GEORGIA DOT RESEARCH PROJECT 20-22

Final Report

ENHANCING AND GENERATING GDOT'S MUTCD CURVE SIGN PLACEMENT DESIGN WITH CURVE FINDER AND CURVE SIGN DETERMINATION

GDOT

Georgia Department of Transportation

Office of Performance-based Management and Research
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May 2023

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To meet MUTCD requirements for curve sign design, the Georgia Department of Transportation (GDOT) developed a MUTCD-compliant curve sign design practice that uses the Curve Advisory Reporting System (CARS) system developed by the Rieker company. However, processing the CARS data collected by GDOT using Rieker devices is labor-intensive, time-consuming, and requires manual identification and processing of each separate curve. The objectives of this project are: 1) to enhance GDOT's current curve sign design practice by refining and using the curve finder (Smart-Curve Information Extraction, Smart-CIE) and the MUTCD curve sign design computation algorithms, both of which have already been developed by Georgia Tech; 2) to process GDOT's already-collected CARS data more consistently, accurately, and efficiently on nearly 18,000 centerline miles of state-maintained routes; and 3) to generate inventories of curves and MUTCD-compliant curve warning signs in both tabular and GIS formats to meet MUTCD curve sign design requirements and to support GDOT's sharp curve safety analysis using the AASHTOware Safety Powered by Numetric system. The enhanced curve finder and MUTCD-compliant curve warning sign design computation algorithm have been used to successfully process nearly 18,000 miles of Georgia state-maintained routes. A total of 13,262 curves have been identified, and 29,093 signs have been designed. These generated inventories of curves and the MUTCD-compliant curve signs have been delivered in both tabular and GIS formats to GDOT. GDOT has already successfully implemented and used these outcomes for its sharp curve safety analysis and safety improvement planning.
Descriptive statistics have been produced on the generated curves and curve sign inventory, and the outcome shows that: 1) District 1 has 4,190 curves, accounting for 31.59% of the total 13,262 identified curves. District 6 ranks second, with 2,434 curves (18.35% of the total). Conversely, District 5 has the lowest number of curves, with 848 curves (6.39% of the total curves); and 2) District 1 accounted for the largest number of signs, with 15,420 (53% of the total 29,093 designed signs). District 6 was the second largest, with 7,760 signs (26.67% of the total). These two districts, which cover the mountainous areas in the north of Georgia, required approximately 80% of all curve warning signs in Georgia. The remaining signs were distributed across the other
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GDOT Research Project No. 20-22

Final Report

ENHANCING AND GENERATING GDOT'S MUTCD CURVE SIGN PLACEMENT DESIGN WITH CURVE FINDER AND CURVE SIGN DETERMINATION

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Contract with
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In cooperation with

U.S. Department of Transportation

Federal Highway Administration

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AADT	Annual Average Daily Traffic
BBI	Ball Bank Indicator
CARS	Curve Advisory Reporting System
CFR	Code of Federal Regulations
CIE	Curve Information Extraction
GDOT	Georgia Department of Transportation
FHWA	Federal Highway Administration
GPS	Global Positioning System
GIS	Geographic Information System
MUTCD	Manual on Uniform Traffic Control Devices
ML	Machine Learning
PC	Point of Curve
PT	Point of Tangent
SPF	Safety Performance Function

EXECUTIVE SUMMARY

A disproportionately high number of serious vehicle crashes occur on horizontal curves. Horizontal curves make up only about 5% of highway miles, but approximately 25% of fatal crashes occur on them (Donnell et al., 2019; FHWA, 2018). Studies have shown that the use of consistent and appropriate curve warning signage can reduce the number of crashes by more than 40% (Albin et al., 2016; Montella, 2009). To ensure safety on horizontal curves, the Manual on Uniform Traffic Control Devices (MUTCD) requires various horizontal alignment warning signs for freeways, expressways, and roadways with more than 1,000 AADT; they are functionally classified as arterials or collectors (USDOT, 2009). For roadways with AADT less than 1,000, cities and counties have also installed curve warning signs based on the assessment of roadway characteristics, crash history, referring to the MUTCD even if it is not mandated. The United States Code of Federal Regulations, Title 23, declares the MUTCD to be the national standard for traffic control devices on all public roads (U.S.CFR, 2009). Non-compliance with MUTCD guidelines could result in a loss of federal aid funds for states and can also expose states to tort liability in the case of a lawsuit following a traffic accident (USDOT, 2009).

Thus, to meet MUTCD requirements for curve sign design, the Georgia Department of Transportation (GDOT) developed a MUTCD-compliant curve sign design practice that uses the Curve Advisory Reporting System (CARS) system developed by the Rieker company (Green et al., 2016). However, processing the CARS data, collected by GDOT using Rieker devices, is labor-intensive, time-consuming, and requires manual identification and processing of each separate curve. This manual process is prone to inconsistencies and subjectivity, resulting in inefficiencies. Additionally, the CARS portal lacks the ability to consider groups of nearby curves (e.g., reverse curves, compound curves, spiral curves, and winding curves), which necessitates a manual approach to designating reverse curve and winding road signs. Furthermore, there is no GIS format output available that integrates all identified curves and designed curve signs, making it challenging to visualize, validate, and utilize the manual method's results holistically. Given these limitations, GDOT has taken the initiative to improve its data processing efficiency and existing practices by having Georgia Tech (GT) develop an enhanced data processing procedure. In addition, GDOT has also requested Georgia Tech extract detailed curve information at the network level in a GIS data format that can be used to support GDOT's use of AASHTOware Safety Powered by Numetric for sharp curve safety analysis and improvement planning.

The objectives of this project are 1) to enhance GDOT's current curve sign design practice by refining and using the curve finder (Smart-Curve Information Extraction, Smart-CIE) and the MUTCD curve sign design computation algorithms, both already developed by Georgia Tech, 2) to process GDOT's already-collected CARS data more consistently, accurately, and efficiently on nearly 18,000 centerline miles of state-maintained routes, 3) to generate inventories of curves and MUTCD-compliant curve warning signs in both tabular and GIS formats to meet MUTCD curve sign design requirements and to support GDOT's sharp curve safety analysis using the AASHTOware Safety Powered by Numetric system. The following are the conclusions for this research project:

1) A procedure has been developed to prepare raw data acquired from CARS, including batch data downloading, missing data cleaning, data smoothing, data combining, spatial data selection, and data filtering. The prepared data is used to support curve inventory

generation, advisory speed computation, and curve sign designs.

2) The curve finder computation algorithm (Smart-Curve Information Extraction, Smart-CIE, already developed by Georgia Tech) has been enhanced to increase accuracy (high recall and precision), improve reliability (no false negative), create better user control (only three thresholds with physical meaning involved), and promote the capability of compound curve identification. Using selected curves with diverse characteristics on SR-2, 11, and 17 in GDOT District 1, the enhanced GT curve finder has been validated by comparing detected curves in GT curve finder with manual identified curves in CARS. The results demonstrate the promising results of generated curve inventory from GT curve finder.

3) The MUTCD curve sign design computation algorithm (already developed by Georgia Tech) has been enhanced to efficiently process curve warning sign design automatically at the network-level and to have the capability to handle reverse curve and winding road signs by grouping adjacent curves and analyzing their relationships. The enhanced GT curve sign design computation algorithm has been validated by comparing its curve sign design results with the outcomes derived using CARS. The results demonstrate the promising results of designed curve signs from GT curve sign design computation algorithm.

4) The enhanced curve finder and MUTCD-compliant curve warning sign design computation algorithm have been used to successfully process nearly 18,000 miles Georgia state-maintained routes. A total of 13,262 curves have been identified and 29,093 signs have been designed. These generated inventories of curves and the MUTCD-

compliant curve signs have been delivered as tabular and GIS formats to GDOT. GDOT has already successfully implemented and used these outcomes for its sharp curve safety analysis and safety improvement planning.

5) Descriptive statistics have been produced on generated curves and curve sign inventory to summarize research outcomes. GIS maps have been plotted to visualize identified curves and designed signs according to location. Summary statistics (such as mean, median, and standard deviation) have been provided to help understand the characteristics of generated curve inventory. Histograms have been created to identify patterns and trends in the curve inventory, such as the frequency of curves with different radii, deviation angles, lengths, BBI values, and advisory speeds. Bar and pie charts and box plots have been created to identify distributions of curve inventory (including their characteristics) and warning signs by GDOT districts, which can be used to improve future decision-making (such as budgeting at district-level). Finally, a correlation study has been conducted to examine potential relationships between variables (such as curve radius, deviation angle, BBI, and advisory speed). Findings from the descriptive statistics are summarized as follows:

    a. Areas in the north of Georgia, particularly in the mountainous regions (Districts 1 and 6), as well as the Atlanta metropolitan area (District 7), have higher concentrations of curves and curve warning signs that may require additional safety measures.

    b. The district with the highest number of curves is District 1, with 4,190 curves, accounting for 31.59% of the 13,262 identified curves. District 6 ranks second, with 2,434 curves, which represents 18.35% of the total. Both Districts 1 and 6 are situated in the mountainous northern region of Georgia. Conversely, District 5, which covers the coastal regions, reports the lowest number of curves, with only 848 curves identified, representing just 6.39% of the total curves.

c. Districts 1 and 6, which cover mountainous areas, have observed lower values of curve radii, higher values of deviation angles, lower values of curve lengths, higher BBI values, and lower values of estimated advisory speeds in the box plots. These trends follow the laws of mechanics among curve radius, deviation angle, curve length, BBI, and estimated advisory speed.

d. Correlation analyses find that higher curve radii are somewhat correlated with lower BBI values and strongly correlated with higher advisory speeds. However, deviation angle is not found to be strongly correlated with either BBI or advisory speed when the deviation angle ranges from 0-100 degrees. For deviation angles greater than 100 degrees, larger deviation angles tend to have larger BBI values and lower advisory speeds, but the distribution displays significant dispersion.

e. District 1 accounted for the largest number of signs, with 15,420 (53%) of the total 29,093 designed signs. District 6 was the second largest, with 7,760 signs (26.67% of the total). These two districts, which cover the mountainous areas in the north of Georgia, require approximately 80% of all curve warning signs in Georgia. The remaining signs (20.33%) were distributed across the other districts.

The following are the recommendations for future work:

1) **Low-cost data collection method to establish a sustainable and systemic curve safety assessment:** It is recommended that the cost of data collection (currently done by Rieker devices) be reduced by introducing low-cost mobile devices (e.g., smartphones and dash cameras) and/or using intra-agency crowdsourcing techniques. Considering that the Rieker device is proprietary, it is recommended to explore non-proprietary alternatives, particularly these low-cost mobile devices.

2) **GPS correction using roadway centerline geometry**: It is recommended to develop a method to correct/calibrate disrupted GPS or GPS with offsets using roadway centerline geometry data. Therefore, these GPS data can be salvaged to minimize data re-collection.

3) **Confidence level of estimated advisory speed**: To enhance the reliability of the estimated advisory speed, a model that provides a confidence level should be developed. This confidence level, categorized as high, medium, or low, will serve as an indicator of the reliability of the computed advisory speed based on the data collected using either the Rieker device or other low-cost mobile devices from multiple runs (i.e., repeated tests). This will provide a means for transportation agencies to differentiate good and bad data that can be used to target roadway segments (with low confidence) from which data must be re-collected. This will significantly improve the reliability of agencies' safety decision-making and the productivity of data re-collection.

4) **Enhanced web-based data management tool with well-structured database and flexible data query capabilities:** It is recommended that an advanced web-based tool for managing data from low-cost mobile devices be developed. This tool would offer

functionalities like data uploading, manipulation, and visualization (e.g., missing data, confidence level, curve geometry, locations). It would identify routes with sufficient data coverage and routes requiring more data collection, thereby optimizing the data collection process. Given the large data volume, a well-structured database is essential for efficient and flexible data querying and review. Flexible query features, such as click-based route selection or keyword searches (e.g., route name, county code), are recommended for accessing relevant data.

5) **Automated MUTCD compliance checking system:** It is recommended to develop a low-cost, frequent, and automatic system that uses low-cost mobile devices with video log data capture capabilities (e.g., smartphones and dash cameras) and machine learning (ML) technologies to perform MUTCD compliance checking for curve warning signs. This system will include 1) roadway image/video data collection using low-cost mobile devices, 2) an automated curve sign detection model, 3) an automated MUTCD-compliant curve sign design (expected to be developed in this study) method, and 4) an automated MUTCD compliance checking model that compares designed curve sign with real-world existing signs. Therefore, missing curve warning signs can be identified promptly by examining existing signs with designed MUTCD-compliant curve signs.

6) **Refinement of MUTCD by incorporating reverse curve and winding road sign design procedures into MUTCD:** The current version of the MUTCD advises users to employ engineering judgment for determining curve warning sign designs on continuous curves; however, this method is subjective and lacks detailed specifications. To address this issue, it is recommended to include the procedures for designing reverse curve signs

and winding road signs by grouping adjacent curves and analyzing their relationships, which have been developed in this study, into the MUTCD. This will provide more objective, consistent and comprehensive guidelines for the design of curve warning signs.

7) **Enhanced comprehensive curve safety assessment and improvements using comprehensive risk factors:** It is recommended to use this project as a base to establish an enhanced curve safety assessment and improvement/treatment planning by comprehensively considering and examining the following risk factors: 1) BBI, 2) curve characteristics (e.g., curve radius, deviation angle, curve length), 3) vertical slope, 4) super elevation, 5) side friction, 6) estimated advisory speed, 7) speed difference between advisory speed and speed limit, etc. Besides curve sign compliance checking, other safety improvements, such as high-friction surface treatment, shoulder widening, curve realignment, rumble strips, guardrails, and line marking improvement, etc., can be applied using the extracted comprehensive risk factors that are previously difficult to obtain.

8) **Identifying contributing factors and establishing more accurate SPFs for curve crashes using detailed curve characteristics and historical crashes:** It is recommended to further leverage detailed curve characteristics (in the extracted curve inventory) and historical crashes to achieve the following goals: 1) identify contributing factors to curve crashes by correlating individual variables (e.g., curve radius, deviation angle, curve length, BBI, and advisory speed) with historical curve crashes, 2) establish more accurate safety performance functions (SPFs) for curve crash prediction using multiple variables, including data (e.g., curve radius, deviation angle, curve length, BBI, and advisory speed)

that were previously difficult to collect at the network-level. To achieve this level of analysis, accurate spatial locations (latitude and longitude) from historical crash reports are crucial. However, obtaining this information has been a continuing challenge. For example, if the police move the vehicles involved in an accident to a safe location out of the curve and then report the GPS location, it does not accurately represent where the actual crash occurred. Therefore, it is recommended to establish a standard operating procedure or methodology for capturing more accurate locations of crashes.

CHAPTER 1. INTRODUCTION

A disproportionately high number of serious vehicle crashes occur on horizontal curves. Horizontal curves make up only about 5% of highway miles, but approximately 25% of fatal crashes occur on them (Donnell et al., 2019; FHWA, 2018). Studies have shown that the use of consistent and appropriate curve warning signage can reduce the number of crashes by more than 40% (Albin et al., 2016; Montella, 2009). To ensure safety on horizontal curves, the Manual on Uniform Traffic Control Devices (MUTCD) requires various horizontal alignment warning signs for freeways, expressways, and roadways with more than 1,000 AADT; they are functionally classified as arterials or collectors (USDOT, 2009). For roadways with AADT less than 1,000, cities and counties have also installed curve warning signs based on the assessment of roadway characteristics, crash history, referring to the MUTCD even if it is not mandated. The United States Code of Federal Regulations, Title 23, declares the MUTCD to be the national standard for traffic control devices on all public roads (U.S.CFR, 2009). Non-compliance with MUTCD guidelines could result in a loss of federal aid funds for states and can also expose states to tort liability in the case of a lawsuit following a traffic accident (USDOT, 2009).

Thus, to meet MUTCD requirements for curve sign design, the Georgia Department of Transportation (GDOT) developed a MUTCD-compliant curve sign design practice that uses the Curve Advisory Reporting System (CARS) system developed by the Rieker company (Green et al., 2016). This practice involves the following steps:

1) Collecting field data (including GPS coordinates, Ball-bank Indicator (BBI) readings, driving speeds, and posted speed limits) using Rieker devices and uploading the data to the CARS portal.

2) Detecting sharp curves manually (one at a time) using the CARS portal. The Point of Curve (PC) and Point of Tangent (PT) are identified through a trial-and-error method.

3) Estimating the advisory speed by processing GPS, BBI, driving speed, and posted speed limit data, one curve at a time, using the CARS portal.

4) Conducting curve sign design, including curve type selection and sign location determination, one curve at a time, using the CARS portal.

5) Generating a curve sign inventory and plan sets to support the installation of MUTCD-compliant curve signs in the field.

The GDOT has invested significant resources in collecting field data. However, the current Curve Assessment and Rating System (CARS) used to process the collected data is labor-intensive, time-consuming, and requires manual identification and processing of each curve individually. This manual process is prone to inconsistencies and subjectivity, resulting in inefficiencies. Additionally, the CARS portal lacks the ability to consider groups of nearby curves (e.g., reverse curves, compound curves, spiral curves, and winding roads), which necessitates a manual approach to designing reverse curve and winding road signs. Furthermore, there is no GIS format output available that integrates all identified curves and designed curve signs, making it challenging to visualize, validate, and utilize the manual method's results holistically. Given these limitations, there is a pressing need to improve GDOT's existing practice to ensure efficient and consistent MUTCD-compliant curve sign design. In addition, GDOT has requested Georgia Tech to extract detailed curve information at the network level in a GIS data format that can support GDOT's use of AASHTOware Safety Powered by Numetric for sharp curve safety analysis and improvement planning.

RESEARCH OBJECTIVES AND TASKS

The objective of this project is to enhance GDOT's current curve sign design practice to meet the requirement of the MUTCD by refining and using the curve finder (Smart-Curve Information Extraction, Smart-CIE) and the MUTCD curve sign design computation algorithms, both already developed by Georgia Tech. These refined algorithms will be used to process GDOT’s already collected CARS data more consistently, accurately, and efficiently on nearly 18,000 centerline miles of state-maintained routes. The generated inventories of curves and MUTCD-compliant curve warning signs will ultimately be used to improve GDOT’s compliance with MUTCD requirements and support GDOT’s sharp curve safety analysis using the AASHTOware Safety Powered by Numetric system. This project consists of performing the following four tasks:

1) Review GDOT’s current practices and prepare raw data acquired from CARS.

2) Refine and validate the curve finder and MUTCD curve sign design computation algorithms to generate the inventories of sharp curves and MUTCD-compliant curve warning signs more accurately and efficiently.

3) Generate and deliver the inventories of sharp curves and MUTCD-compliant curve warning signs in tabular and GIS formats for GDOT state-maintained routes in Georgia.

4) Produce descriptive statistics on the generated curves and curve warning signs to summarize research outcomes.

In addition, the generated curve inventory will be in a format that is compatible with the AASHTOware Safety Powered by Numetric system, which will allow for more efficient and effective analysis of curve-related crashes by GDOT engineers.

REPORT ORGANIZATION

This research project report is structured as follows:

- Chapter 1: Introduction - Covers background, research objectives, and tasks.
- Chapter 2: Existing GDOT Curve Sign Management - Reviews existing GDOT practices and identifies their challenges for complying curve warning sign with MUTCD.
- Chapter 3: Enhanced MUTCD Curve Sign Design - Presents an enhanced, automated method developed for generating inventories of sharp curves and designing MUTCD-compliant curve warning signs.
- Chapter 4: Validation and Comparison of Results - Validates the developed method through comparison with CARS.
- Chapter 5: Descriptive Statistics of Results - Provides descriptive statistics for the generated curves and curve warning signs.
- Chapter 6: Conclusions and Recommendations - Summarizes findings, provides conclusions, and makes future work suggestions.

CHAPTER 2. EXISTING GDOT CURVE SIGN MANAGEMENT

This chapter reviews existing GDOT practices for complying with the requirements of the Manual on Uniform Traffic Control Devices (MUTCD) for curve warning signs. The MUTCD is a federal law that governs all traffic control devices, and non-compliance can result in the loss of federal aid funds. Section 2C of the MUTCD mandates the appropriate placement of curve warning signs at specified locations and at specified spacings to ensure the safety of drivers navigating the curves.

GDOT currently determines the types and locations of MUTCD-compliant curve warning signs using either the manual ball-bank device method or the Curve Advisory Reporting System (CARS) from the Rieker company. GDOT also conducts in-field manual and visual assessments, allowing its experienced experts to proactively identify safety concerns on curves, such as lack of signs, insufficient sight distance, poor pavement conditions (low friction and potholes), missing striping, insufficient superelevation, etc. Consequently, this chapter is divided into the following three sections for reviewing the current GDOT practices for complying with the requirements of the MUTCD for curve warning signs:

1) **Curve sign design using the manual ball-bank device method:** This method determines advisory speed using the manual ball-bank device by traveling multiple times on the testing curve with gradually increasing speed. After the advisory speed is determined, traffic engineers follow MUTCD guidelines to designate sign locations and types. This review provides a context for this traditional method. Although simple, this method is labor-intensive and potentially unsafe.

