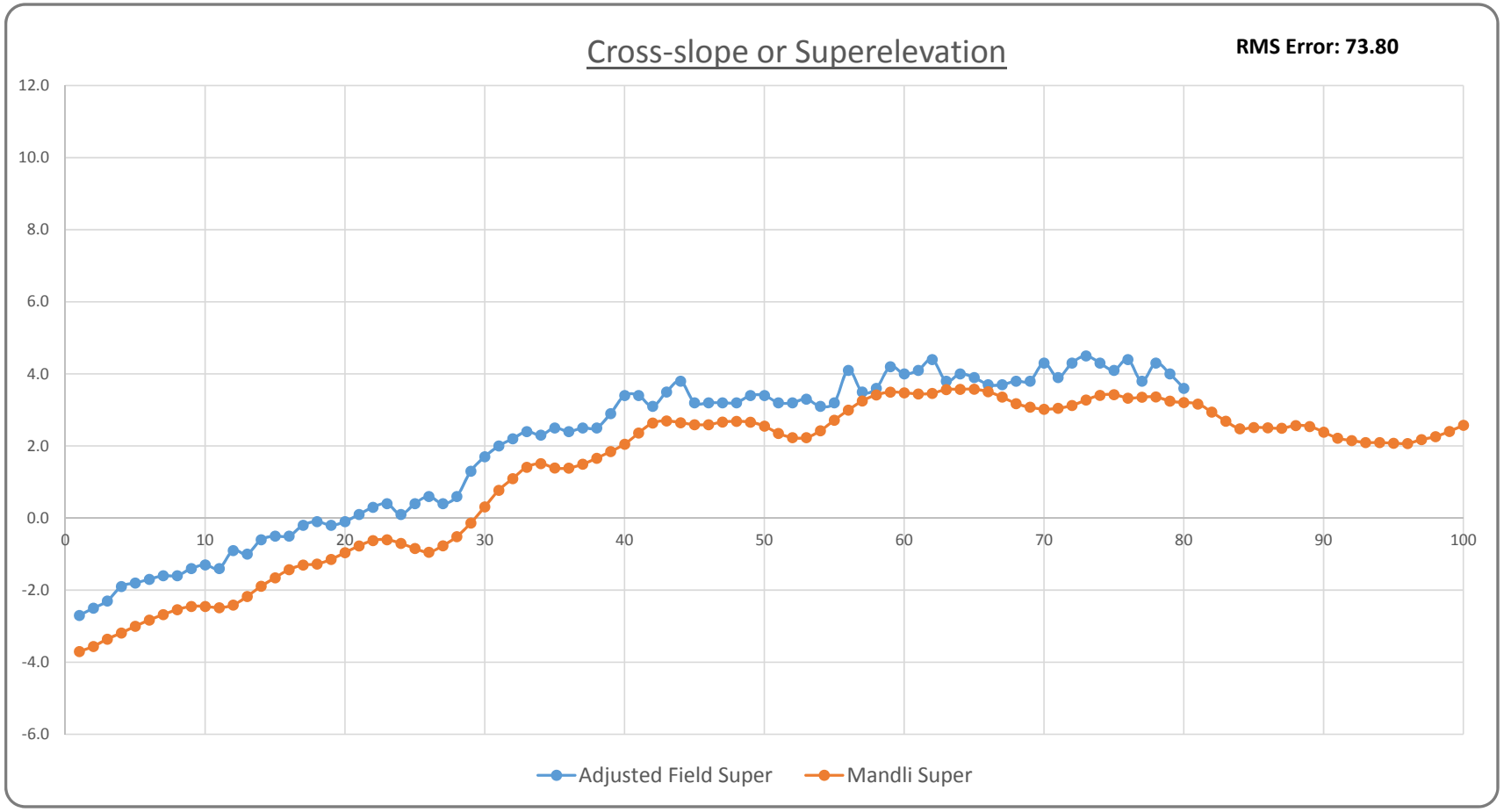
US 127: Milepoint 11.1-11.4 (Vertical Curve - Southeastbound)



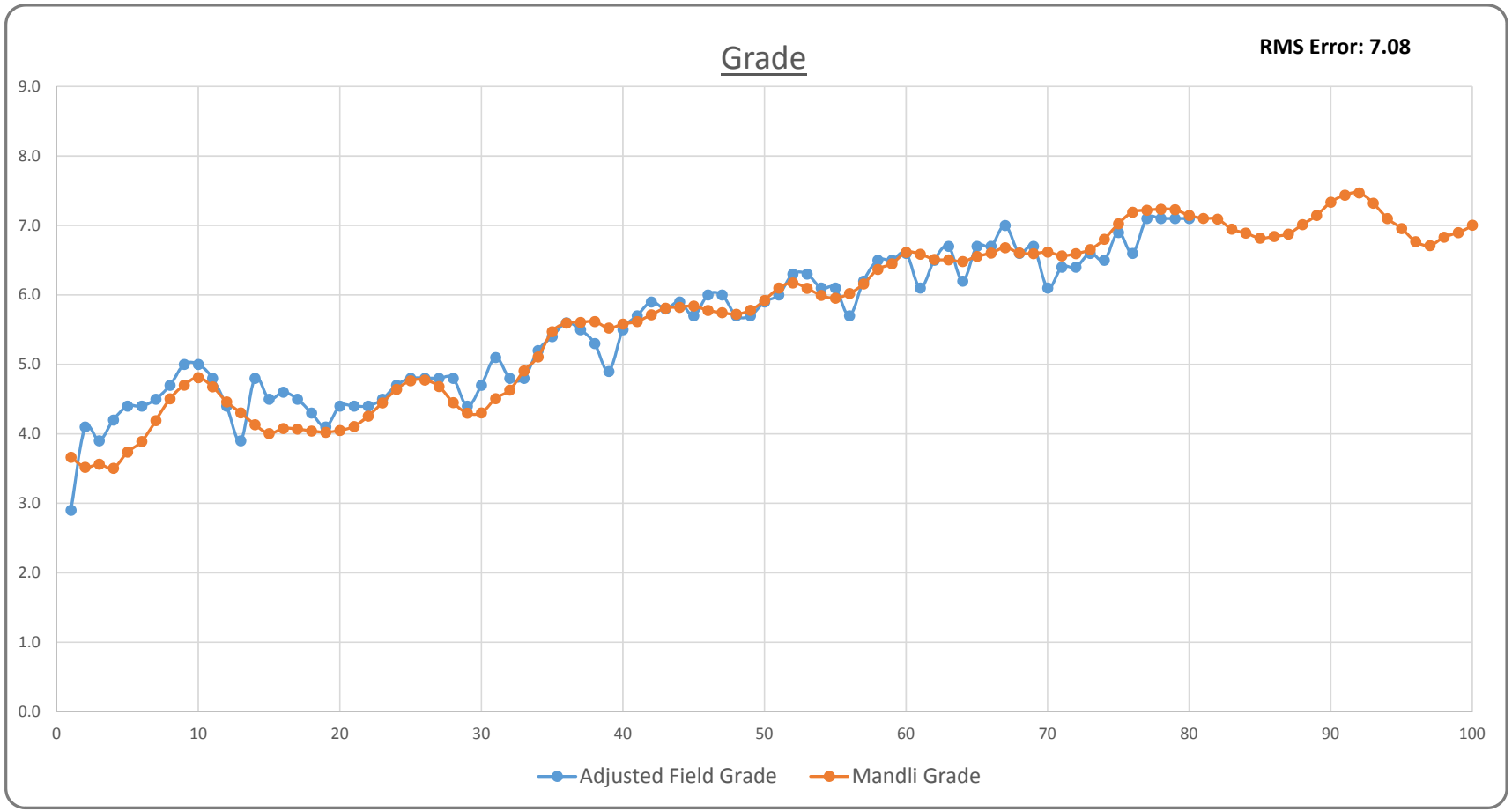