2) **Curve sign design using CARS:** The CARS method allows users to collect GPS, BBI, and posted speed limit data using electronic sensors and a tablet, then process the data in the office. This method enhances data collection efficiency and safety, but data processing with CARS is time-consuming and repetitive. This section will reveal current challenges within the CARS method, identify necessary improvements, and set the stage for the proposed new method (to be introduced in Chapter 3) to overcome these challenges and fulfill all requirements.

3) **Field curve safety assessment:** Understanding field curve safety assessment practices will help pinpoint GDOT's requirements and expectations for the generated inventories of curves and curve warning signs. This includes considerations like representative BBI values in the curve inventory and the location accuracy of designated signs, among others. By this means, the output data structure in this study can be tailored to GDOT's needs.

CURVE SIGN DESIGN USING MANUAL BALL-BANK DEVICE METHOD

A traditional ball-bank indicator consists of a curved glass tube (or slope meter) filled with liquid and a weighted ball. The ball floats outward in the glass tube as a vehicle travels. The ball's movement away from the center of the tube is measured in degrees. As a vehicle experiences more lateral forces, the BBI reading is higher. A traditional ball-bank indicator is shown in **Figure 1.** The movement of the ball is measured in degrees, and this reading is indicative of the combined effect of superelevation, lateral (centripetal) acceleration, and vehicle body roll.

Figure 1. Illustration. A Traditional Ball-bank Indicator Device

During testing, the ball-bank indicator is mounted to the dashboard with rubber suction cups or by other stable methods. The device position is then adjusted to allow the ball to rest freely at zero degrees when the vehicle is standing on a level surface (i.e., on a tangent section). Vehicle movement around a curve causes the ball to swing from the zero position (e.g., vehicle movement to the left causes the ball to swing to the right). The faster the vehicle moves around the curve (or the sharper the curve), the greater the distance the ball swings away from the zero-degree position. This method is labor-intensive and unsafe because it requires testers to drive through the test curve multiple times and increasing the driving speed to yield a BBI value that meets a threshold (such as 12 degrees), as illustrated in **Figure 2.**

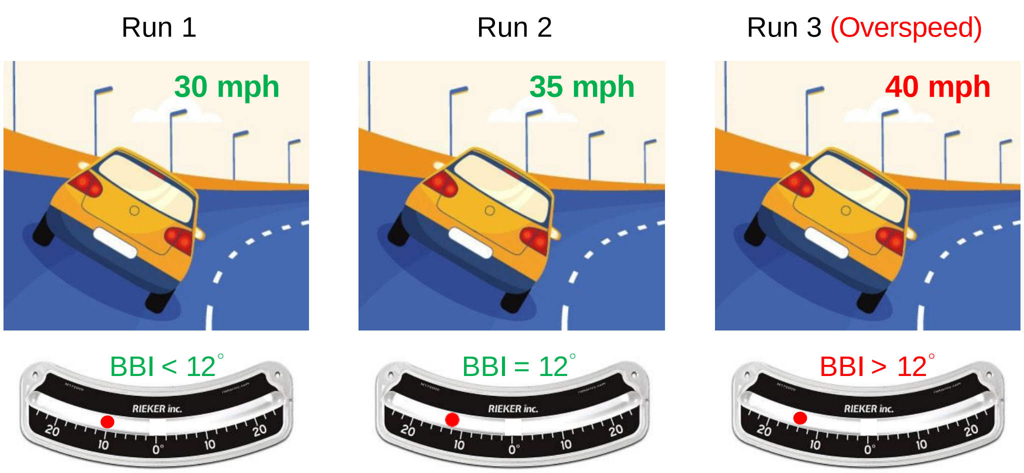


Figure 2. Graphs. Determine Curve Advisory Speed Using A Manual Ball Bank Device

The following steps briefly describes the testing procedures:

4) **First Trial:** Start the test at a predetermined speed that has been estimated by the in-field traffic engineer. Ensure the vehicle is correctly positioned in the lane and the speed is maintained consistently.

5) **Adjust Speed:** Increase the vehicle speed in subsequent test runs in regular increments, such as 5 mph. Monitor the ball-bank readings each time.

6) **Find the Ideal Speed:** Continue the tests until a speed is found that yields ball-bank readings that meet the Manual on Uniform Traffic Control Devices (MUTCD) criteria: 16 degrees for speeds of 20 mph or less, 14 degrees for speeds of 25 to 30 mph, and 12 degrees for speeds of 35 mph or higher. This speed will become the advisory speed for the curve.

After the advisory speed is determined using manual ball-bank devices, traffic engineers will follow MUTCD guidelines to designate sign locations and types.

CURVE SIGN DESIGN USING CARS

The Curve Advisory Reporting System (CARS) is a web tool developed by Rieker Inc. This tool allows a user to 1) upload and manage field data (e.g., GPS, BBI, and posted speed limit) collected using Rieker devices, 2) extract curve properties, including point of curve, point of tangent, curve radius, length, vertical grade, super elevation at the apex, etc., 3) determine the curve advisory speed using the curve properties extracted, and 4) determine curve warning sign per the MUTCD.

Designing curve signs using CARS greatly improves efficiency and accuracy much better than manual curve sign design by semi-automatically processing data with a web-based portal. However, CARS still requires a subjective and inconsistent manual and visual method to identify a curve's location, especially when fitting the curve by manually drawing a rectangle or a square. Additionally, determining the sign type, spacing, and location for one curve at a time is time-consuming, and visualizing and validating the curve sign placement for each curve individually is labor-intensive. Other challenges, such as limited identification capabilities for compound and spiral curves, limited design capabilities for warning signs on consecutive curves, and the lack of GIS output formats, are also summarized in the "Challenges" section of this chapter.

The following subsections describe the GDOT’s current processing practices for curve sign design using CARS, which include: 1) data collection, 2) determination of curves, 3) determination of curve advisory speeds, 4) determination of curve signs, and 5) report generation for the required curve signs.

Data Collection Using CARS

GDOT first collects the horizontal curve trajectory, inclination, and posted speed limit data simultaneously, using dedicated devices (model: the Rieker RDS7-GPS-PRO) as GPS trackers and electronic ball-bank indicators (BBIs, also known as inclinometers), and a tablet as a controller that is synchronized on GDOT's vehicles. As the yellow box in the **Figure 3** shows, the BBI is mounted on the vehicle’s dashboard, while the GPS antenna is fixed on the roof of the vehicle. The BBI is calibrated to zero level before starting the data collection. After the start of data collection, the GPS and BBI data is recorded automatically and continuously with certain frequencies (GPS: nearly 5 samples/second, BBI: nearly 14 samples/second). To improve GPS data collection and reduce the effects of drivers’ inconsistent steering behaviors, drivers were instructed to consistently drive no faster than 35 mph during the data collection. The posted speed limit is recorded by GDOT personnel, who use the tablet system at the beginning of their run or pull off the road to record the posted speed limit whenever it changes. After completing the run, the driver connects to a Wi-Fi site and uploads the data collected during their session to the CARS server. More details regarding the data collection set-up can be found in Rieker Inc.'s user manual (Rieker, 2018). In summary, data collection using Rieker device is far safer and more efficient than the previously used manual ball-bank device method.

Figure 3. Photo. Rieker Inc.'s Ball-bank Indicator and the Tablet Device Fitted into a Data Collection Vehicle (Green et al., 2016)

Determination of Curves Using CARS

The user selects the data collection session to load the GPS points of the vehicle trajectory onto a map interface. The user zooms and pans through the vehicle trajectory until they visually identify curves on the GPS trajectory. Users select two points on the map to draw a bounding box that encompasses an identified curve, as shown in **Figure 4**. The GPS points inside the bounding box are highlighted, and the curve is fit through these points.

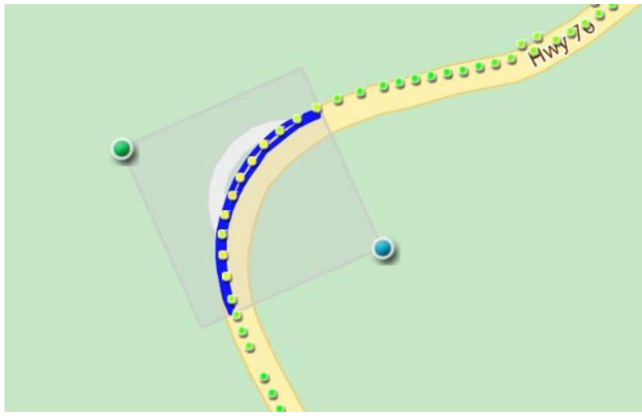


Figure 4. Screenshot. Bounding Box to Encompass a Curve

The goodness of fit is evaluated through a "GPS fit" function that quantifies the percentage of the fit (as shown in **Figure 5**). If the fit is 95% or greater, the curve is deemed acceptable; if the curve is less than 95%, the user redraws the bounding box until a 95% fit is achieved. The process is repeated for every curve in the data collection session. As pointed out by GDOT engineers, this curve identification process is very time-consuming.

a) GPS Points for Fitting

Passes

#	GPS Fit	Min. test speed	Turn Direction	Radius	Length	Nudge PC		Nudge PT		
1	98.2%	25.8 mph	Right	154 ft	274 ft	-	+	-	+	Delete
2	97.5%	25.6 mph	Left	155 ft	288 ft	-	+	-	+	Delete

b) GPS Fitting Panel

Figure 5. Screenshot and Table. Example of GPS Fit for the Two Passes on the Same Curve

Determination of Curve Advisory Speed Using CARS

CARS determines the recommended curve advisory speed based on the physical equation defining the motion of the vehicle on a curved roadway as described in the AASHTO Green Book (AASHTO, 2011). Before computing the curve advisory speed, CARS calculates the superelevation (e) based on the ball-bank indicator angle measured in the field; the radius of the curvature (R) is extracted from the curves determined by the previous step and the test speed. GPS data is collected at a frequency of 15 Hz, and inclinometer data is collected at a frequency of 10 Hz. CARS then uses this raw data to fit a model for the curve trajectory and the inclination along the curve. Next, using the radius of curvature (R), the maximum allowable side friction force (f_{mmmmmm}) and the calculated superelevation (e), the recommended curve advisory speed (V_{cmmcc}) is calculated using the following formula:

$$V_{cmmcc} = \sqrt{15R(f_{mmmmmm} + e)}$$

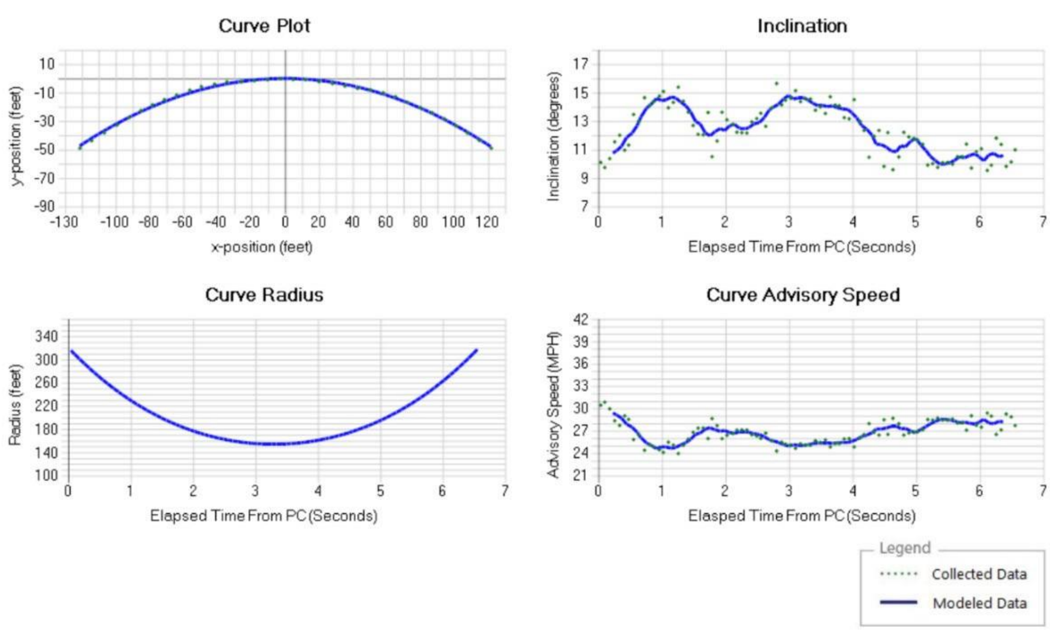


Figure 6. Screenshot. Example of Graphs Displaying the Computation of Advisory Speed for Selected Curves in the CARS Web Portal

Theoretical side friction at the point producing the minimum calculated advisory speed and generating the maximum side friction

Advisory Speed (mph)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Auto Side friction guideline (deg)	16	16	16	16	14	14	12	12	12	12	12	12	12	12
Max side friction (deg)	-3.5	-1.9	0.9	4.7	9.6	15.4	21.8	28.5	35.3	41.7	47.5	52.7	57.2	61.1

Radius: 173 ft; Super elevation: 7.1%

Figure 7. Table. Example of Determining Minimum Advisory Speed Based on Maximum Allowable Side Friction in the CARS Web Portal

For each data collection session, the users identify multiple curves to extract their properties (radius, length, superelevation, etc.) and determine a curve's recommended advisory speed. For each data session, a list of curves with their associated properties and the recommended advisory speed is stored in the CARS web portal. The summary of the items stored in the portal is shown in **Table 1**.

Table 1. CARS Web Portal Report on Curve Properties and Advisory Speed

S. No	Curve Property Name
1	Turn Direction (Left/Right)
2	Travel Direction (East, West, North, South)
3	Point of Curvature (Latitude, Longitude)
4	Point of Tangent (Latitude, Longitude)
5	GPS Fit (%)
6	Avg. test speed (mph)
7	Curve radius (feet)
8	Curve length (feet)
9	Deflection angle (degrees)
10	Curve Classification [class]
11	Super Elevation at apex (%)
12	Vertical Grade [class]
13	Min. calculated advisory speed (mph)
14	Recommended advisory speed (mph)

Determination of Curve Signs

The MUTCD requirements for the appropriate curve signs are automatically recommended by the CARS system. The recommendation system takes into account the curve details (point of curve, point of tangent, posted and recommended advisory speeds) to recommend the signs required on the curve. The output of the signs recommended includes sign type, its location (latitude and longitude), distance from the PC of the curve, direction of sign placement, and the location (which side of the road). It must be noted that the recommendation system only recommends “required” signs for the curve if the speed difference between the posted speed and the recommended advisory speed is greater than or equal to a threshold speed of 10 mph. Otherwise, it recommends only “optional” signs when the speed difference is below that threshold (Table 2C-5 of Horizontal Alignment Sign Selection, MUTCD).

Report Generation for the Required Curve Signs

The final output product is a report listing signs with their details (e.g., sign type, location, roadside, facing direction, etc.) and the curve names to which they belong. An example of the curve sign report is shown in **Figure 8**.

Inventory Number	Sign Code Requirement		Distance from PC	Corridor Name Last Inspection Note	Mile Marker	Latitude Longitude	Turn Direction	Travel Direction	Road Side	Facing Direction
SIGN-402972-ADVISORY-DIRECTION-L	W1-1L required		-200 ft			34.87951° -83.57804°	Left	South-West Decreasing	Right	Towards
SIGN-402972-ADVISORY-L	W13-1P-25mph required		-200 ft			34.87951° -83.57804°	Left	South-West Decreasing	Right	Towards
SIGN-402972-0 FT-L	W1-8L required		0 ft		0.00	34.87933° -83.57856°	Left	South-West Decreasing	Right	Towards
SIGN-402972-40 FT-L	W1-8L required		40 ft		0.00	34.87928° -83.57868°	Left	South-West Decreasing	Right	Towards
SIGN-402972-80 FT-L	W1-8L required		80 ft		0.00	34.87921° -83.57878°	Left	South-West Decreasing	Right	Towards
SIGN-402972-120 FT-L	W1-8L required		120 ft		0.00	34.87912° -83.57886°	Left	South-West Decreasing	Right	Towards
SIGN-402972-160 FT-L	W1-8L required		160 ft		0.00	34.87902° -83.57890°	Left	South-West Decreasing	Right	Towards
SIGN-402972-200 FT-L	W1-8L required		200 ft		0.00	34.87892° -83.57893°	Left	South-West Decreasing	Right	Towards
SIGN-402972-240 FT-L	W1-8L required		240 ft		0.00	34.87881° -83.57892°	Left	South-West Decreasing	Right	Towards
SIGN-402972-280 FT-L	W1-8L required		280 ft		0.00	34.87870° -83.57889°	Left	South-West Decreasing	Right	Towards

Figure 8. Table. Example of Generated Curve Sign Report

FIELD CURVE SAFETY ASSESSMENT

In addition to curve sign design using the CARS portal at office location, district maintenance crews also routinely drive over the roadways and make engineering judgments based on their knowledge of roadway guidelines (AASHTO, MUTCD, GDOT Signing and Marking Guide, etc.) to proactively assess safety concerns on curves (such as insufficient sight distance, lack of signs, poor pavement condition, missing striping, insufficient superelevation, etc.). GDOT also responds to citizen concerns (for example, people report frequent crashes on specific curves), investigates the locations, and identifies unsafe curves. After the maintenance crews identify the safety concerns on the curves, they coordinate with the GDOT Office of Traffic Operation. The Office of Traffic Operations investigates the issue and evaluates the suitability of signage to resolve the safety concern. Based on recommendations and analysis, new signage is approved for installation by the maintenance crews.

CHALLENGES

This section identifies the challenges of the current GDOT practice, which uses the CARS tool to comply with the MUTCD requirements curve warning signs. The next subsection will provide suggested improvements based on the identified challenges.

Challenges in Collecting CARS Data (GPS, BBI, Posted Speed Limit)

- **Constrained survey vehicle operating speed:** To enhance GPS data collection and to minimize inconsistent steering behavior, drivers were instructed to maintain a consistent speed of no more than 35 mph during data collection. Any data associated with driving speeds below 5 mph will be excluded. This means that data collection should occur at speeds ranging from 5 to 35 mph.
- **Limited data collection runs:** GDOT typically collects one run in each direction on most state-maintained routes due to the high cost and demand of data collection. However, the CARS method suggests collecting at least two runs in each direction for accurate results.
- **GPS disruptions and offsets:** The GPS connection may be lost in mountainous areas or during cloudy weather, causing data offset and requiring re-collection.
- **Incorrect BBI readings:** Driving over poor roads, conditions, such as potholes, and erratic steering, can affect BBI readings.
- **Data collection frequency differences:** GPS data is collected at around 5 times per second, BBI data is collected at around 14 times per second, and speed limit data is collected over several miles at varying intervals with three different devices. These data

sources need to be combined and matched by timestamps for curve identification and sign allocation.

Challenges of Using the CARS Portal for Data Management

- **Slow map loading operations:** The CARS portal, being a heavy web-based platform, takes a considerable amount of time to load map tiles for every zoom or pan action, which causes slow operations.

Challenges of Using the CARS Method for Generating Curve Inventory

- **Time-consuming curve selection process:** Selecting an ideal bounding box around a curve using the CARS tool can be a time-consuming process due to the need for multiple pan and zoom actions, as shown in Figure 9's subfigures a, b, and c (manual try-and-error operations of Zoom 1 and Zoom 2 before correct selection at Zoom 3).
- **Subjective PC and PT determination:** The accuracy of determining the PC and PT points using the CARS tool can be subjective due to variations in visual perception of the curve at different zoom levels.
- **Lengthy PC and PT determination process:** The CARS method includes GPS fitting and allows for adjusting the PC and PT points to improve the fit for the curve on the GPS trajectory. However, this process can be lengthy and requires about 3-5 minutes per curve to achieve adequate accuracy.
- **Limited compound and spiral curves identification capabilities:** The CARS method does not differentiate compound and spiral curves automatically. Users have to identify and split them subjectively and manually.

(a) Zoom 1 - initial bounding box

(b) Zoom 2 - modified bounding box

(c) Zoom 3 - ideal bounding box

Figure 9. Photos. Example of Panning and Zooming to Reach the Ideal Bounding Box

Challenges of Using the CARS Method for Curve Sign Design

- **Time-consuming process:** The CARS method requires a significant amount of time to process data for each curve individually to determine the type, spacing, and location of the curve warning signs.
- **Inefficient visualization:** The lack of a GIS format output that combines all designed curve signs makes it labor-intensive to visualize and validate the curve sign placement for each curve.
- **Limited design capabilities on consecutive curves:** The CARS tool is not equipped to design warning signs for consecutive curves, making manual operation necessary for winding and reverse curve sign design.

Challenges of Conducting Accurate In-field Curve Sign Assessments

- **Difficulty in performing comprehensive MUTCD assessment:** Maintenance crews may be able to identify missing signs on familiar roads, but it can be difficult for them to systematically and accurately evaluate each curve warning sign's compliance with MUTCD standards (such as advisory speed, sign type, and sign spacing). For example, measuring the distance between signs to check compliance with placement and spacing requirements is labor-intensive and time-consuming.

RECOMMENDATIONS FOR IMPROVING THE CURRENT PRACTICES

This subsection provides suggested improvements based on challenges identified from the above critical review of existing GDOT curve sign management practices. This research project will achieve some of the suggested improvements, not all. It is recommended that GDOT consider the remaining suggestions as future research needs. These suggested improvements are as follows:

- **Low-cost data collection method to establish a sustainable and systemic curve safety assessment:** It is recommended that the cost of data collection (currently done by Rieker devices) be reduced by introducing low-cost mobile devices (e.g., smartphones and dash cameras) and/or using intra-agency crowdsourcing techniques. Considering that the Rieker device is proprietary, it is recommended to explore non-proprietary alternatives, particularly these low-cost mobile devices.
- **GPS correction using roadway centerline geometry**: It is recommended to develop a method to correct/calibrate disrupted GPS or GPS with offsets using roadway centerline geometry data. Therefore, these GPS data can be salvaged to minimize data re-collection.
- **Confidence level of estimated advisory speed**: To enhance the reliability of the estimated advisory speed, a model that provides a confidence level should be developed. This confidence level, categorized as high, medium, or low, will serve as an indicator of the reliability of the computed advisory speed based on the data collected using either the

Rieker device or other low-cost mobile devices from multiple runs (i.e., repeated tests). This will provide a means for transportation agencies to differentiate good and bad data that can be used to target roadway segments (with low confidence) from which data must be re-collected. This will significantly improve the reliability of agencies' safety decision-making and the productivity of data re-collection.

- **Enhanced web-based data management tool with well-structured database and flexible data query capabilities:** It is recommended that an advanced web-based tool for managing data from low-cost mobile devices be developed. This tool would offer functionalities like data uploading, manipulation, and visualization (e.g., missing data, confidence level, curve geometry, locations). It would identify routes with sufficient data coverage and routes requiring more data collection, thereby optimizing the data collection process. Given the large data volume, a well-structured database is essential for efficient and flexible data querying and review. Flexible query features, such as click-based route selection or keyword searches (e.g., route name, county code), are recommended for accessing relevant data.
- **Automated MUTCD compliance checking system:** It is recommended to develop a low-cost, frequent, and automatic system that uses low-cost mobile devices with video log data capture capabilities (e.g., smartphones and dash cameras) and machine learning (ML) technologies to perform MUTCD compliance checking for curve warning signs. This system will include 1) roadway image/video data collection using low-cost mobile devices, 2) an automated curve sign detection model, 3) an automated MUTCD-compliant curve sign design (expected to be developed in this study) method, and 4) an automated MUTCD compliance checking model that compares designed curve sign with

real-world existing signs. Therefore, missing curve warning signs can be identified promptly by examining existing signs with designed MUTCD-compliant curve signs.

- **Refinement of MUTCD by incorporating reverse curve and winding road sign design procedures into MUTCD:** The current version of the MUTCD advises users to employ engineering judgment for determining curve warning sign designs on continuous curves; however, this method is subjective and lacks detailed specifications. To address this issue, it is recommended to include the procedures for designing reverse curve signs and winding road signs by grouping adjacent curves and analyzing their relationships, which have been developed in this study, into the MUTCD. This will provide more objective, consistent and comprehensive guidelines for the design of curve warning signs.
- **Enhanced comprehensive curve safety assessment and improvements using comprehensive risk factors:** It is recommended to use this project as a base to establish an enhanced curve safety assessment and improvement/treatment planning by comprehensively considering and examining the following risk factors: 1) BBI, 2) curve characteristics (e.g., curve radius, deviation angle, curve length), 3) vertical slope, 4) super elevation, 5) side friction, 6) estimated advisory speed, 7) speed difference between advisory speed and speed limit, etc. Besides curve sign compliance checking, other safety improvements, such as high-friction surface treatment, shoulder widening, curve realignment, rumble strips, guardrails, and line marking improvement, etc., can be applied using the extracted comprehensive risk factors that are previously difficult to obtain.

CHAPTER 3. ENHANCED MUTCD CURVE SIGN DESIGN

This chapter presents an enhanced automated method developed for generating inventories of curves and designing curve warning signs. Four modules are included in this developed method in addition to the field data collection (which has already been collected by GDOT using Rieker devices). The first module prepares CARS data (GPS, driving speed, BBI, and posted speed limit) by downloading the raw data from the CARS portal and preprocessing it using programs developed in this study. The second module measures and generates a curve inventory using an enhanced Curve Finder (developed by GT and refined in this study) with smoothed roadway centerline GIS data provided by GDOT. The third module determines the advisory speed through a combined consideration of the processed CARS data and the generated curve inventory. The fourth module determines the curve sign types and locations based on curve locations, adjacent curves, and their computed advisory speeds following the MUTCD. **Figure 10** presents a flowchart of all modules and data, and **Figure 11** presents the flowchart of detailed processing steps.

Thus, the Curve Finder tool and the curve sign design tool (already developed by GT in previous HFST projects) have been refined to consistently, accurately, and efficiently process GDOT's already collected CARS data from nearly 18,000 centerline miles of state-maintained routes. This will enhance GDOT's curve sign design practices and enable GDOT to meet MUTCD requirements.

This chapter will sequentially present details of modules and steps following the flowcharts shown in **Figure 10** and **Figure 11**.

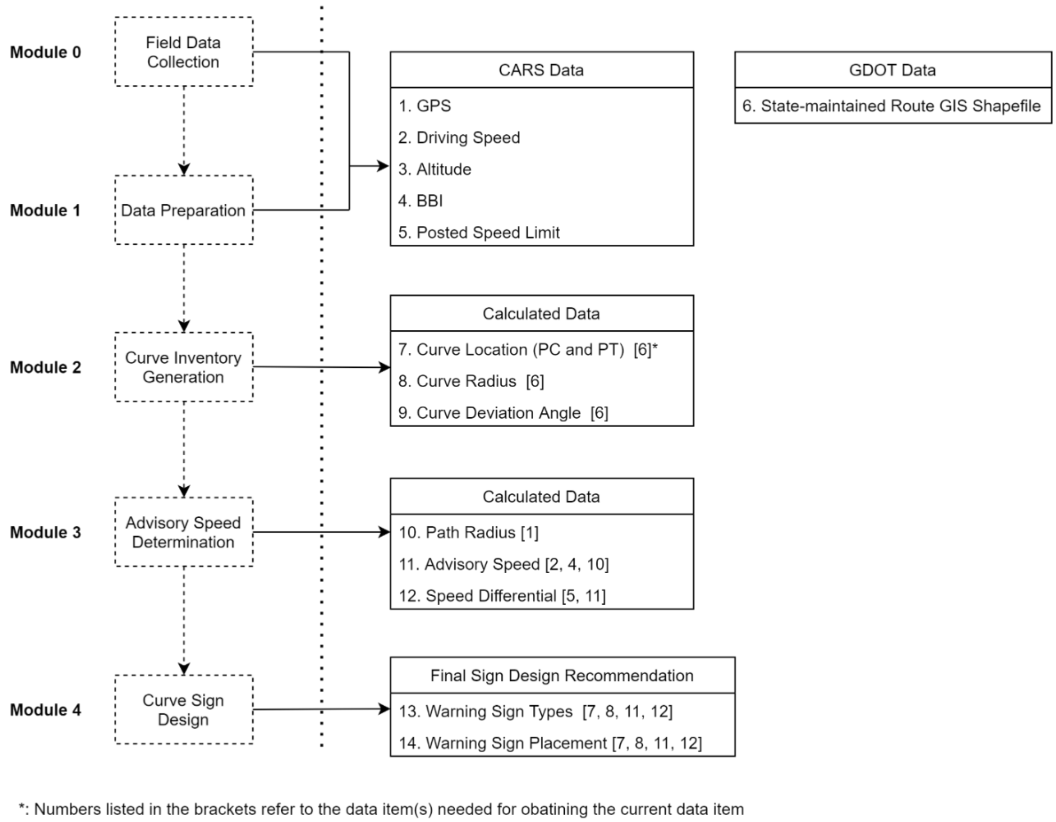


Figure 10. Chart. The Overall Flowchart of Modules and Data

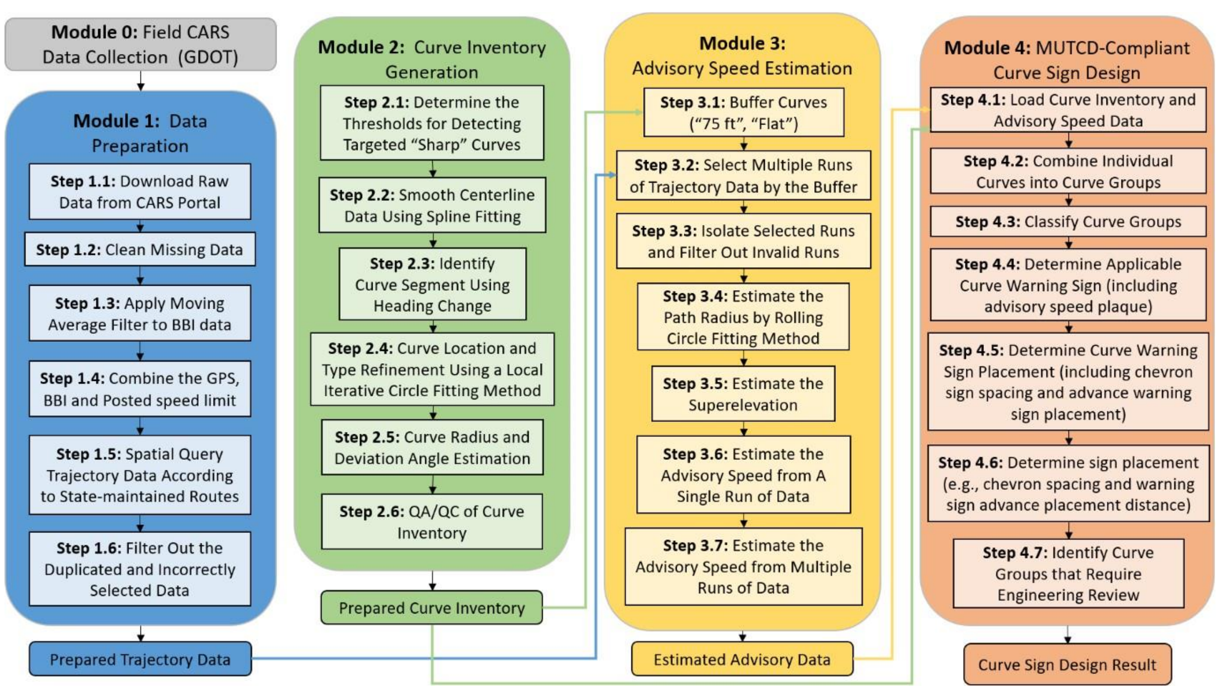


Figure 11. Chart. The Overall Flowchart of Data Processing Steps

MODULE 1: DATA PREPARATION

The challenges of using the already collected CARS raw data (e.g., GPS, BBI, speed limit data) for curve sign design is that the GPS, BBI and speed limit data are collected individually using different devices, and they are collected at different frequencies. The GPS data is collected at around 5 times per second, BBI data is collected at around 14 times per second, and speed limit data is collected at intervals of several miles with three different devices. These data must be combined based on the nearest timestamp before using them. Signal variation and discontinuity have been observed from raw data, so these data must be cleaned, filtered, and smoothed before using. This section will briefly introduce the developed procedures for preparing CARS data, which includes acquiring, cleaning, smoothing, combining, spatial querying, and filtering the data. The more detailed operating procedures, with sample data processing examples, have been documented in **Appendix A**. The processed data will be used following this project to support the tasks of curve inventory generation, advisory speed computation, and curve sign design. A flowchart for illustrating the procedures of CARS data preparation is shown in **Figure 12** .

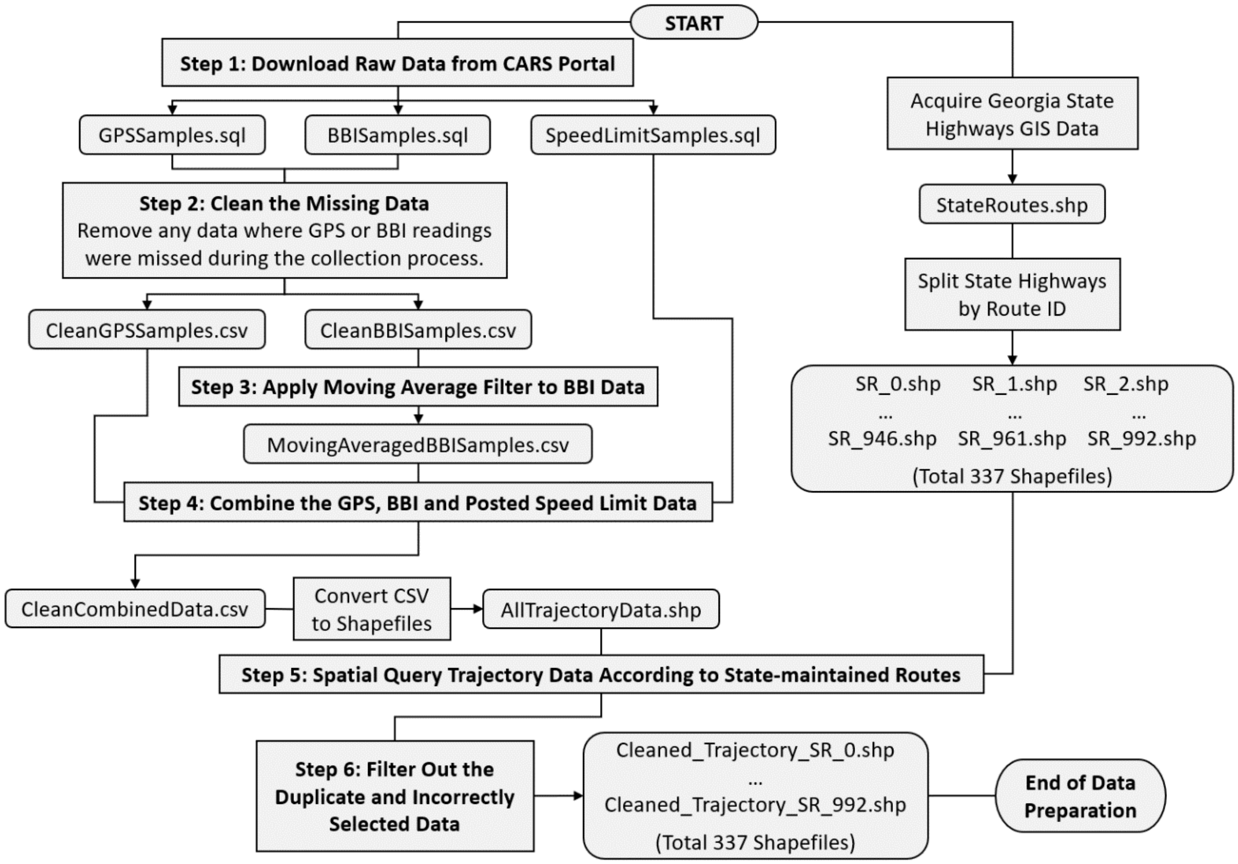


Figure 12. Flowchart. Procedures of CARS Data Preparation

Step 1: Download Raw Data from CARS Portal

This step involves downloading the GPS, BBI, and posted speed limit data in SQL format from the CARS portal. The SQL format is preferred because it provides greater precision by retaining more decimal digits of GPS locations. The downloaded SQL files are then converted to CSV files with unnecessary data trimmed for processing.

Step 2: Clean the Missing Data

This step involves removing any data points for which GPS or BBI readings were omitted during the collection process. Only a very small portion of the raw data contains missing GPS or BBI readings.

Step 3: Apply Moving Average Filter to BBI Data

In this step, a moving average filter (with a window size encompassing 7 spatial location points) is employed on the BBI data to mitigate erratic readings. **Figure 13** shows data before and after applying the moving average filter on a sample of BBI data.

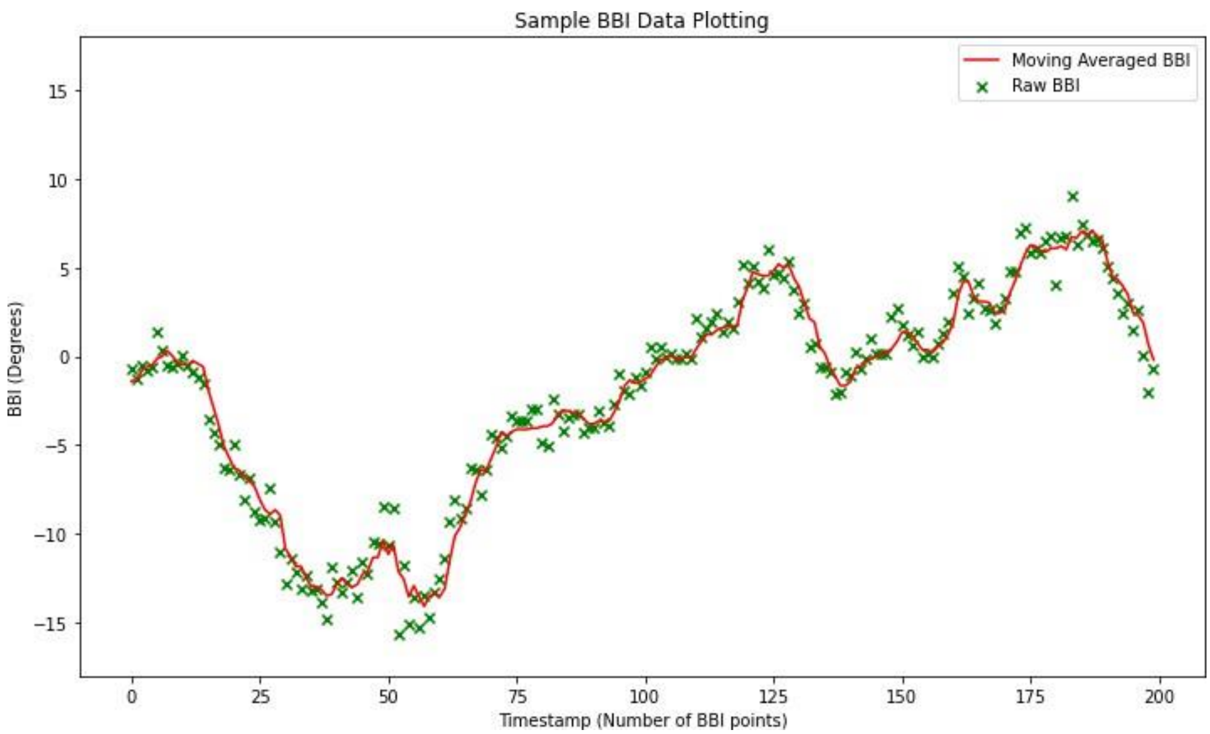


Figure 13. Graph. Moving Average Applied on a Sample BBI Data

Step 4: Combine the GPS, BBI and Posted Speed Limit Data

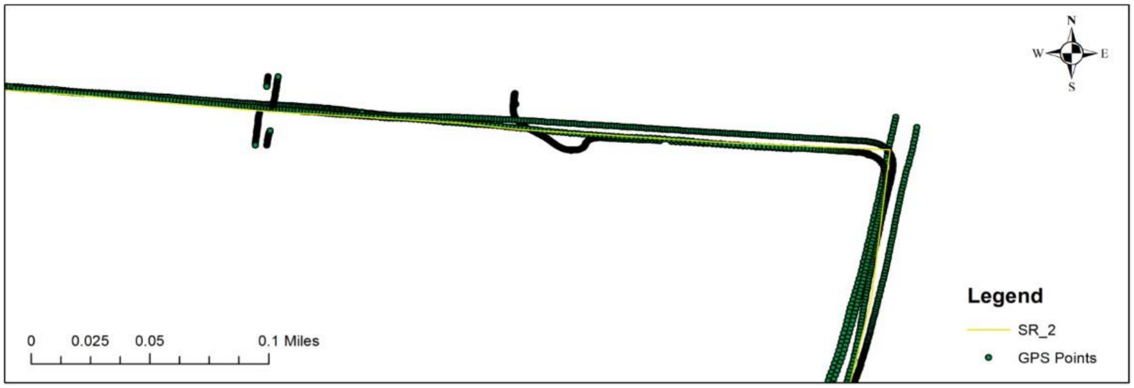
This step aligns the GPS data (collected at 5 Hz), BBI data (collected at 14 Hz), and posted speed limit data using the closest timestamps. The resulting combined data is referred to as "trajectory data" in subsequent steps. A voting method is used to deal with inconsistent posted speed values collected in multiple data collection runs, improving data reliability for curve sign design and data recording in the curve inventory. The voting method resolves inconsistent speed limit values collected over multiple runs by selecting the speed limit with the most votes as the final posted limit. In the event of a tie, the higher speed value is chosen.