US 127: Milepoint 11.1-11.4 (Vertical Curve - Southeastbound)



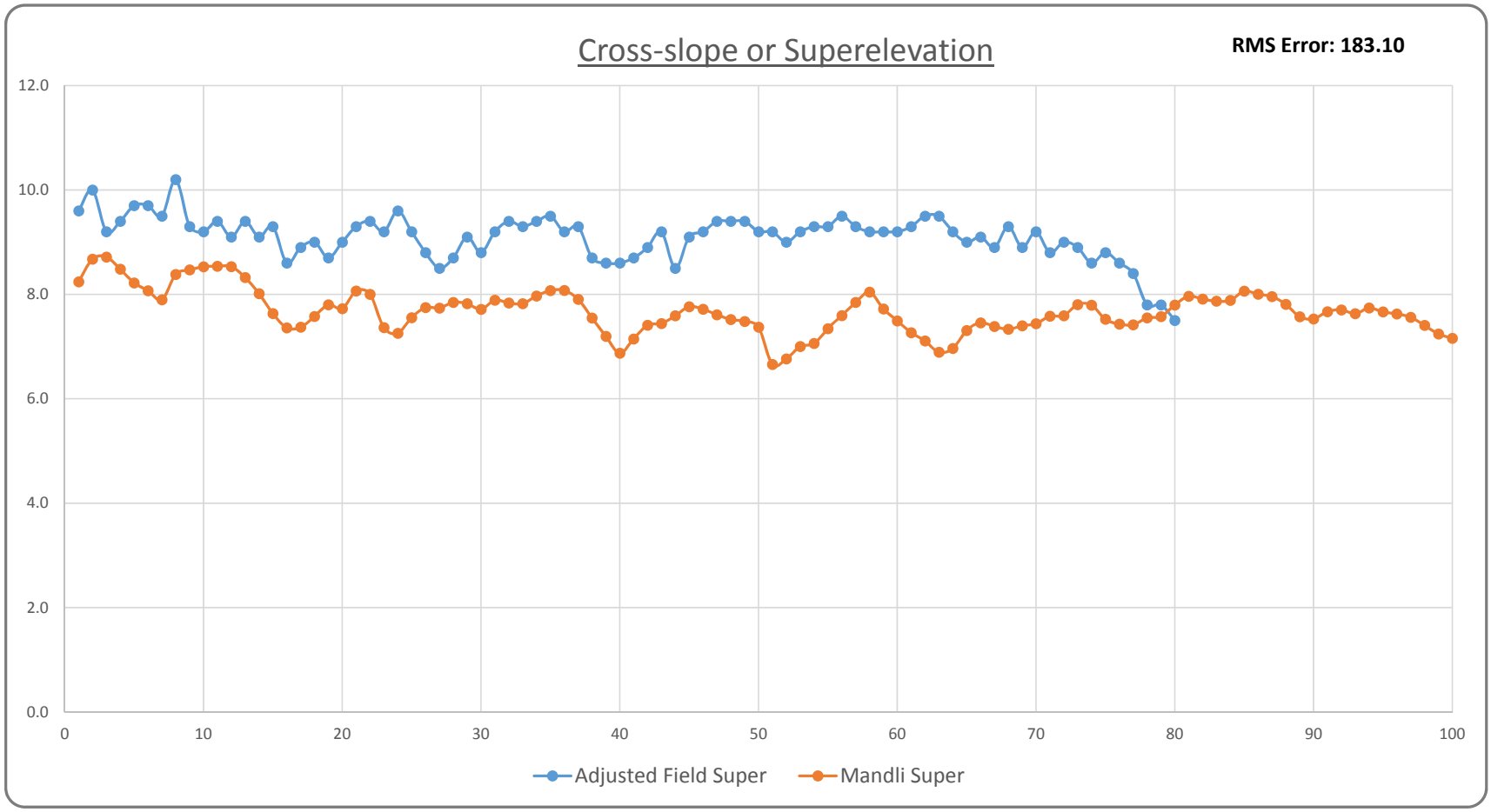
US 127: Milepoint 11.1-11.4 (Vertical