Step 5: Spatial Query Trajectory Data According to State-maintained Routes

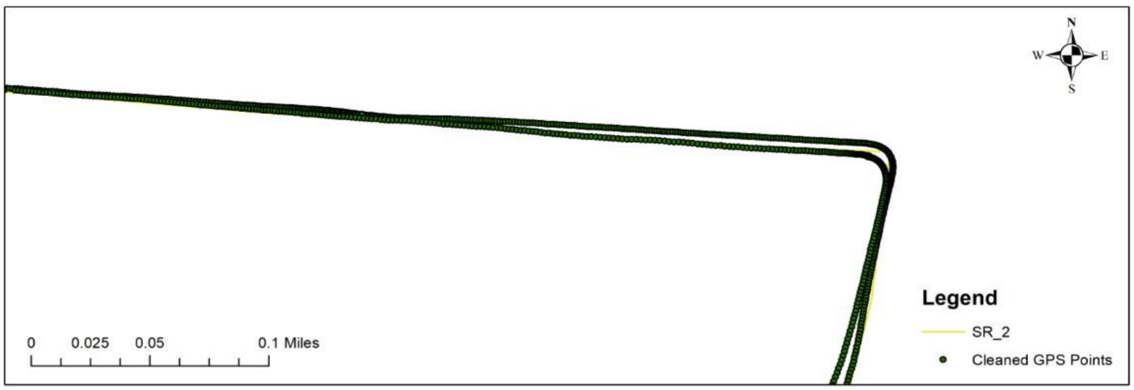
This step involves querying the trajectory data spatially to extract only the data points that fall within 75 ft of a state-maintained route. The queried data is saved as a GIS shapefile for each state-maintained roadway.

Step 6: Filter Out the Duplicate and Incorrectly Selected Data

This step filters out any data points that represent a crossing or overlapping situation, as well as any data segments that contain less than 300 GPS points. **Figure 14** shows a comparison of before and after filtering applied to selected trajectory data.



a) Before Filtering



b) After Filtering

Figure 14. Plots. Comparison Before and After Trajectory Data Filtering

MODULE 2: CURVE INVENTORY GENERATION

This study made significant efforts to improve the existing curve finder algorithm to minimize manual correction. The algorithm was enhanced in several key aspects:

- **Increased accuracy:** The curve detection accuracy was improved from around 80% to over 95%. This means that fewer manual efforts are needed to correct the results.
- **Faster computation:** The computation speed was increased by over 50%, making it faster to get results.
- **Reliability:** The algorithm's reliability was enhanced through conservatively detecting all potential curves, resulting in very low number of false negatives (i.e., missed curves). This means there is less need for concern when conducting manual QA/QC, especially when checking potential missing curves.
- **User control:** The algorithm now allows users to change parameters (maximum curve radius, minimum deviation angle, and allowed fitting errors) to detect targeted curves.
- **Improved maintenance:** The algorithm was transferred from C# to Python, making it easier to maintain and implement in different application environments.

To support these improvements, the following technical modifications were made:

- **Smoothing of roadway centerline data:** The roadway centerline data was smoothed using spline fitting for curve segment identification. This reduced the impact of noisy or inconsistent centerline data on curve identification.
- **Identification of curve segments based on heading change:** A step was added to identify curve segments based on the heading change. This significantly improved the

computation speed and reliability. The method quickly identifies curve segments, allowing computationally expensive iterations to apply only to identified curve segments instead of the entire roadway. This method is also more reliable as heading change is easy to compute and interpret.

- **Reduced number of thresholds:** The number of thresholds used in the curve detection model was reduced, increasing the adaptability to different scenarios. The enhanced Curve Finder now only has three thresholds with physical meanings: maximum radius (by ft), minimum deviation angle (by degree), and allowed maximum fitting errors (by ft).
- **Replacement of the Kasa circle fit:** The Kasa (1976) circle fit was replaced with the least square circle fit (Bullock, 2006), resolving the problem of instability in the Kasa fit on small deviation angle curve computations.
- **Local iterative curve fitting module:** An innovative local iterative curve fitting module was developed to deal with the relationship between curve length and fitting errors. This method identifies curves with maximum lengths that meet the allowed maximum fitting error in a curve segment. The module identifies the precise curve location (PC and PT) and considers nearby curve relations to determine curve types (simple or compound curves).

Subsections below will introduce the detailed steps and methods for generating curve inventory using the enhanced curve finder.

Step 1: Determine the Thresholds for Detecting Targeted "Sharp" Curves

The maximum curve radius and the minimum curve deviation angle are two required thresholds for detecting targeted “sharp” curves for curve warning sign design. To determine these thresholds, a preliminary study was conducted using data on SR-2, 11, 17, and 60 in District 1, as shown in **Appendix C**. The results indicate 2,500 ft as the minimum curve radius, 25 degrees as the maximum angle for simple curves, and 15 degrees for split curves (e.g., compound or spiral curves) can ensure curves with computed advisory speed 30 mph or lower can be captured. These thresholds were presented, discussed, and confirmed with GDOT engineers before being used to process the whole districts’ data.

Step 2: Smooth Centerline Data Using Spline Fitting

This step smooths the road GIS centerline or GPS trajectory data using a spline fitting function. The purpose of this step is to remove the outliers (e.g., signal errors or any spikes) from the raw centerline data because identifying the point of curve (PC) and point of tangent (PT) is highly dependent on the heading change. **Figure 15** shows a comparison of before and after centerline smoothing; with the blue line represents the line before smoothing and the red line represents the smoothed centerline. It is noticeable that the geometric shape of the curve does not change while the coarse vertices are smoothed. The smoothed centerline will be used only in the next step of curve segment identification.

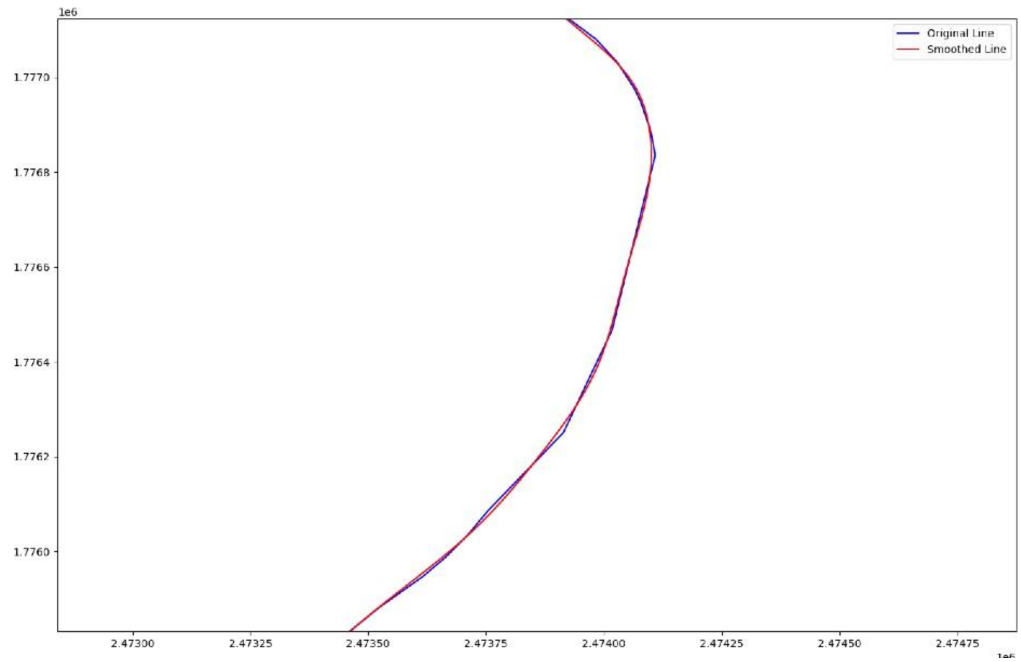
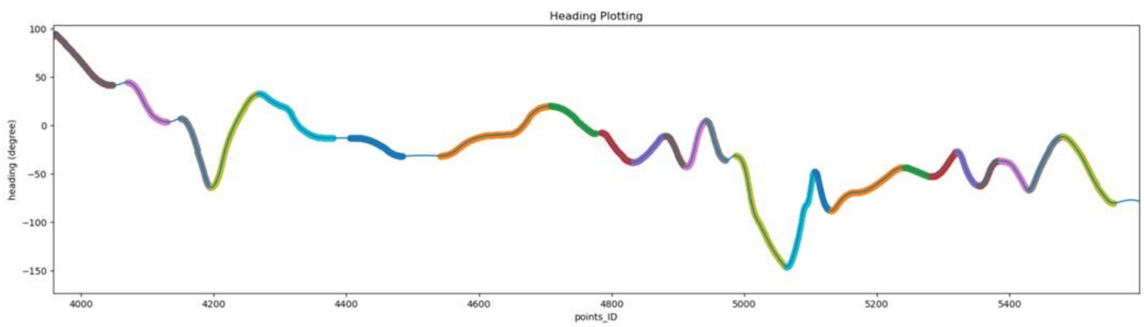


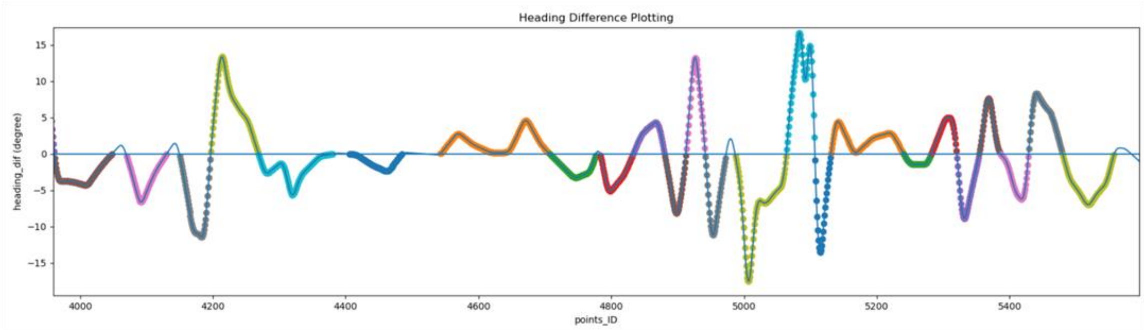
Figure 15. Plot. Comparison Before and After Centerline Smoothing

Step 3: Identify Curve Segment Using Heading Change

This step identifies the curve segments and tangent sections from the domain of heading change, as shown in following figure (bottom one). This method can be called the “bearing angle method.” **Figure 16 (a)** shows the heading and **Figure 16 (b)** shows the corresponded heading change. Curve segments are determined using the profile of heading change when it crosses the zero axis.



(a) Plot of Heading



(b) Plot of Heading Change

Figure 16. Plots. Heading and Heading Change for Identifying Curve Segments

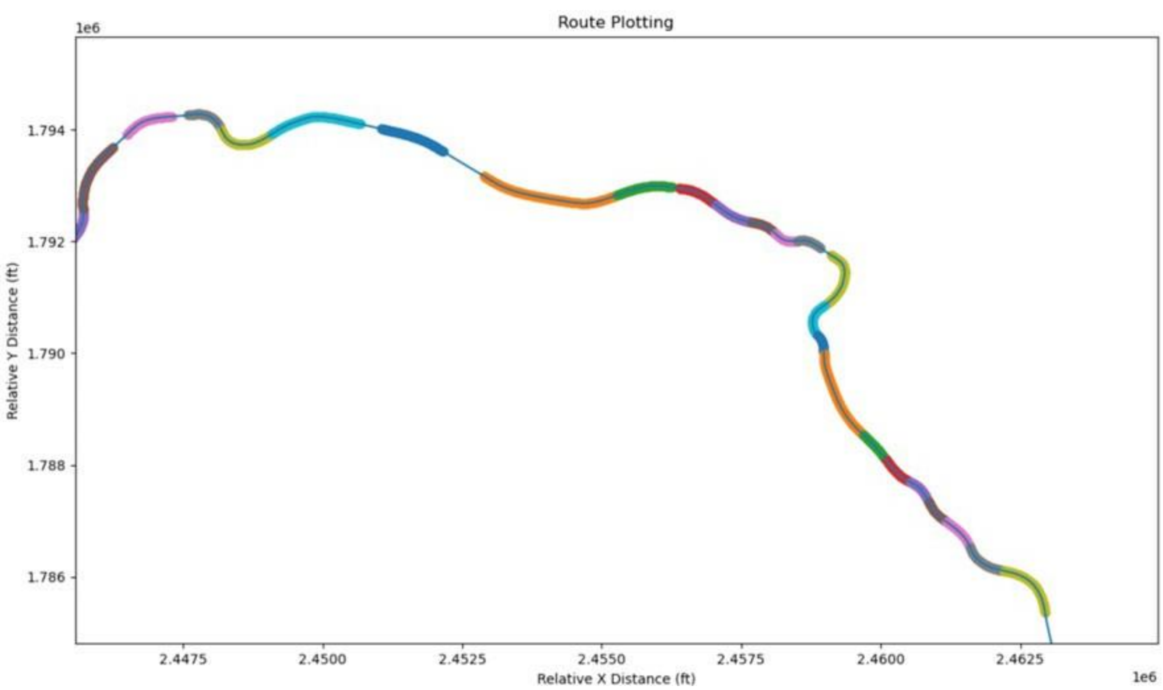


Figure 17. Plot. Identified Curve Segments

Step 4: Curve Location and Type Refinement Using a Local Iterative Circle Fitting Method

In the previous step, the curve segments were identified. To determine the accurate curve within each curve segment, the local iterative circle fitting method is employed. The term "accurate curve" refers to a curve with a constant radius. The circle fitting process is considered successful if the fitting error is within the specified threshold of 2 feet. This threshold of fitting error can be adjusted according to the user’s expectation. This method also splits complex curves (e.g., compound and spiral curves). In this study, the maximum radius is set as 2,500 ft, and the minimum deviation angle is set as 15 degrees for split curves and 25 degrees for simple curves. **Figure 18** plots the results of refined curves. Red fan shapes represent simple curves, and blue fan shapes represent the split curves. Split and simple curves in this study are only used to implement different thresholds of the deviation angle, as mentioned above. The capability of identifying split and simple curves in this enhanced curve finder has the potential to be applied for curve safety analysis or other research and application fields.

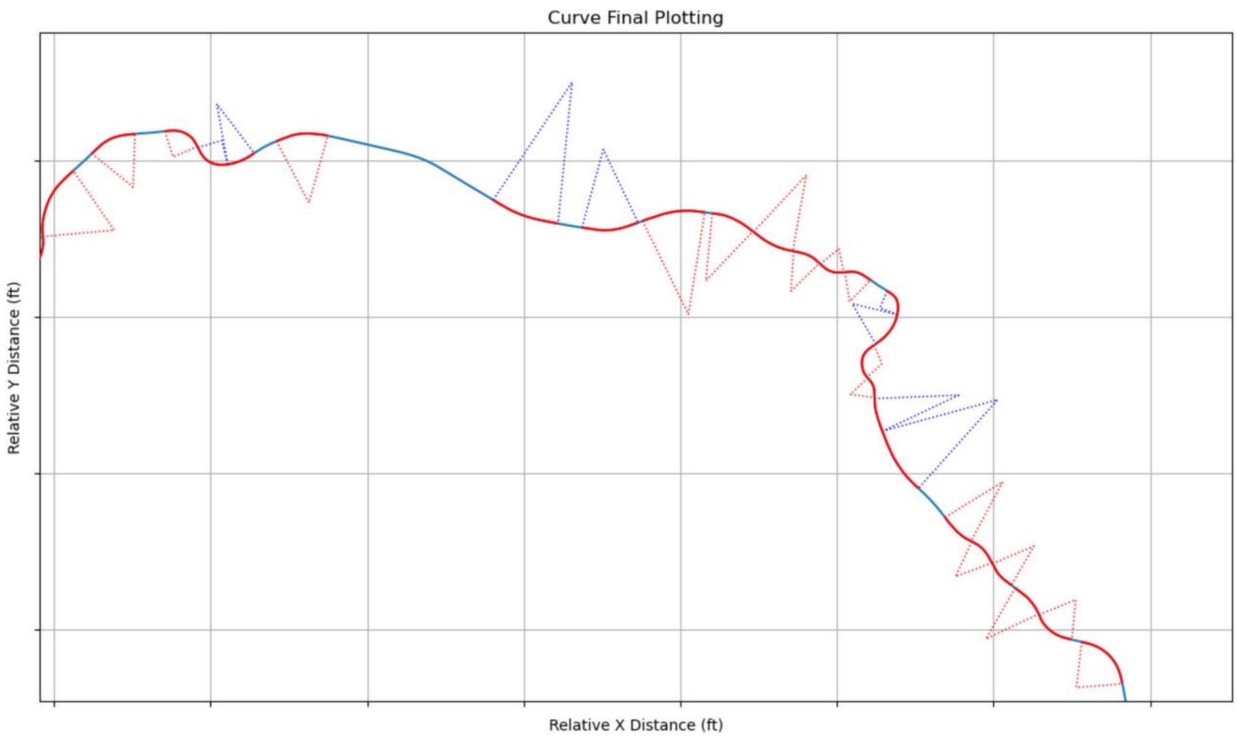


Figure 18. Plot. Results of Refined Curve Identification

Step 5: Curve Radius and Deviation Angle Estimation

After the curve locations are refined, the curve radius and the deviation angle are measured by applying a least square circle fitting algorithm between PC and PT.

Step 6: QA/QC of Curve Inventory

After the curve inventory is generated automatically via Curve Finder, this step performs a manual QA/QC operation to ensure the accuracy of the results. Through the QA/QC processing, researchers found this Curve Finder conservatively detects all potential curves, resulting in very low false negatives (i.e., missed curves). This means manual QA/QC doesn't need to consider adding a curve. In this study, QA/QC was performed once for a district (curve inventory combined in a district) using ArcGIS or QGIS tools.

MODULE 3: ADVISORY SPEED ESTIMATION

The challenge of accurately estimating advisory speeds in this project lies in the limited number of data collection runs. Typically, GDOT collects data from a single run in each direction on most state-maintained routes due to the high cost and demands of data collection. While CARS designs distinct advisory speeds and sign designs for different driving directions, the proposed method currently does not differentiate directions because of GDOT's approach. As a result, data collected from different directions can be leveraged for advisory speed estimation. The subsections below introduce the detailed steps and methods developed for estimating advisory speeds.

Step 1: Buffer Curves

A 75 ft flat buffer is made from each curve centerline for selecting multiple runs of trajectory data. The red lines in **Figure 19** represent the centerlines of curves, and the shallow green polygons in **Figure 19** represent the buffered curves. These buffers are used in the next step.

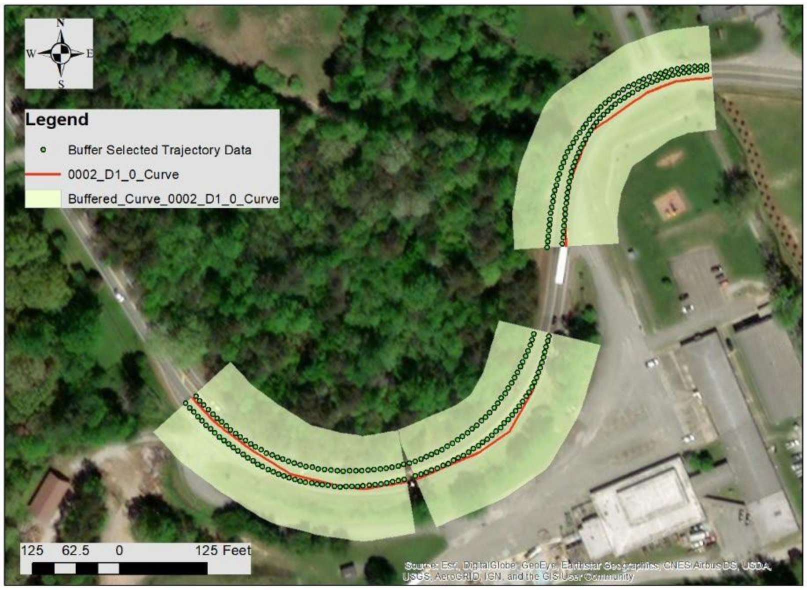


Figure 19. Plot. Buffered Curve with Spatial Selected Trajectory Data

Step 2: Select Multiple Runs of Trajectory Data by Buffered Curves

Spatial selection or query is used to select multiple runs of trajectory data using buffers generated in the previous step. Green dots in **Figure 19** represent selected trajectory data. Only these selected trajectory data are used in the following steps for estimating the curve advisory speed.

Step 3: Isolate Selected Runs and Filter Out Invalid Runs

This step splits multiple runs data by "FileID" and filters out invalid runs of data segments that have driving speeds lower than 5 mph or less than 15 points to eliminate stops or turns at intersections. In addition, GPS fitting and distribution are evaluated along the curve centerline to filter invalid data that might have data discontinuity and incomplete coverage.

Step 4: Estimate the Path Radius by Rolling Circle Fitting Method

Path radius is different than the curve radius. Path radius is estimated using the trajectory that the survey vehicle drives. The path radius is a dynamic changing value, so a rolling circle fitting method applied on a moving window is used to estimate the path radius. This study uses 1/3 of the total points in a data segment with a limit of minimal 9 points and maximal 50 points as the moving window size to roll the circle fittings. The rolling stride is one data point at a time. **Figure 20** shows an estimated dynamic path radius on sample data. The empty data on both sides of the plot are due to the rolling circle fitting. This phenomenon is like applying a non-filling moving average filter on a series of data points.