Curve - Northwestbound)



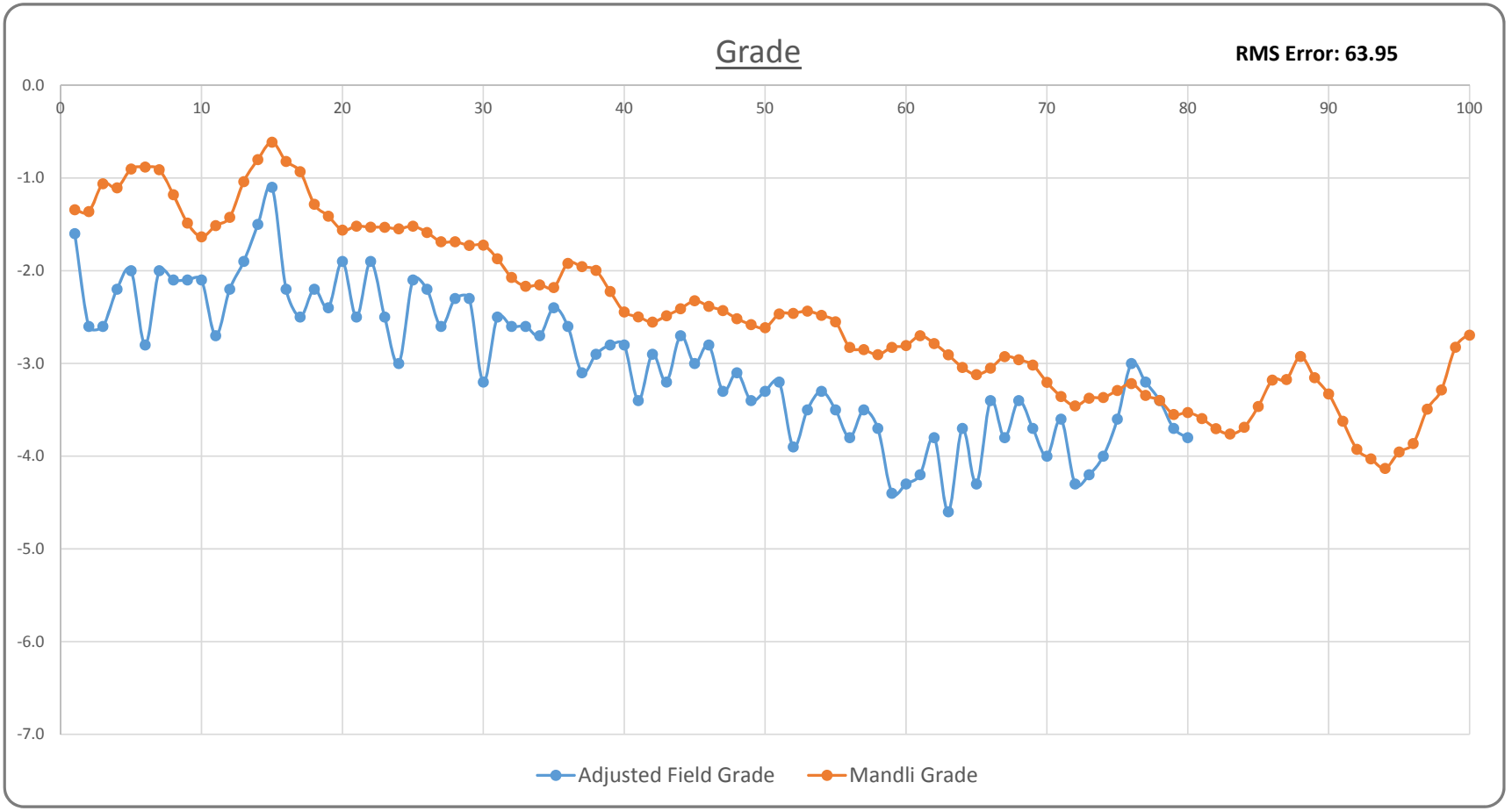
US 127: Milepoint 11.1-11.4 (Vertical Curve - Northwestbound)



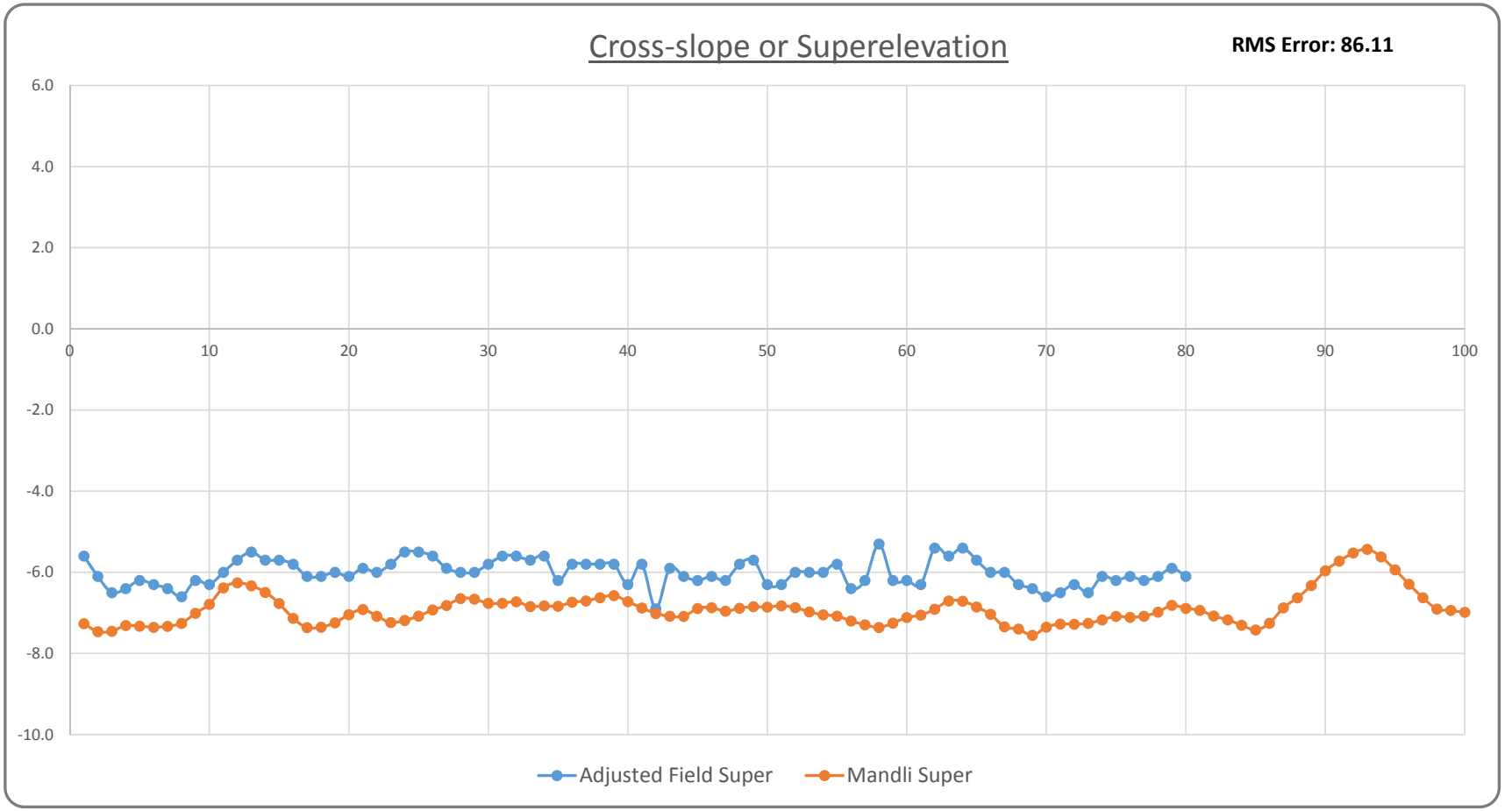
US 127: Milepoint 11.7-11.8 (Horizontal Curve - Southbound)



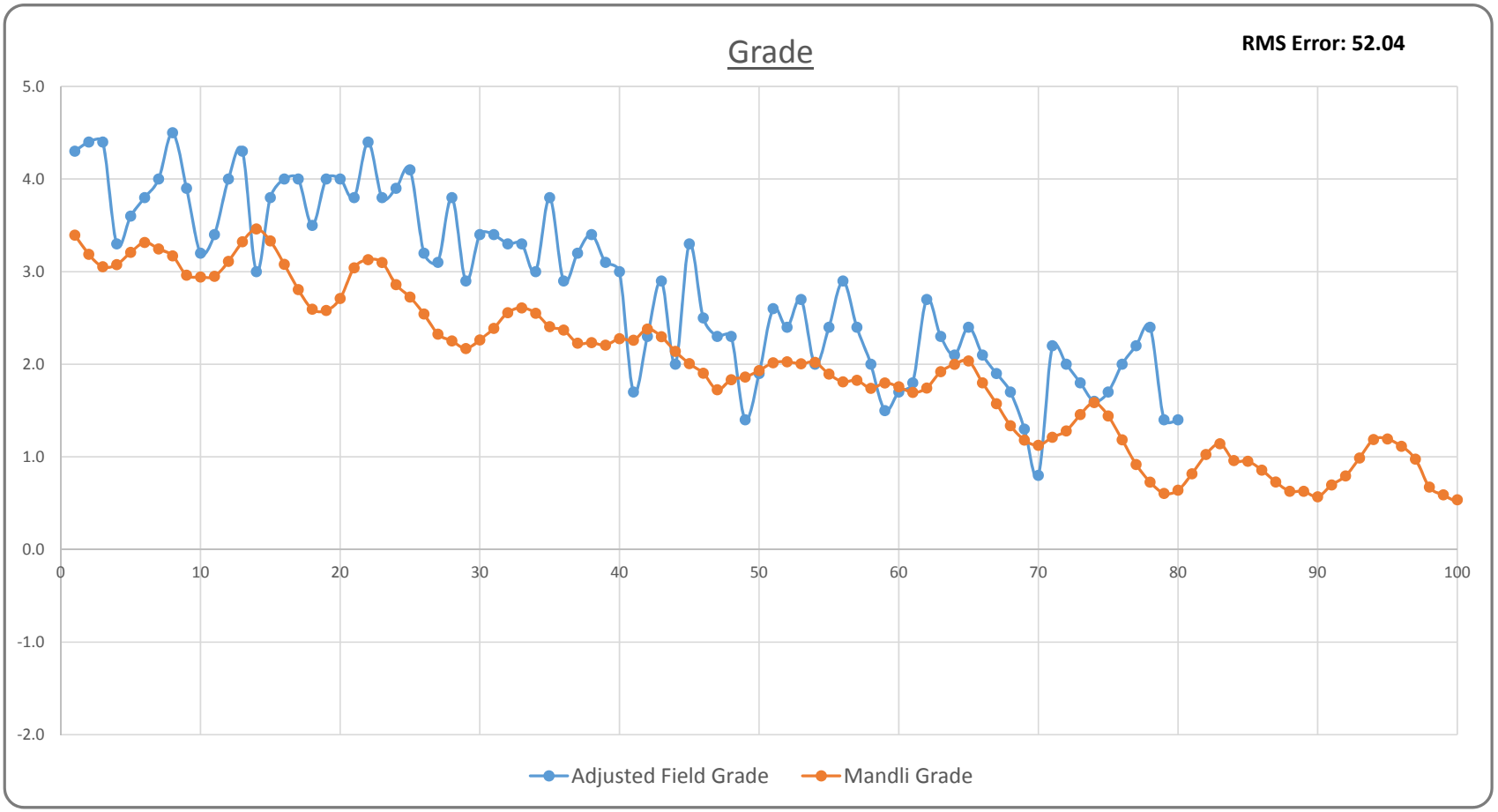