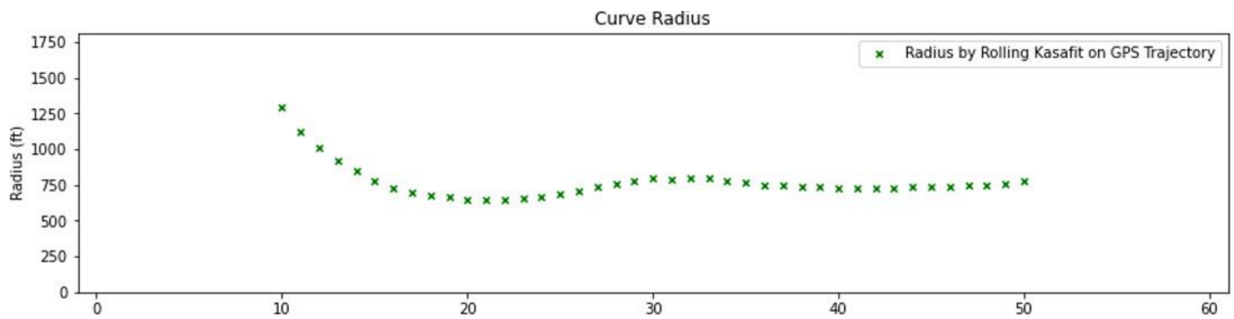


Figure 20. Plot. Estimated Dynamic Path Radius

Step 5: Estimate the Superelevation

The estimated superelevation is a dynamic value that changes along the movement of the survey vehicle. This superelevation is computed on each trajectory point with its corresponding path radius, driving speed, and BBI. **Equation (1)** below is used to compute the superelevation.

$$e(t_i) = 100 * \tan\left(\tan^{-1}\left(\frac{(1.47 * V(t_i))^2}{gR_p}\right) - \beta(t_i)\right) \quad (1)$$

Where,

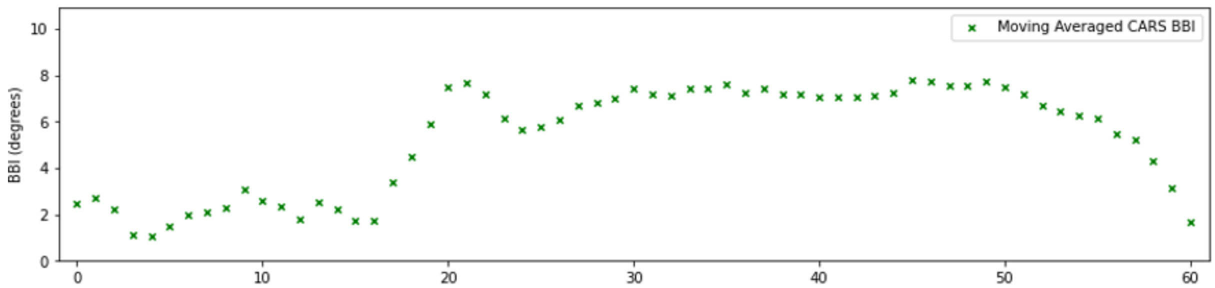
$e(t_i)$ = estimated superelevation at time i, percent

$R_p(t_i)$ = path radius at time i, ft

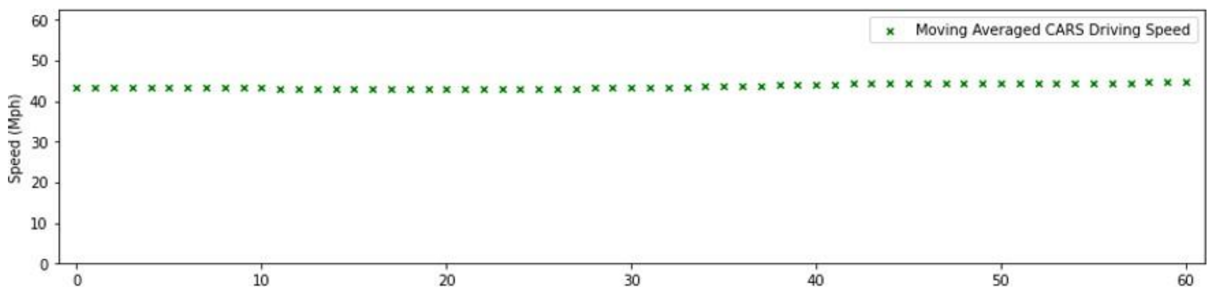
$V(t_i)$ = driving speed at time i, mph

$\beta(t_i)$ = measured BBI angle at time i, radians

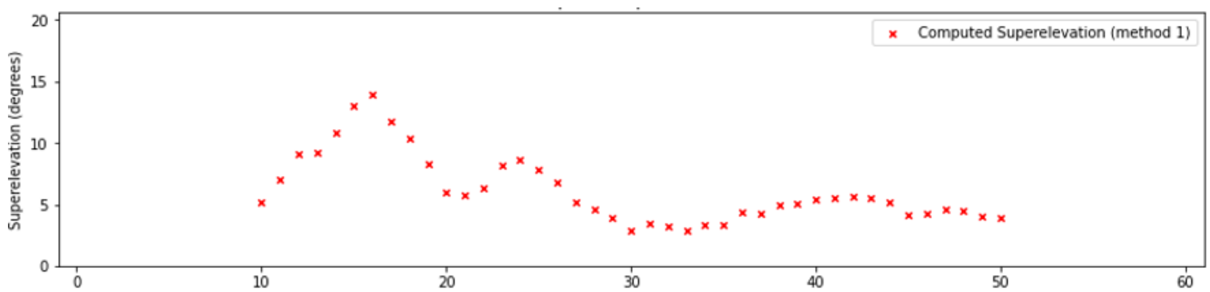
It is noticed that the moving averaged driving speed uses the same rolling window as the previous step. **Figure 21** shows the BBI and moving averaged driving speed in green. Combined with the path radius data generated in the last step, the estimated superelevation can be computed using the **Equation (1)**. **Figure 21** shows the computed superelevation in red.



(a) BBI



(b) Driving Speed (Moving Averaged)



(c) Estimated Superelevation

Figure 21. Plots. BBI, Driving Speed, and Estimated Superelevation

Step 6: Estimate the Advisory Speed from A Single Run of Data

Equation (2) shows the calculation for determining the curve advisory speed limit. This advisory speed limit is a changing value because the superelevation $\boldsymbol{ee}(\boldsymbol{tt}_{\boldsymbol{ii}})$ is changing along the curve. Note that curve radius $\boldsymbol{RR}_{\boldsymbol{cc}}$, not path radius $\boldsymbol{RR}_{\boldsymbol{pp}}$, is used in this calculation, as the advisory speed is dependent on the curve geometry, not a particular driver during a particular data collection run. The curve radius is extracted directly from the curve inventory generated in Module 2.

$$VV_{mmaaaa}(tt_{ii}) = \sqrt{15 * \left(\frac{ee(tt_{ii})}{100} + \tan(\beta\beta_{mmmmmm})\right) * RR_{cc}} \quad (2)$$

Where,

$\beta\beta_{mmmmmm}$ = maximum allowed BBI angle (12 degrees or 0.209 radians is used in Georgia), radian

$ee(tt_{ii})$ = estimated superelevation at time ii, percent

RR_{cc} = curve radius, ft

$VV_{mmaaaa}(tt_{ii})$ = estimated advisory speed limit at time ii, mph

Figure 22 shows a series of estimated advisory speed values on a curve that are computed using one run of trajectory points. The minimum value among these will be selected to represent the advisory speed for this curve as a conservative consideration.

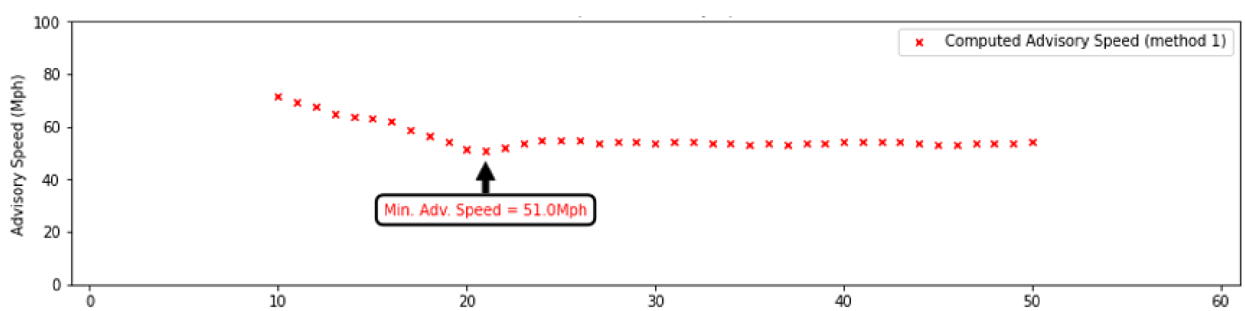


Figure 22. Plot. Estimated Advisory Speed for A Curve Using One Run of Data

Step 7: Estimate the Advisory Speed from Multiple Runs of Data

If multiple runs of data are collected on a curve, the method presented in the last step is used to estimate advisory speed in each run. Then, the maximum value among advisory speeds computed from multiple runs as the final estimated advisory speed is used. This is because survey vehicles may drive differently and may generate underestimated advisory speed limits; only perfect driving (smoothly follow the centerline of the curve) generates the most general advisory speed limit.

MODULE 4: MUTCD-COMPLIANT CURVE SIGN DESIGN

This module provides the technical requirements for curve sign design as defined by the MUTCD and the methodology developed in this study to implement these requirements. The procedures for generating MUTCD-compliant curve warning sign design are summarized in the flowcharts shown in **Figure 23** and **Figure 24**. Compared to the CARS method, the method developed in this study automatically considers adjacent curves for designing reverse and winding curve signs.

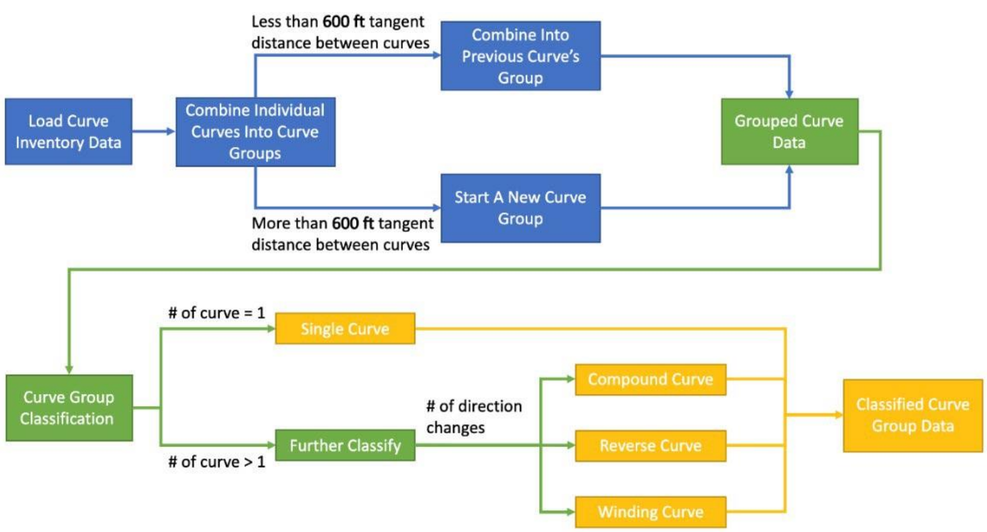


Figure 23. Flowchart. Procedures to Combine Individual Curves into Curve Groups and Classify the Curve Group (Compound, Reverse, or Winding Curves)

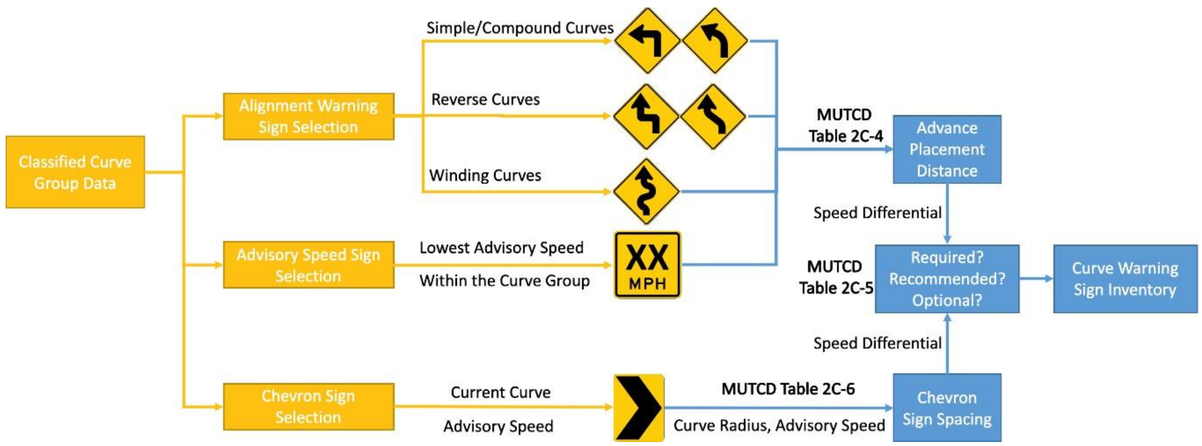


Figure 24. Flowchart. Procedures to Determine Curve Warning Sign and Its Placement

Step 1: Load Curve Inventory and Advisory Speed Data

The curve inventory data generated in Module 2 and estimated advisory speed data in Module 3 are used in this module to automatically generate the location and placement of MUTCD-compliant curve warning signs.

Step 2: Combine Individual Curves into Curve Groups

As curve warning signs are not required on curves where the computed advisory speed is higher than the posted speed limit, these curves can be viewed as non-critical curves when automatically generating the MUTCD-compliant curve warning sign designs. In this section, curves that have computed advisory speeds higher than the posted speed limits will be referred to as "non-critical curves"; curves that have computed advisory speeds lower than the posted speed limits will be referred to as "critical curves."

Step 3: Classify Curve Groups

The MUTCD allows the use of reverse (W1-3, W1-4) and winding (W1-5) signs to be used in place of individual curve signs (W1-1, W1-2) if the distance between curves is shorter than 600 ft. In the step of combining and classifying individual curves, critical curves that are spaced less than 600 ft apart will be combined into a curve group. Each curve group is classified into “compound”, “reverse”, or “winding” curves.

Step 4: Determine Applicable Curve Warning Sign (including advisory speed plaque)

The curve warning sign selection step determines the applicable warning signs for each curve/curve group. MUTCD Chapter 2C is followed for curve warning sign selection; the chapter first provides the principles of warning sign usage, which guides curve sign design engineering judgement. Signs should be used as sparingly as possible to avoid desensitizing drivers (2A.04), and signs should be applied uniformly according to road geometry to maintain a consistent message to drivers (2C.06). Next, the technical guidelines are presented. Curve sign design begins with the advisory speed computation, which should be performed through an engineering study using accepted practices, such as accelerometer, a design speed equation, or BBI. Next, the difference between the advisory speed and the posted speed limit is computed. This result is used to select appropriate horizontal alignment warning signs according to Table 2C-5 in **Figure 25**.

Type of Horizontal Alignment Sign	Difference Between Speed Limit and Advisory Speed				
	5 mph	10 mph	15 mph	20 mph	25 mph or more
Turn (W1-1), Curve (W1-2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W1-10) (see Section 2C.07 to determine which sign to use)	Recommended	Required	Required	Required	Required
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required	Required
Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required	Required
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required	Required

Figure 25. Table. Horizontal Alignment Sign Selection (Table 2C-5 in MUTCD)

By default, the warning sign should be a curve sign, W1-2. If the advisory speed of the curve is 30 mph or less, a turn sign, W1-1, is used. If there are two curves in opposite directions with 600 feet or less of tangent between them, a reverse curve sign, W1-4, or the reverse turn sign, W1-3, is used instead of two curve signs or two turn signs. If there are three or more curves in opposite directions, a winding road sign, W1-5, is used instead of multiple curve or turn signs. For extended sections of winding roads, a supplemental distance plaque, W7-3aP, may be used (XX feet to indicate the length of the winding section). For curves with a deviation angle of 135 degrees or more, a hairpin curve sign, W1-11, is used. A one-direction large arrow sign, W1-6, may be used as a supplement or alternative to chevrons. It may also be used to supplement turn and reverse turn signs. Advisory speed plaques may be used to supplement any warning sign, but they should not be used separately. The table below summarizes the criteria for sign selection.

Sign Type (with L or R for curve direction)	Sign Selection Criteria								
	Optional	**Recommended**	**Required**	**Advisory Speed**	**Length of curve**	**Deviation angle**	**Cross Slope**	**Reverse curve**	**Winding/ Continuous curve**
w1-1		S_diff <=5	S_diff >5	<=30		<135		FALSE	FALSE
w1-2		S_diff <=5	S_diff >5	>30		<135		FALSE	FALSE
w1-3		S_diff <=5	S_diff >5	<=30		<135		TRUE	FALSE
w1-4		S_diff <=5	S_diff >5	>30		<135		TRUE	FALSE
w1-5		S_diff <=5	S_diff >5			<135		FALSE	TRUE
w1-6	S_diff <=5	5< S_diff <=10	S_diff >10						
w1-8	S_diff <=5	5< S_diff <=10	S_diff >10						
w1-11		S_diff <=5	S_diff >5			<270, >=135		FALSE	FALSE
w1-13		S_diff <=5	S_diff >5				>=10		
w1-15		S_diff <=5	S_diff >5			~>=270		FALSE	FALSE
w7-3aP					>=xx miles				
w13-1p		S_diff <=5	S_diff >5						

Speed differential, **S_diff = Posted speed – Curve advisory speed**

Figure 26. Table. Sign Selection Criteria (*MUTCD*)

Step 5: Determine Curve Warning Sign Placement (including chevron sign spacing and advance warning sign placement)

Once the appropriate warning sign is selected, it is necessary to determine its placement relative to the curve. The difference between the advisory speed and posted speed limit should be used according to **Table 2**, which is refined from Table 2C-4 in the MUTCD, to determine this distance.

Table 2. Guidelines for Advance Placement of Warning Signs (refined from Table 2C-4 in MUTCD)

Posted Speed (mph)	Advance Placement Distance (ft)										
	Speed Differential to Advisory Speed (mph)										
	0	5	10	15	20	25	30	35	40	45	50
20	100										
25	100										
30	100										
35	100	100	100								
40	125	100	100	100	100						
45	175	150	125	125	100	100	100				
50	250	200	200	200	175	150	125	100	100		
55	325	275	275	275	225	225	200	150	125	100	
60	400	375	350	350	325	300	275	250	200	150	100
65	475	450	450	425	400	400	350	325	275	225	200
70	550	550	525	525	500	475	450	425	375	325	275
75	650	650	625	625	600	575	550	500	475	425	375

Finally, the chevron sign placement should be designed. Chevrons are installed on the outside of the curve. The spacing between chevrons should be determined using the advisory speed and curve radius according to Table 2C-6, shown in **Figure 27**.

Advisory Speed	Curve Radius	Sign Spacing
15 mph or less	Less than 200 feet	40 feet
20 to 30 mph	200 to 400 feet	80 feet
35 to 45 mph	401 to 700 feet	120 feet
50 to 60 mph	701 to 1,250 feet	160 feet
More than 60 mph	More than 1,250 feet	200 feet

Figure 27. Table. Typical Spacing of Chevron Alignment Signs on Horizontal Curves (Table 2C-6 in MUTCD)

Step 6: Identify Curve Groups that Require Engineering Review

One particular issue that may arise by grouping individual curves that are 600 ft apart is that individual curves with very different advisory speeds may be included in the same group. Since only one advisory speed plaque can be used at the beginning or the end of each curve group, only the lowest advisory speed of the curve group can be shown. As this may lead to distrust in drivers of traffic control devices, these curve groups might require an engineering review to determine if the curves should be grouped or signed differently. In this step, curve groups with differences between the highest advisory speed and the lowest advisory speed larger than 5 MPH are flagged to provide an easy way to be filtered for engineering review. Each flagged curve group is also categorized based on the extent of an advisory speed difference. “ASD_5+” is used to flag a curve group with an advisory speed difference of between 5-10 MPH, “ASD_10+” is used to flag curve group with advisory speed difference between 10-15 MPH, and “ASD_15+” is used to flag a curve group with an advisory speed difference more than 15 MPH.

CHAPTER 4. VALIDATION OF RESULTS

This chapter validates the developed GT method by comparing it with CARS on selected curves with diverse curve characteristics. There are three stages in the process of validation: 1) curve inventory generation, 2) advisory speed estimation, 3) curve sign design. The purpose of the validation is to build confidence that the developed method can achieve the same results/performance as CARS (the baseline method). In addition, new features (such as compound curve identification and, winding and reverse curve sign design) developed by GT are also compared with CARS to demonstrate the extra contributions that the GT solution made; the results prove it is more robust than the current CARS method.

VALIDATION OF CURVE INVENTORY GENERATION

Before discussing the comparison of curve inventory generation results, a comparison is made between the GT and CARS methods to recap their differences. This comparison is useful for understanding the differences that may be found in the later comparison of curve inventories generated from these two methods. **Table 3** summarizes the differences between the GT curve finder and the CARS method. Due to the limitations of the CARS method, which does not handle compound curves, only simple curves are selected and used in the validation. Additionally, because the CARS method does not detect curve locations (PC and PT) automatically, the curve locations detected in the GT curve finder are referred to and manually inputted into the CARS method for an “apple-to-apple” comparison. It should be noted that the curve locations in CARS might be adjusted manually if they do not meet the 95% GPS fitting requirement.