US 127: Milepoint 11.7-11.8 (Horizontal Curve - Southbound)



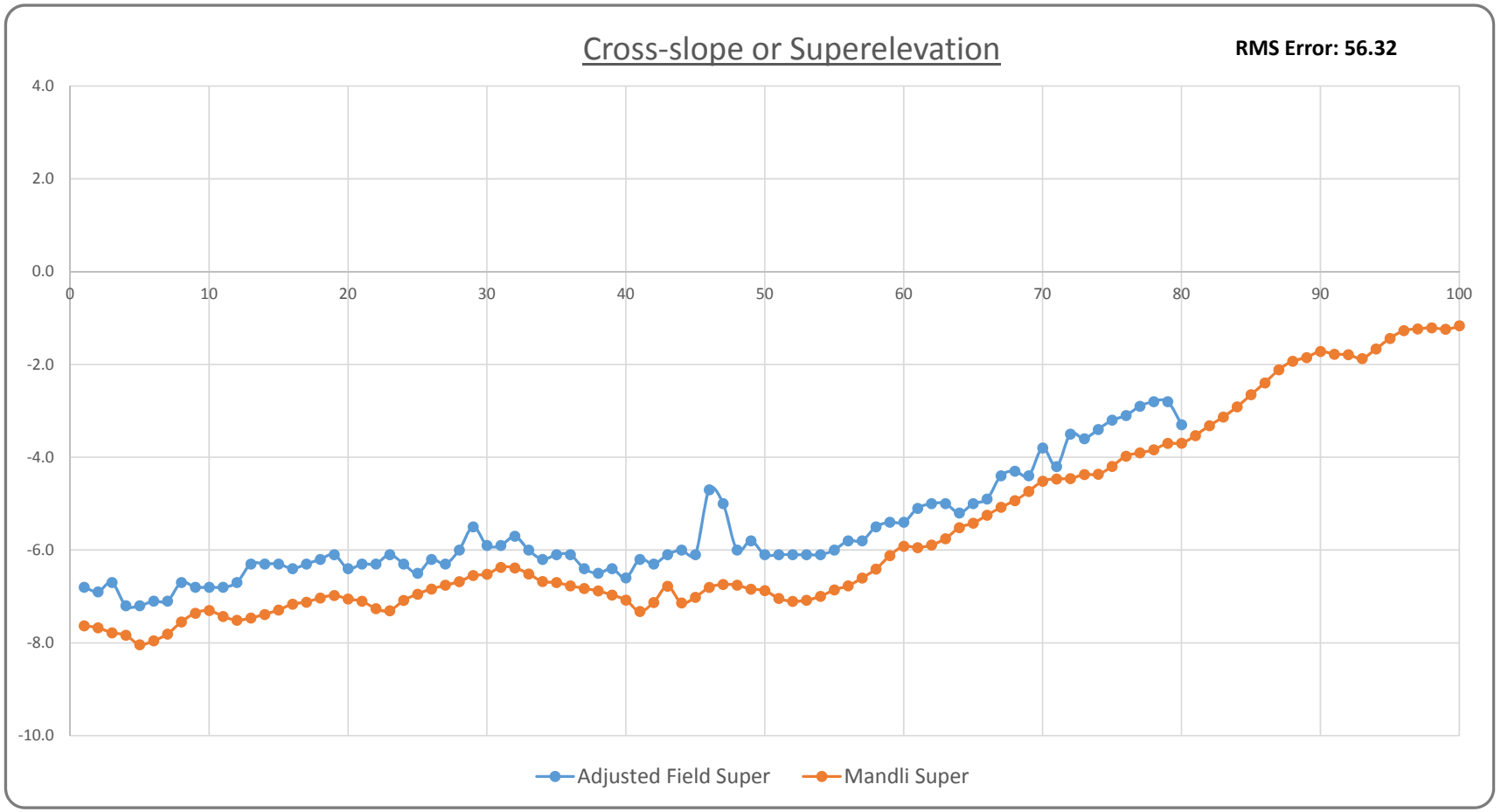
US 127: Milepoint 11.7-11.8 (Horizontal Curve - Northbound)



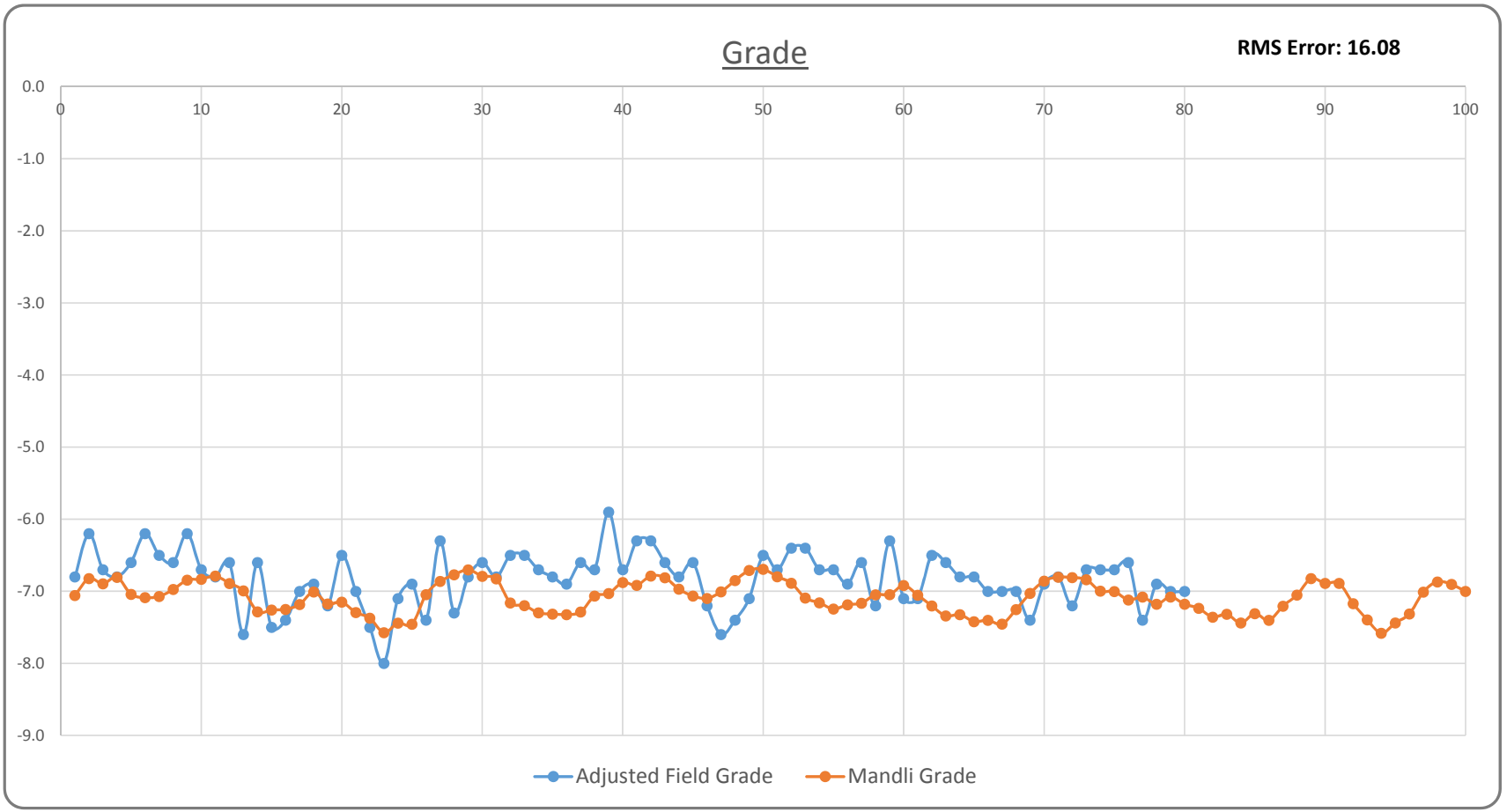
US 127: Milepoint 11.7-11.8 (Horizontal Curve - Northbound)



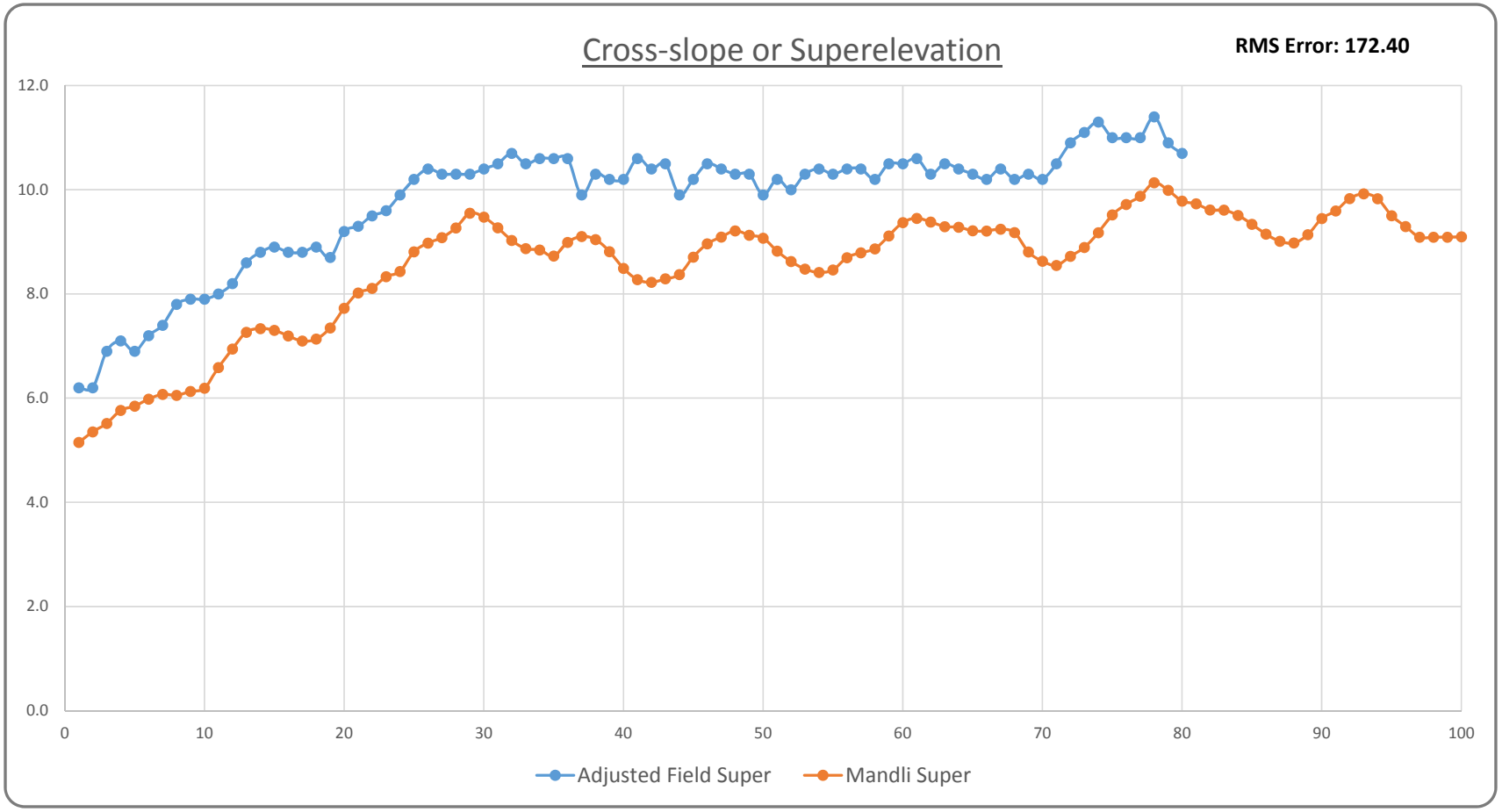