To ensure a comprehensive and effective validation of the developed method's data, 27 curves with diverse curve characteristics (e.g., different curve radii, deviation angles, and lengths) were selected on SR-2, 11, and 17 in GDOT District 1. The selected range of characteristics of the selected curves are described as follows:

- Curve radius ranges from 70 to 2,500 ft.
- Deviation angle ranges from 15 to 180 degrees.
- Curve length ranges from 250 to 1,800 ft.

Table 3. Differences Between GT Curve Finder and CARS Methods

GT Curve Finder	CARS
• Automatically identifies curve location (PT and PC)	• Manually selects and adjusts curve location to meet 95% GPS fitting requirement
• Automatically splits compound curves and estimates characteristics of split curves individually	• Does not handle compound curves because they may fail to meet the 95% GPS fitting requirement in CARS
• Uses GDOT-provided roadway centerline for curve detection and curve characteristics (i.e., curve radius, deviation angle, and curve length) estimation	• Uses GPS data (collected by survey vehicles) for curve characteristics estimation; uses the best GPS fitting run if multiple runs of data are collected

The validation of the curve inventory generation is made by comparing curve radii estimated from the GT curve finder and the CARS method on selected validation curves. **Table 4** lists curve characteristics (i.e., curve radius, deviation angle, and curve length) estimated from both methods for these curves. Curve radii are shown in bold fonts for comparison, while deviation angles and curve lengths are just for describing these curves. Curve radius is critical because it will be used for advisory speed estimation, which will ultimately determine curve sign design. Besides describing curves in the curve inventory, deviation angle and curve length can, potentially, be used for curve safety analysis.

To visualize the comparison of curve radii, **Figure 28** and **Figure 29** are plotted. **Figure 28** shows the absolute difference in a histogram along with a cumulative percentile. From this figure, it is apparent that curve radii estimated with the GT curve finder are similar to the curve radii obtained using the CARS method. For nearly half of the curves (48 percent), the difference between the curve radius from the GT curve finder and the CARS method was within 50 ft; for 78 percent of the curves, the difference was within 100 ft; and for 93 percent of the curves, the difference was within 200 ft. **Figure 29** shows the scatter plot that displays the curve radii estimated from the GT curve finder method and the CARS method. If the two methods yielded the same advisory speed for all curves, they would be perfectly correlated. As such, all points would fall along the $yy = xx$ line, which is the orange diagonal line in the figure. A trend/regression line using slope and intercept from the regression equation, and R-square from correlation analysis was added for objective comparison. With slope, intercept, and R-square closer to 1, 0, and 1, respectively, curve radii from two methods are closer. Results of 0.93 (slope), 1.32 (intercept), and 0.98 (R-square) indicate the radii from the two methods are close. This demonstrates the promising results of the curve radius from the GT curve finder.

The differences in results between the GT and CARS methods might be due to the following reasons:

- Because the driving trajectory (used in CARS) may slightly deviate from the exact shape of the centerline (used in the GT curve finder), the curve geometry may appear to be different between these two data sources.
- Because the curves in CARS are manually selected; the bounds of the curve (PC and PT) may be different, changing the curve length and deviation angle.

To visualize these differences, **Table 5** plots some selected curves with their geometries overlaid onto maps.

Table 4. Comparison of Generated Curve Inventory Between GT and CARS

Route	Curve ID	GT			CARS		
		Radius (ft)	Deviation Angle (degree)	Length (ft)	Radius (ft)	Deviation Angle (degree)	Length (ft)
SR-2	1	**1447**	58	1455	**1326**	37	925
	3	**2391**	28	1185	**2008**	47	1830
	4	**1019**	44	781	**938**	30	521
	7	**2408**	42	1785	**2395**	19	807
	10	**933**	78	1276	**841**	55	939
	12*	**773**	67	900	**717**	44	607
	23	**1228**	38	811	**1144**	24	510
	44	**1020**	39	690	**960**	28	502
	79*	**213**	89	329	**184**	82	264
	95	**1041**	42	765	**927**	24	415
	122	**1001**	62	1080	**1005**	34	631
	127	**1218**	40	855	**1110**	18	370
	128	**1017**	41	735	**955**	26	457
	133	**742**	45	585	**748**	20	275
SR-11	67	**1510**	38	991	**1508**	28	783
	33	**846**	45	661	**789**	38	570
	107*	**827**	52	750	**828**	39	605
	120	**922**	37	599	**629**	30	354
	143*	**115**	142	283	**129**	89	294
SR-17	37	**1439**	42	1050	**1383**	26	645
	63	**729**	48	615	**570**	24	251
	69*	**628**	37	405	**626**	28	323
	73	**979**	28	480	**934**	27	465
	83*	**87**	178	268	**72**	106	238
	86	**101**	153	272	**75**	108	265
	89	**77**	157	207	**79**	73	131
	90	**111**	124	241	**136**	60	171

* Note: These curves are selected for visual comparison in **Table 5**.

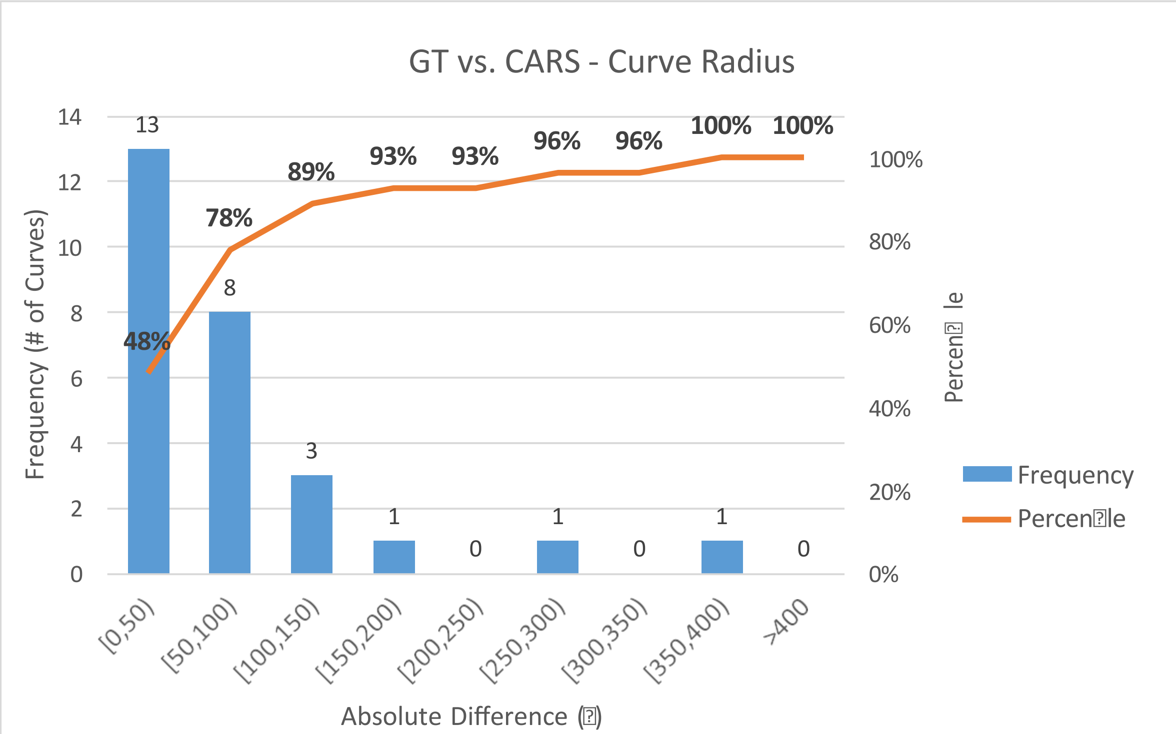


Figure 28. Graph. Histogram and Percentile for Curve Radii Comparison

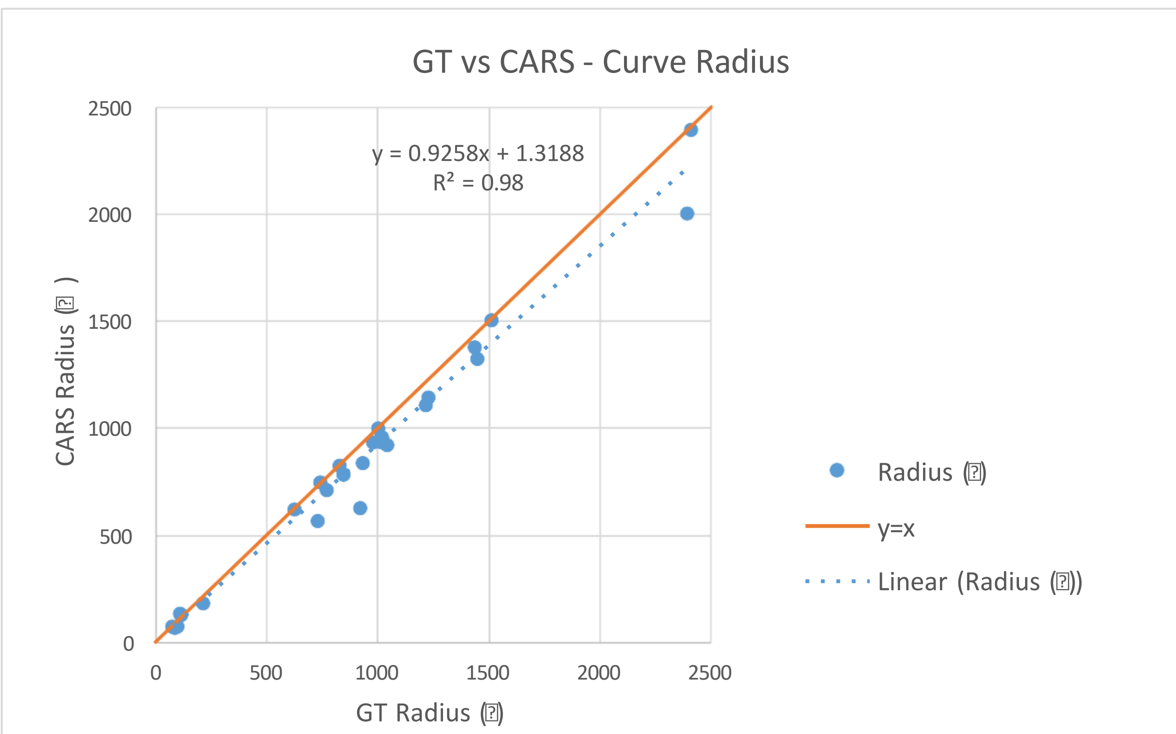
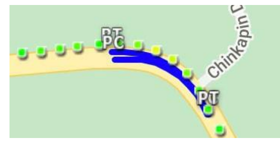
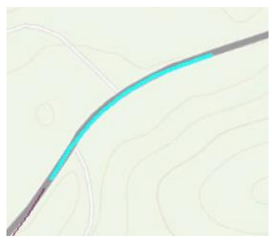
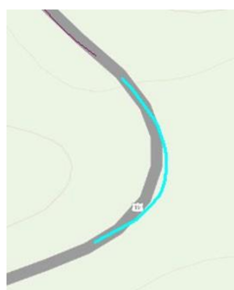
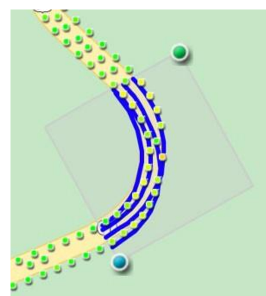
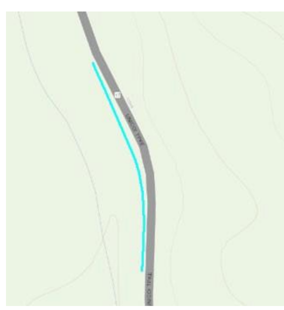
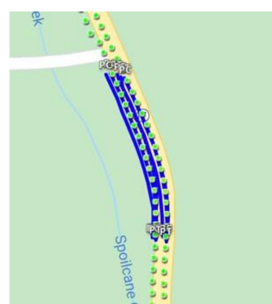
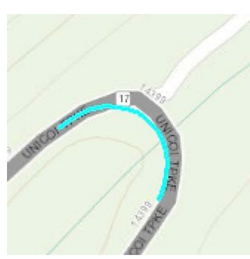


Figure 29. Graph. Scatter Plot for Curve Radii Comparison

Table 5. Visual Comparison of Identified Curves Between GT and CARS Methods

Route	Curve ID	GT Curve Finder	CARS
SR-2	12		
	79		
SR-11	107		
	143		
SR-17	69		
	83		

VALIDATION OF ADVISORY SPEED ESTIMATION

Both the GT and CARS methods utilize an equation derived from the laws of mechanics, which describes the relationship between superelevation, side friction factor, and radius curvature, to estimate advisory speed (Green et al., 2016; Milstead et al., 2011). However, they may differ in data preprocessing techniques, including smoothing methods for BBI and driving speed, and path and curve radius estimation. Furthermore, CARS has different advisory speeds for different driving directions, but currently, the GT method does not differentiate driving direction. This is because GDOT typically only collects one run in each driving direction.

Curves with diverse characteristics are selected to validate the advisory speed estimation, including different curve radius, deviation angles, and types (e.g., simple, compound, reverse). **Table 6** shows the selected curves with descriptions of their main characteristics. The reverse and compound curves are split into multiple individual curves for comparison due to the limited capability of the CARS method to handle curves other than simple curves.

Table 7 shows the detailed characteristics of each curve and the estimated advisory speeds from both the GT and CARS methods. Their differences are computed and recorded in the last column. This "difference" column is used to plot **Figure 31**, which shows the absolute difference in a histogram along with a cumulative percentile. From this figure, it is apparent that advisory speeds estimated with the GT method are similar to advisory speeds obtained using the CARS method. For 37 percent of the curves, the GT and CARS methods returned the same advisory speed; for 81 percent of curves the difference was within 1 mph, and for all curves, the difference was within 5 mph. Similar to the curve radii comparison, a scatter plot, along with regression analysis, was made to compare the advisory speed. The results for a slope of 1.0094, an intercept of -0.4175, and an R-square of 0.9932 indicate advisory speeds from two methods are very close. This further demonstrates the promising results of obtaining the advisory speed from GT method.

Table 6. Selected Curves for Validating Advisory Speed Estimation

Route	Curve ID	Characteristics
SR-2	12	High Advisory Speed
	18	Reverse Curve
	19	
	39	Simple Curve
	47	Simple Curve
	57	Small Radius
	62	Compound Curve
	63	
	70	Low Advisory Speed
	72	Low BBI
	102	High Deviation Angle
	104	Small Radius
SR-11	20	Low Deviation Angle
	203	Large Radius
	254	Small Radius
SR-17	42	Large Radius
	60	High Deviation Angle
	63	Small Radius
	64	Low Advisory Speed

Table 7. Comparison of Estimated Advisory Between GT and CARS Methods

Route	Curve ID	GT Centerline Radius (ft)	GT GPS Radius (ft)	CARS Radius (ft)	Max BBI (degree)	GT Advisory Speed (mph)	CARS Advisory Speed (mph)	Difference (mph)
SR-2	1	1447	1472	1326	5.2	**70**	**70**	**0**
	3	2391	2608	2008	2.6	**87**	**82**	**5**
	4	1019	1073	938	5.4	**59**	**60**	**1**
	7	2408	2404	2395	2.4	**87**	**91**	**4**
	10	933	918	841	8.7	**56**	**55**	**1**
	12	773	774	717	7.9	**52**	**51**	**1**
	23	1228	1278	1144	3.3	**63**	**63**	**0**
	44	1020	1046	960	3.6	**60**	**59**	**1**
	79	213	205	184	11.4	**29**	**29**	**0**
	95	1041	1107	927	5.4	**57**	**58**	**1**
	122	1001	1070	1005	3.1	**63**	**64**	**1**
	127	1218	1350	1110	5.0	**66**	**66**	**0**
	128	1017	1085	955	3.5	**62**	**61**	**1**
	133	742	838	748	5.1	**52**	**53**	**1**
SR-11	67	1510	1021	1508	4.4	**73**	**76**	**3**
	33	846	858	789	6.5	**57**	**57**	**0**
	107	827	860	828	8.8	**53**	**53**	**0**
	120	922	920	629	7.2	**47**	**48**	**1**
	143	115	138	129	16.9	**26**	**25**	**1**
SR-17	37	1439	1454	1383	4.4	**69**	**69**	**0**
	63	729	707	570	4.5	**49**	**47**	**2**
	69	628	563	626	8.3	**41**	**42**	**1**
	73	979	1077	934	3.0	**60**	**62**	**2**
	83	87	89	72	10.9	**18**	**18**	**0**
	86	101	103	75	15.8	**19**	**18**	**1**
	89	77	93	79	11.3	**20**	**20**	**0**
	90	111	176	136	9.5	**20**	**20**	**0**

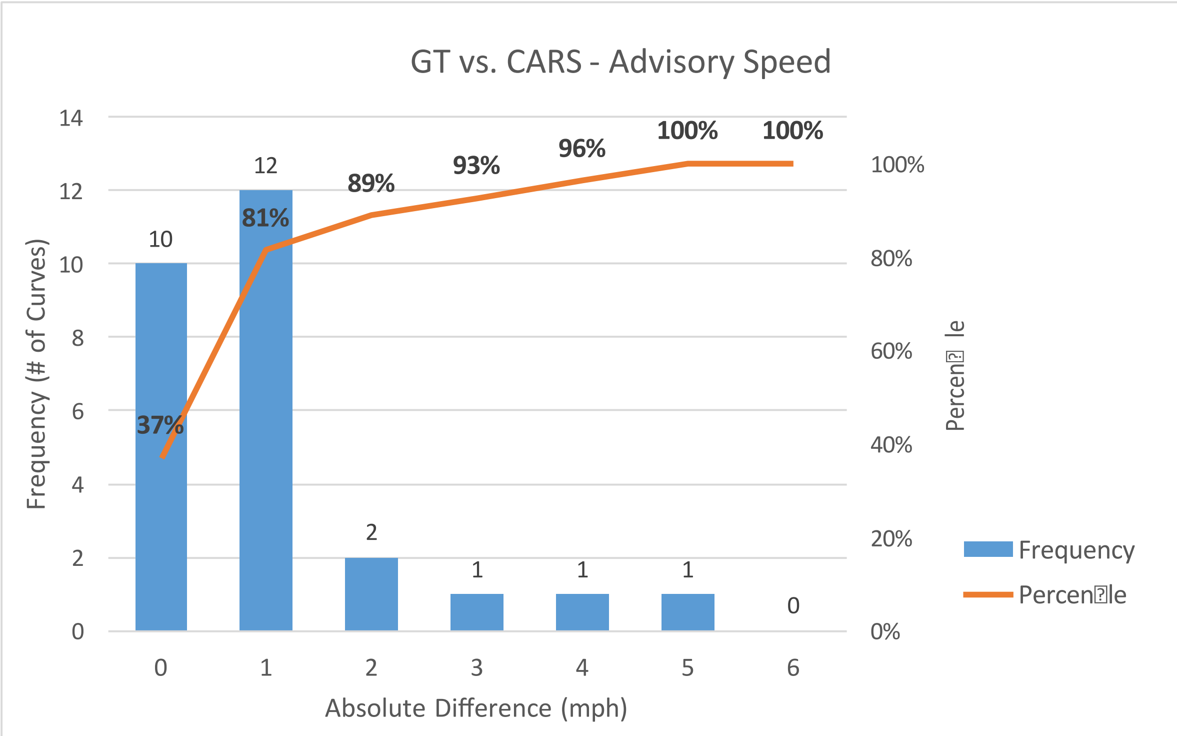


Figure 30. Graph. Histogram and Percentile for Advisory Speed Comparison

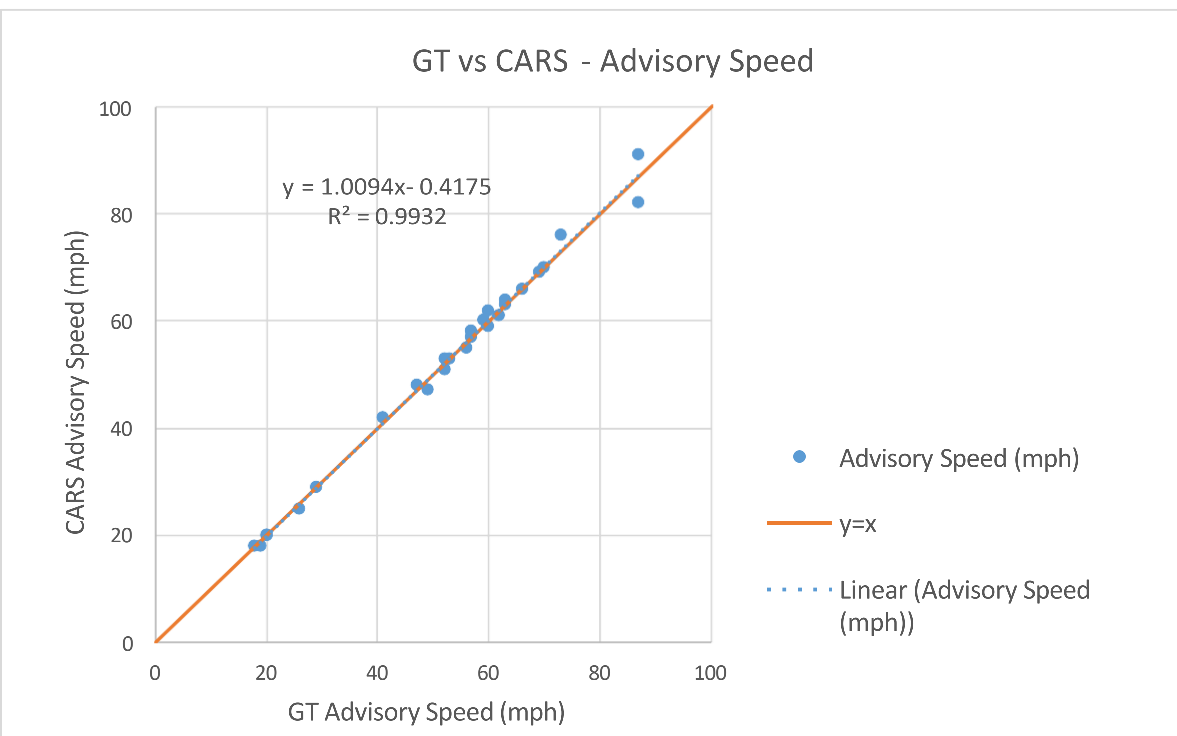


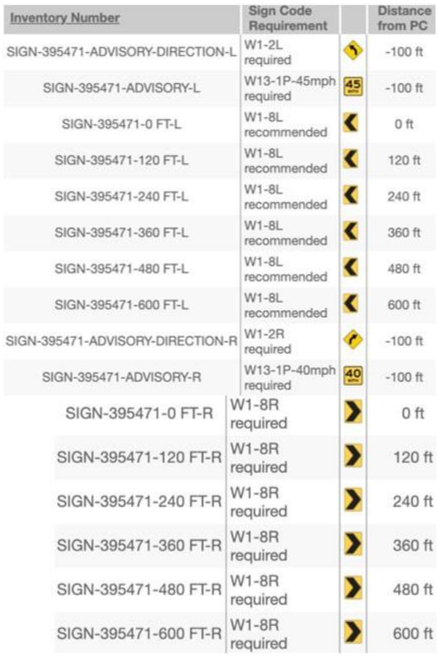
Figure 31. Graph. Scatter Plot for Curve Advisory Speed Comparison

VALIDATION OF CURVE SIGN DESIGN

Both the GT and CARS methods follow Chapter 2 of the MUTCD to design curve warning signs. However, CARS does not consider sign design for continuous curves (e.g., reverse curves, compound curves, and winding roads). CARS only designs warning signs for individual curves and cannot design differently for different types of curve groups. Meanwhile, the MUTCD lacks detailed specification of sign design on continuous curves. To address these challenges, GT researchers had close discussions with GDOT traffic engineers to develop a procedure for designing reverse curve signs and winding road signs by grouping adjacent curves and analyzing their relationships. Programs have been developed to automatically handle these challenging designs automatically. In addition, the GT method allows users to visualize the curve sign design results overlaid on a map, which is more intuitive than the CARS results in tabular formation. This direct visualization makes the QA/QC and future utilization more efficient. Compared to CARS, these are unique strengths that have been developed by the GT research team. These unique features will be demonstrated using figures in the next section.

Due to the limited curve sign design capability of CARS method, this validation selected only simple curves for comparing the GT method's and CARS method's results in terms of sign types, sign requirements, number of signs, and sign spacing. Three curves are selected on SR-2, 11, and 17, and their comparisons are summarized in **Table 8, Table 9,** and **Table 10**. The results indicate that the GT method is promising for generating designs that are like the CARS method for simple curves.

Table 8. Comparison of Curve Sign Design Between GT and CARS Methods (SR-2 #85)

SR-2 #85		GT	CARS
Advisory Speed Plaque	*Required?*	Yes	Yes
	Speed	40 mph	45/40 mph
Warning Sign	*Required?*	Yes	Yes
	Type	Curve	Curve
Chevrons	*Required?*	Yes	Recommend
	Number	6	6
Sign Design Results			

Inventory Number	Sign Code Requirement		Distance from PC
SIGN-395471-ADVISORY-DIRECTION-L	W1-2L required		-100 ft
SIGN-395471-ADVISORY-L	W13-1P-45mph required		-100 ft
SIGN-395471-0 FT-L	W1-8L recommended		0 ft
SIGN-395471-120 FT-L	W1-8L recommended		120 ft
SIGN-395471-240 FT-L	W1-8L recommended		240 ft
SIGN-395471-360 FT-L	W1-8L recommended		360 ft
SIGN-395471-480 FT-L	W1-8L recommended		480 ft
SIGN-395471-600 FT-L	W1-8L recommended		600 ft
SIGN-395471-ADVISORY-DIRECTION-R	W1-2R required		-100 ft
SIGN-395471-ADVISORY-R	W13-1P-40mph required		-100 ft
SIGN-395471-0 FT-R	W1-8R required		0 ft
SIGN-395471-120 FT-R	W1-8R required		120 ft
SIGN-395471-240 FT-R	W1-8R required		240 ft
SIGN-395471-360 FT-R	W1-8R required		360 ft
SIGN-395471-480 FT-R	W1-8R required		480 ft
SIGN-395471-600 FT-R	W1-8R required		600 ft

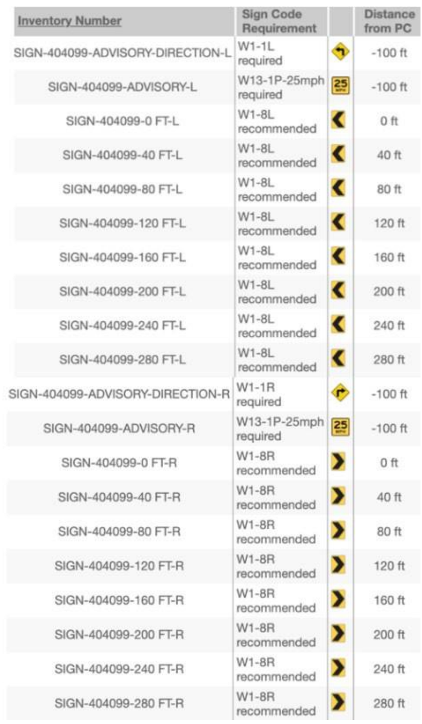
Table 9. Comparison of Curve Sign Design Between GT and CARS Methods (SR-11 #108)

SR-11 #108		GT	CARS
Advisory Speed Plaque	*Required?*	Recommend	Recommend
	Speed	50 mph	50 mph
Warning Sign	*Required?*	Recommend	Recommend
	Type	Curve	Curve
Chevrons	*Required?*	Optional	Optional
	Number	6	7
Sign Design Results			see CARS table below

CARS sign design results:

Inventory Number	Sign Code Requirement		Distance from PC
SIGN-404097-ADVISORY-DIRECTION-L	W1-2L recommended		-100 ft
SIGN-404097-ADVISORY-L	W13-1P-50mph recommended		-100 ft
SIGN-404097-0 FT-L	W1-8L optional		0 ft
SIGN-404097-120 FT-L	W1-8L optional		120 ft
SIGN-404097-240 FT-L	W1-8L optional		240 ft
SIGN-404097-360 FT-L	W1-8L optional		360 ft
SIGN-404097-480 FT-L	W1-8L optional		480 ft
SIGN-404097-600 FT-L	W1-8L optional		600 ft
SIGN-404097-720 FT-L	W1-8L optional		720 ft
SIGN-404097-ADVISORY-DIRECTION-R	W1-2R recommended		-100 ft
SIGN-404097-ADVISORY-R	W13-1P-50mph recommended		-100 ft
SIGN-404097-0 FT-R	W1-8R optional		0 ft
SIGN-404097-120 FT-R	W1-8R optional		120 ft
SIGN-404097-240 FT-R	W1-8R optional		240 ft
SIGN-404097-360 FT-R	W1-8R optional		360 ft
SIGN-404097-480 FT-R	W1-8R optional		480 ft
SIGN-404097-600 FT-R	W1-8R optional		600 ft
SIGN-404097-720 FT-R	W1-8R optional		720 ft

Table 10. Comparison of Curve Sign Design Between GT and CARS Methods (SR-17 #113)

SR-17 #113		GT	CARS
Advisory Speed Plaque	*Required?*	Yes	Yes
	Speed	25 mph	25 mph
Warning Sign	*Required?*	Yes	Yes
	Type	Turn	Turn
Chevrons	*Required?*	Recommend	Recommend
	Number	12	8
Sign Design Results			

Inventory Number	Sign Code Requirement		Distance from PC
SIGN-404099-ADVISORY-DIRECTION-L	W1-1L required		-100 ft
SIGN-404099-ADVISORY-L	W13-1P-25mph required		-100 ft
SIGN-404099-0 FT-L	W1-8L recommended		0 ft
SIGN-404099-40 FT-L	W1-8L recommended		40 ft
SIGN-404099-80 FT-L	W1-8L recommended		80 ft
SIGN-404099-120 FT-L	W1-8L recommended		120 ft
SIGN-404099-160 FT-L	W1-8L recommended		160 ft
SIGN-404099-200 FT-L	W1-8L recommended		200 ft
SIGN-404099-240 FT-L	W1-8L recommended		240 ft
SIGN-404099-280 FT-L	W1-8L recommended		280 ft
SIGN-404099-ADVISORY-DIRECTION-R	W1-1R required		-100 ft
SIGN-404099-ADVISORY-R	W13-1P-25mph required		-100 ft
SIGN-404099-0 FT-R	W1-8R recommended		0 ft
SIGN-404099-40 FT-R	W1-8R recommended		40 ft
SIGN-404099-80 FT-R	W1-8R recommended		80 ft
SIGN-404099-120 FT-R	W1-8R recommended		120 ft
SIGN-404099-160 FT-R	W1-8R recommended		160 ft
SIGN-404099-200 FT-R	W1-8R recommended		200 ft
SIGN-404099-240 FT-R	W1-8R recommended		240 ft
SIGN-404099-280 FT-R	W1-8R recommended		280 ft

UNIQUE FEATURES IN GT METHOD

This section presents two unique features in the GT method:

- The GT method has the unique capability to identify compound or spiral curve automatically so the curve radius and advisory speed can be estimated more accurately.
- The GT method has the unique capability to design reverse curve signs and winding roadway curves.

Automatic Compound/Spiral Curve Identification

A compound curve on SR-2 near Clayton, Georgia, was selected to compare the GT method with the CARS method on their capabilities of compound curve processing. Three scenarios were compared:

- Scenario 1: Using the CARS method with an imperfect curve fitting, as shown in Figure 32;
- Scenario 2: Using the CARS method with refined curve fitting, as shown in Figure 33;
- Scenarios 3: Using the GT method with compound curves split automatically, as shown in Figure 34.

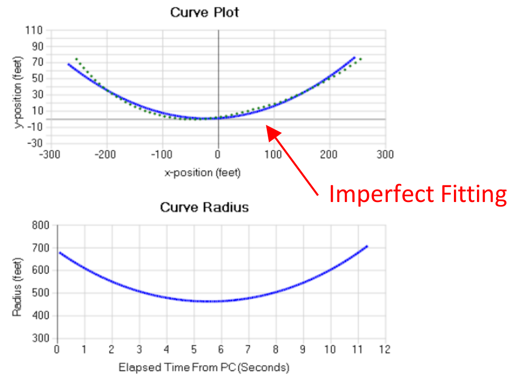
For Scenario 1, the whole curve segment was manually selected. In this scenario, the GPS fittings are 95.8% and 96.3%, which barely meet the 95% requirement when using a parabolic model. However, **Figure 32 (b)** shows that the curve fitting is imperfect. Gaps between the modeled curve and the actual trajectory are obvious. The estimated curve radii are 463 ft (left turn) and 518 ft (right turn), and the estimated advisory speeds are 38.7 mph (left turn) and 39.2 mph (right turn). These numbers will be used to compare Scenarios 2 and 3.

For Scenario 2, PC and PT were carefully identified to have a higher GPS fitting score on the right side of the curve, which is more critical and has a smaller radius. At this time, the GPS fittings increased 2.5% and 1.2% compared to Scenario 1. **Figure 33 (b)** shows that the circle curve fitting in this scenario is almost perfect. A gap was not found between the modeled circle and the actual trajectory. In this scenario, the estimated curve radii were 281 ft (left turn) and 287 ft (right turn), which are around 40% and 43% less than the radii from Scenario 1. Meanwhile, the estimated advisory speeds were 35 mph (left turn) and 32.8 mph (right turn), which are 3.7 mph and 6.4 mph (different than in Scenario 1). These differences are large enough to result in totally different sign design results (e.g., whether curve warning signs are required or not).

For Scenario 3, **Figure 34 (a)** shows the compound curve split into two segments automatically using the GT curve finder. **Figure 34 (b)** shows the estimated curve radii of 267 ft for both left and right turns, which are very close to 281 ft (left turn) and 287 ft (right turn) in Scenario 2. **Figure 34 (b)** also shows the estimated advisory speeds of 35.1 mph (left turn) and 31 mph (right turn), which are also very close to the 35 mph (left turn) and 32.8 mph (right turn) in Scenario 2.

These comparisons demonstrate the promising results of the GT method on processing the compound/spiral curve that CARS cannot process automatically.

(a) Curve Selection



(b) Parabolic Fitting and Curve Radius

Analysis Summary

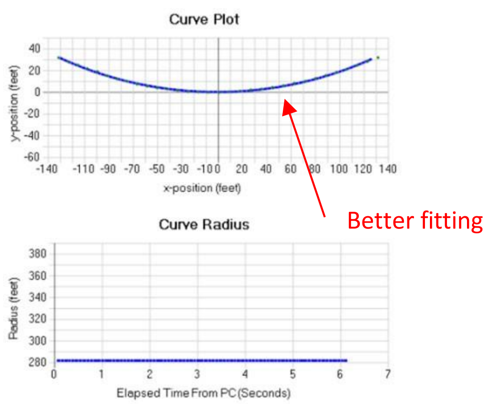
Posted Speed Limit	Side friction	Curve Model	2009 FHWA MUTCD	
Collected: 45 MPH Saved: 55 MPH	Auto side friction limit: 12° Custom side friction limit:	Parabolic model	12° (0.21 ft/ft) for speed of 35mph or more 14° (0.24 ft/ft) for speed of 21mph to 34mph 16° (0.28 ft/ft) for speed of 20mph or less	Update

Selected Passes	Pass #	Turn Direction	Travel Direction	Point of Curvature Latitude Longitude	Point of Tangent Latitude Longitude	GPS Fit	Avg. test speed	Curve radius	Curve length	Deflection angle	Curve Class.	Super Elevation at apex	Vertical Grade	Min. calculated advisory speed	Recommended advisory speed
☑	1	Left	North-West Decreasing	34.88284° -83.41147°	34.88306° -83.41314°	95.8%	31.9 mph	463 ft	547 ft	58°	F	9.3%	A	38.7 mph	35 mph
☑	2	Right	East Decreasing	34.88303° -83.41317°	34.88285° -83.41149°	96.3%	25.5 mph	518 ft	537 ft	52°	F	6.0%	A	39.2 mph	40 mph

(c) Estimated Curve Radius and Advisory Speed

Figure 32. Plot, Graph, and Table. Curve Identification, Radius and Advisory Speed Estimation Using CARS (on a Compound Curve with an Imperfect Fitting)

(a) Curve Selection



(b) Parabolic Fitting and Curve Radius

Analysis Summary

Posted Speed Limit	Side friction	Curve Model	2009 FHWA MUTCD	
Collected: 45 MPH Saved: 55 MPH	Auto side friction limit: 12° Custom side friction limit:	Circular model	12° (0.21 ft/ft) for speed of 35mph or more 14° (0.24 ft/ft) for speed of 21mph to 34mph 16° (0.28 ft/ft) for speed of 20mph or less	Update

Selected Passes	Pass #	Turn Direction	Travel Direction	Point of Curvature Latitude Longitude	Point of Tangent Latitude Longitude	GPS Fit	Avg. test speed	Curve radius	Curve length	Deflection angle	Curve Class.	Super Elevation at apex	Vertical Grade	Min. calculated advisory speed	Recommended advisory speed
☑	1	Left	North Decreasing	34.88268° -83.41134°	34.88312° -83.41204°	98.3%	29.7 mph	281 ft	273 ft	55°	F	11.0%	A	35.0 mph	35 mph
☑	2	Right	South-East Decreasing	34.88309° -83.41206°	34.88267° -83.41134°	97.5%	25.2 mph	287 ft	273 ft	54°	F	4.5%	B	32.8 mph	30 mph

(c) Estimated Curve Radius and Advisory Speed

Figure 33. Plot, Graph, and Table. Curve Identification, Radius and Advisory Speed Estimation Using CARS (on One Part of a Compound Curve with a Better Fitting)

(a) Automatic Curve Identification

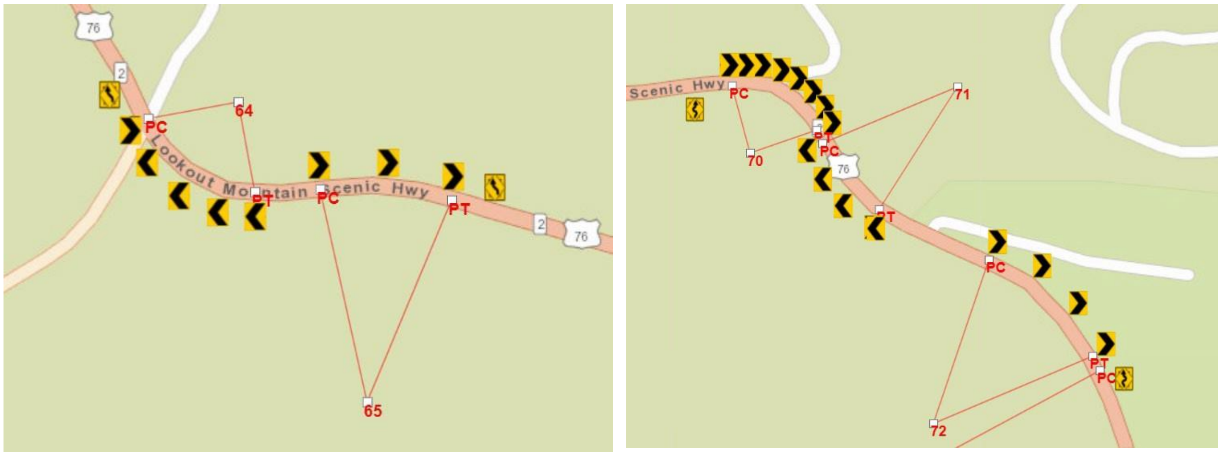
Curve ID	Trajectory ID	Vehicle Heading (degrees)	Average Velocity (mph)	Centerline Radius (ft)	Trajectory Radius (ft)	Deviation Angle	Posted Speed Limit (mph)	Estimated Advisory Speed (mph)
98	80147	-34.7 (Left Turn)	29.9	267.0	292.2	68.8	35.0	**35.1**
98	80148	147.9 (Right Turn)	25.1	267.0	298.8	68.8	35.0	**31.0**

(b) Estimated Curve Radius and Advisory Speed

Figure 34. Plot and Table. Automatic Curve Identification, Radius and Advisory Speed Estimation Using GT Method

Automatic Reverse and Winding Curve Sign Design

As mentioned previously, the CARS method only designs warning signs for individual curves and cannot design differently for different types of curve groups. It might be because the MUTCD lacks detailed specification of sign design on continuous curves. In this study, the GT and GDOT traffic engineers developed a procedure for designing reverse curve signs and winding road signs by grouping adjacent curves and analyzing their relationships. **Figure 35** shows an example of curve sign design on reverse curve and winding roads using the GT method. This demonstrates the promising results of the GT method on processing the curves sign design for combined and successive curves that CARS cannot process automatically.



(a) Reverse Curve (b) Winding Road

Figure 35. Plots. Sign Design on Reverse Curve and Winding Road Using GT Method

CHAPTER 5. DESCRIPTIVE STATISTICS OF RESULTS

This chapter provides descriptive statistics to provide a comprehensive overview, summary, description, and interpretation of the generated curve inventory and the designed curve warning signs on Georgia's state-maintained routes. This includes 1) visualizing the extracted curves and designed curve warning signs according to location using GIS mapping, 2) providing summary statistics (such as mean, median, and standard deviation) to better understand the characteristics of the extracted curve inventory, 3) identifying patterns and trends in the curve inventory, such as the frequency of curves across different radii, deviation angles, lengths, BBIs, and advisory speeds, 4) identifying distributions of the curve inventory (including their characteristics) and warning signs by GDOT districts, which can be used to inform future decision-making (such as budgeting at the district level), and 5) examining the relationships between variables (radius vs. BBI, radius vs. advisory speed, deviation angle vs. BBI, and deviation angle vs. advisory speed) to explore the potential impacts of curve characteristics on BBI and estimated advisory speed.