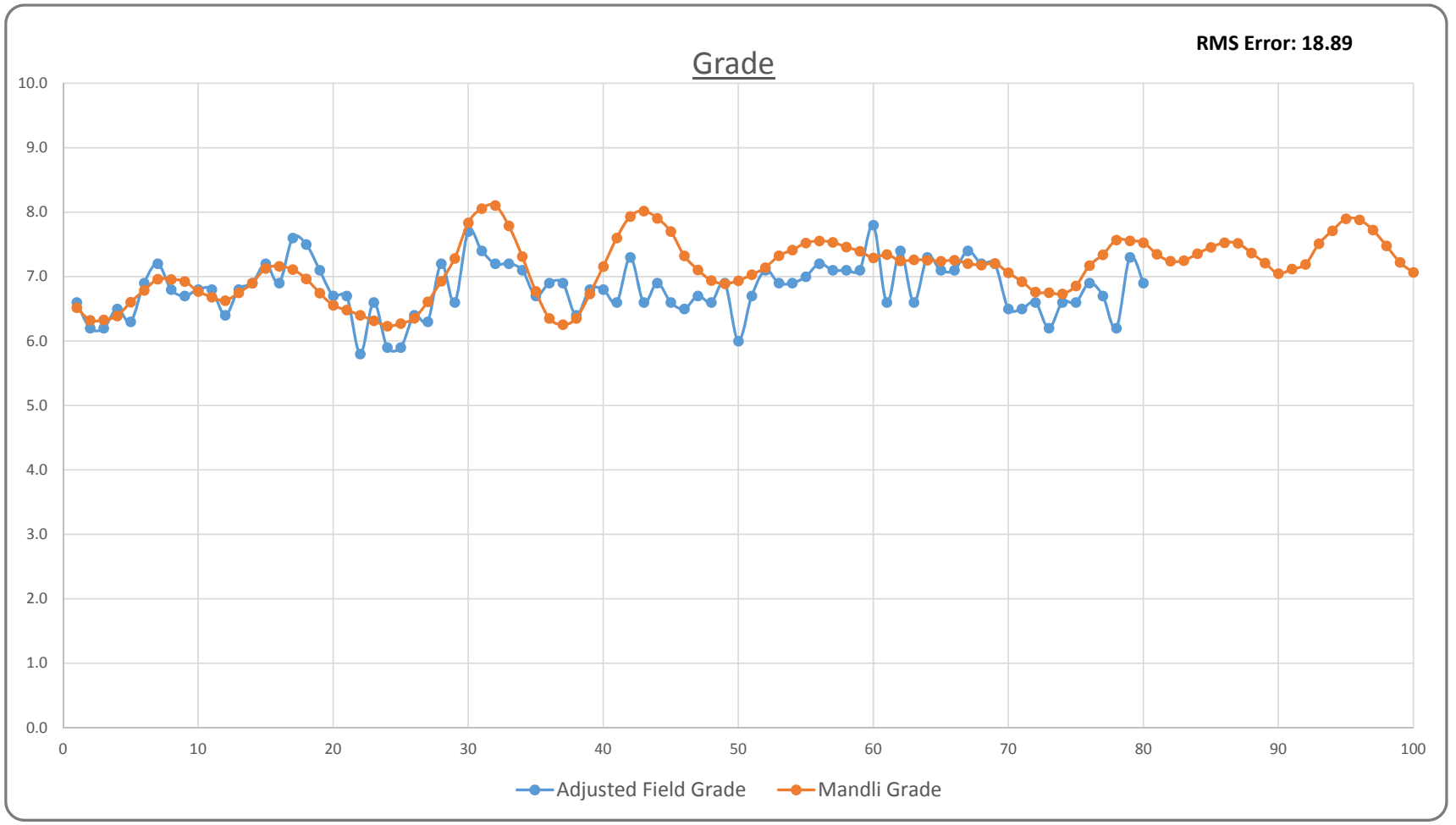
US 127: Milepoint 11.1-11.4 (Horizontal Curve - Southbound)



US 127: Milepoint 11.1-11.4 (Horizontal Curve - Southbound)



US 127: Milepoint 11.1-11.4 (Horizontal Curve - Northbound)



US 127: Milepoint 11.1-11.4 (Horizontal Curve - Northbound)