RESULTS OF CURVE INVENTORY

In this project, a total of 13,264 curves were identified on nearly 18,000 centerline miles of Georgia's state-maintained routes. To provide a visual representation of the distribution of these curves, a GIS map was created that overlays the curves onto the state-maintained routes. As shown in **Figure 36**, the curves are represented in red and are overlaid onto the state-maintained routes, which are shown in grey. This map provides an at-a-glance overview of the spatial distribution of curves across Georgia's state-maintained routes, and it reveals that areas in the north of Georgia, particularly in the mountainous regions and the Atlanta metropolitan area, have higher concentrations of curves that may require additional safety measures.

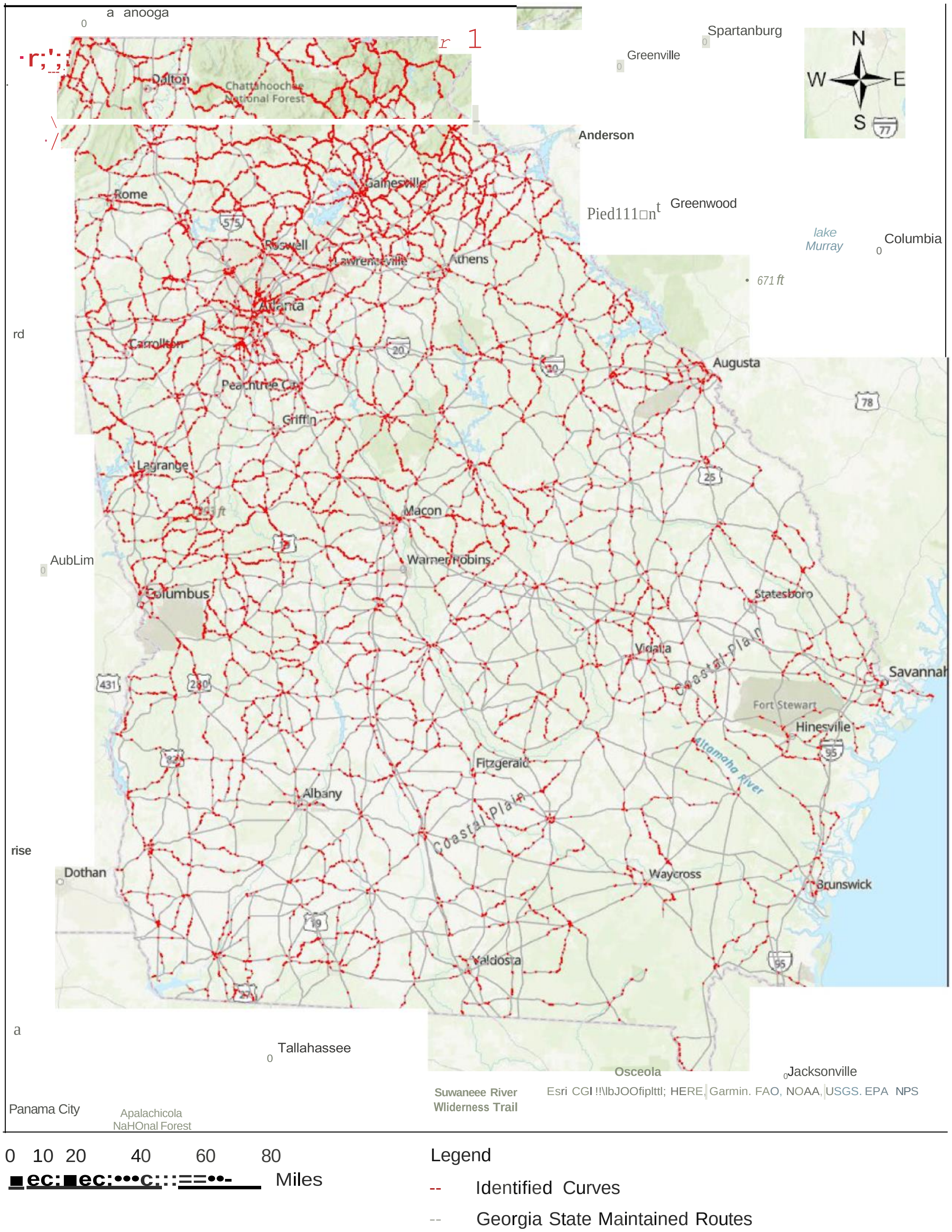


Figure 36. Plot. Identified Curves on Georgia State-maintained Routes

Five variables in the generated curve inventory were selected for conducting summary statistics to describe the identified curves. These variables are 1) curve radius, 2) deviation angle, 3) curve length, 4) 95th BBI, and 5) estimated advisory speed. These variables were selected because 1) curve geometry can be described by curve radius, deviation angle, and curve length, 2) curve radius, deviation angle, and curve length are commonly used factors in creating safety prediction functions (SPFs) on curves, 3) BBI represents the lateral forces used to pass the curve, as well as drivers' comfort, and 4) estimated advisory speed is one of decisive factor for curve warning sign design.

The results of the summary statistics are listed in **Table 11**, which describes the count, mean, standard deviation, minimum, 25% percentile, 50% percentile, 75% percentile, and maximum values for the above mentioned five variables. From this table, it is found that only 12,656 curves (out of 13,264 curves) have the 95th BBI and advisory speed. This is due to invalid CARS data, which might be because of poor GPS fitting (to the roadway centerline) or the missing data collection.

Table 11. Descriptive Statistics of Curve Inventory Results

Description	Curve Radius (ft)	Deviation Angle (degrees)	Curve Length (ft)	95th_BBI (degrees)	Advisory Speed (mph)
count	13262 (# of All Curves)			12759 (# of Curves with Valid CARS Data)	
mean	1371.3	49.5	1058.4	5.3	64.7
std	614.2	21.8	485.6	3.0	17.5
min	32.6	15.0	90.9	0.9	6.1
25%	908.3	34.6	734.3	3.2	53.5
50%	1417.3	44.1	1034.8	4.6	67.4
75%	1897.7	58.2	1318.9	6.7	78.4
max	2499.2	225.8	4110.2	27.1	134.1

Histograms of Selected Variables

To gain a better understanding of the frequency of curves distributed across the selected variables (i.e., curve radius, deviation angle, curve length, 95th BBI, and estimated advisory speed), five histograms were plotted and are shown in **Figure 37** through **Figure 41**. The y-axis of each histogram represents the number of curves, while the x-axis displays the different variable being analyzed. These histograms provide a visual representation of the distribution of curves across each variable and allow for a quick identification of patterns and trends in the data.

Figure 37 displays the histogram of the curve radius, which ranges from between 32.6-2,499.2 ft, with the maximum radius capped at 2,500 ft by the GT Curve Finder. The y-axis represents the frequency of curves, measured by the number of curves falling into each radius bin, while the x-axis shows the different radius intervals. The histogram reveals that curve frequency sharply increases from 0-250 ft, followed by a relatively uniform distribution of 250-2,500 ft. Three prominent peaks are observed at around 1,200 ft, 1,500 ft, and 1,900 ft, respectively. After the radius exceeds 2,000 ft, the curve frequency starts to decline.

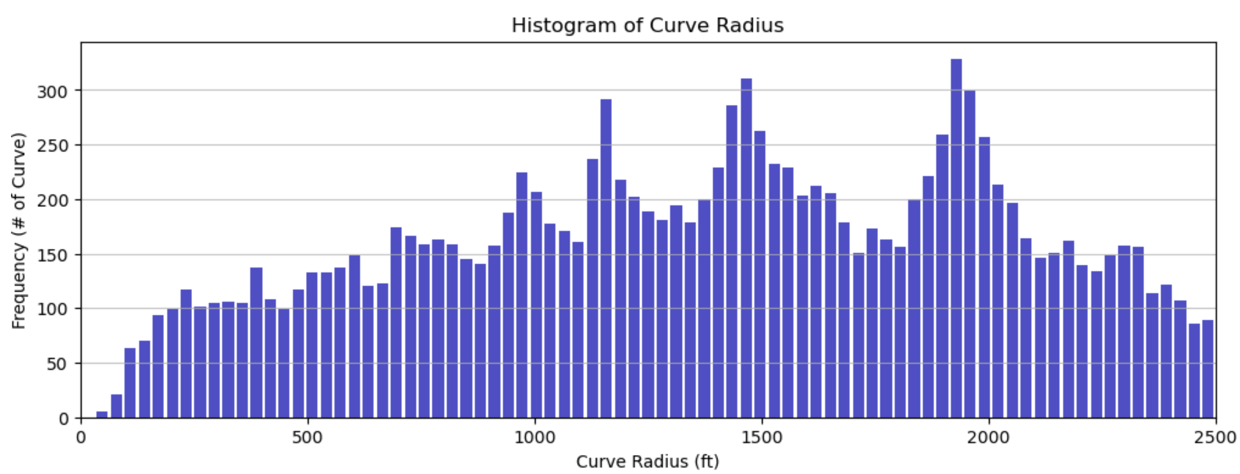


Figure 37. Chart. Histogram of Curve Radius

The histogram of deviation angle is shown in **Figure 38**. The actual deviation angle data ranges from 15-225.8 degrees, but for better display, the histogram is set to range from 0-130 degrees. The histogram displays a right-skewed pattern in which more curves have a low deviation angle. The peak occurs at around 35 degrees, and 50% of the curves have a deviation angle of 34.6-58.2 degrees. After 140 degrees, the curve frequency reaches almost zero. There is an obvious gap at 30 degrees, as only curve segments belonging to a compound curve with a deviation angle of 15-30 degrees are detected in the GT curve finder. The minimum deviation angle for a simple curve was set to 30 degrees.

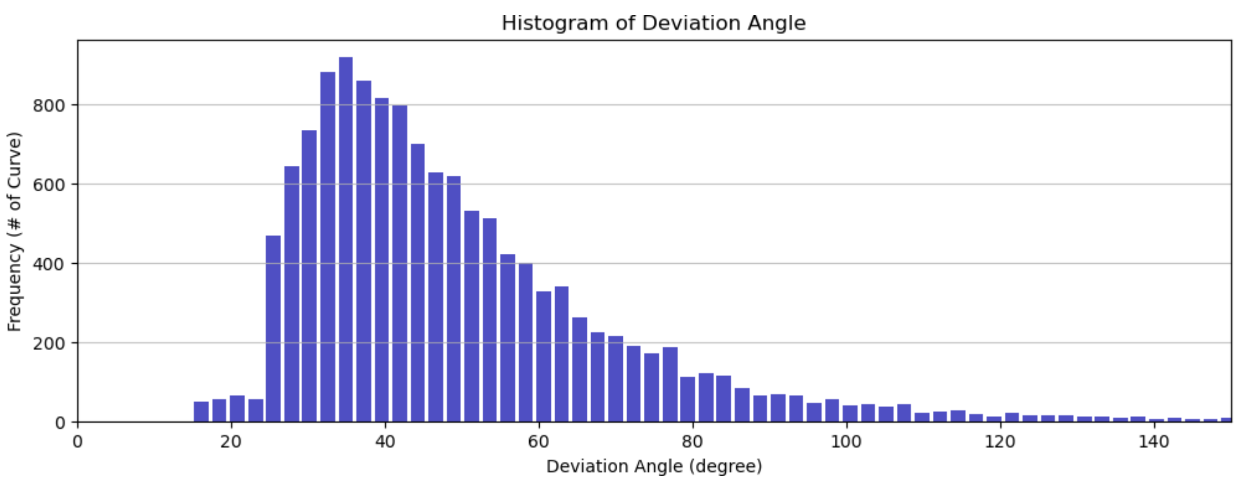


Figure 38. Chart. Histogram of Deviation Angle

Figure 39 displays the histogram of curve length. The actual curve lengths range from 90.9-4,110.2 ft, but the histogram is truncated at 3,000 ft for better display. The distribution is roughly bell-shaped, with half of the curves having lengths of 734.3-1,318.9 ft. The mean, mode, and median are all around 1,000 ft. As curve length increases beyond 2,000 ft, the frequency decreases steadily, and there are very few curves longer than 3,000 ft.

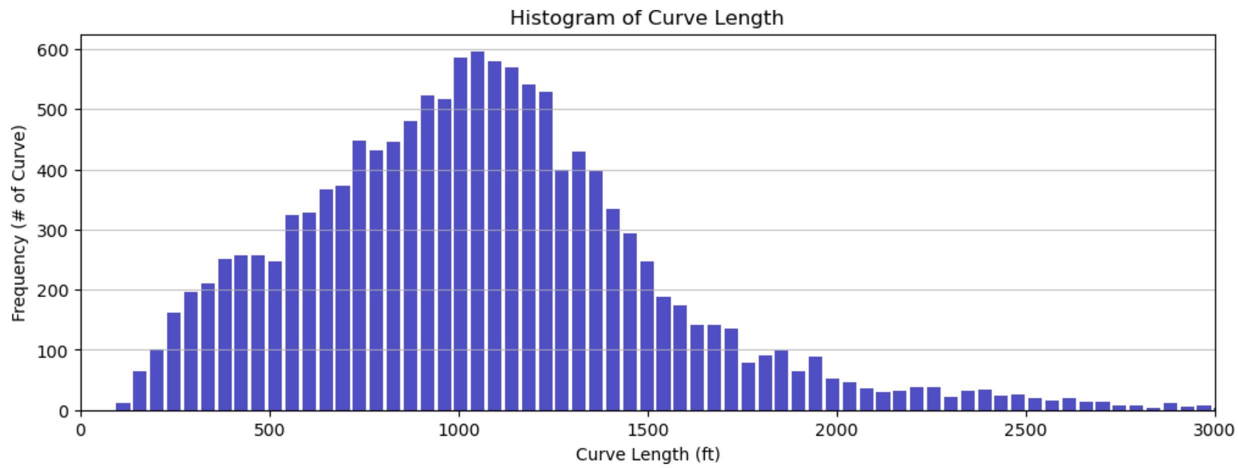


Figure 39. Chart. Histogram of Curve Length

Figure 40 presents the histogram of 95th BBI values, which range from 0-25 degrees. The distribution is right-skewed, with a higher concentration of curves at low BBI values. The peak of the distribution occurs at around 3.5 degrees of the 95th BBI. The median and mean 95th BBI values are 4.6 degrees and 5.3 degrees, respectively. About 75% of the curves have 95th BBI values within 6.7 degrees. Few curves have 95th BBI values greater than 15 degrees.

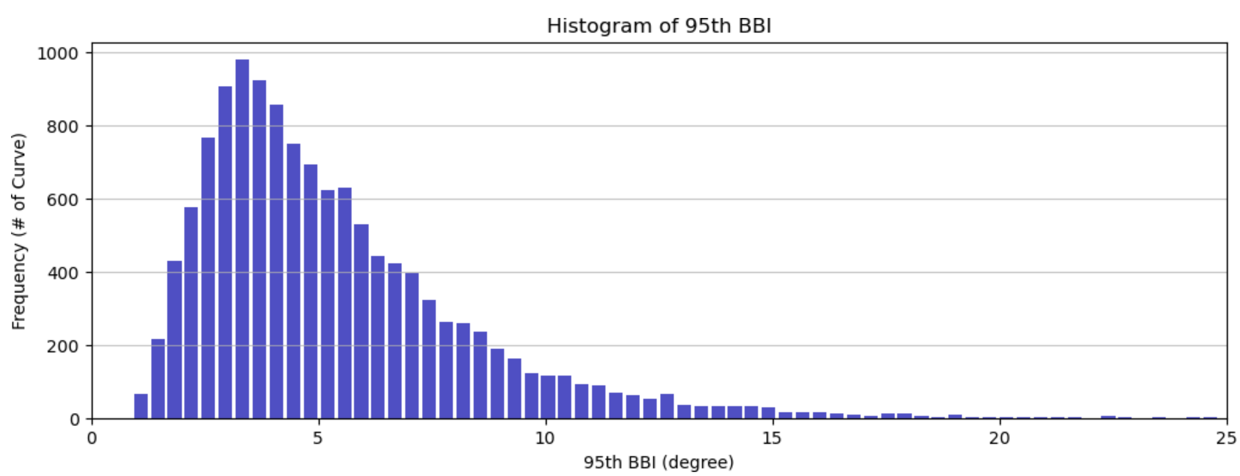


Figure 40. Chart. Histogram of 95th BBI

Figure 41 displays the histogram of estimated advisory speed. The actual results range from 4.8-134.1 mph, but for better display, the histogram is set to range from 0 to 100 mph. The distribution is left-skewed and has a higher concentration of curves at high estimated advisory speeds. Only 25% of the curves have estimated advisory speeds lower than 53.5 mph. Curve sign design is required when the advisory speed is lower than the posted speed limit.

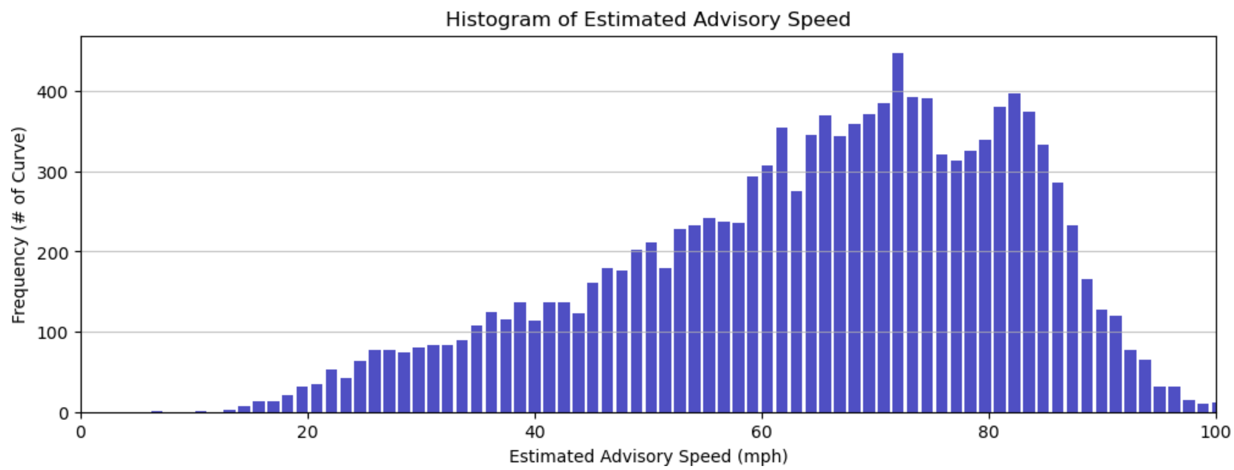
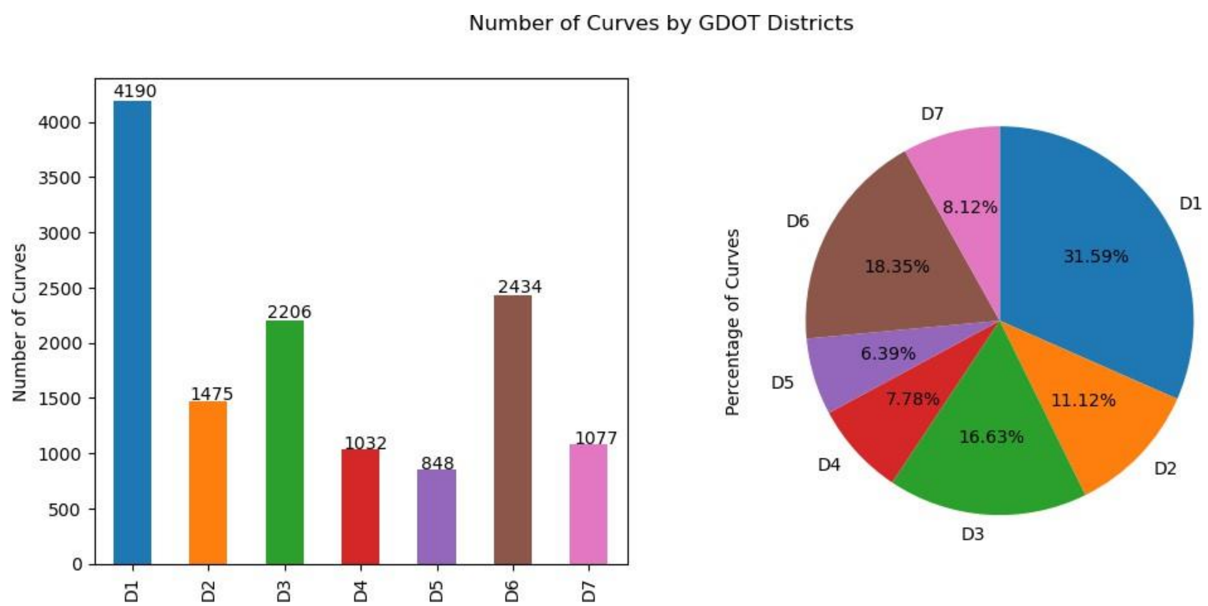


Figure 41. Chart. Histogram of Estimated Advisory Speed

Distribution of Curves by GDOT Districts

Analyzing the distribution of curve inventory, including their characteristics, across different GDOT districts can provide valuable insights (such as budget allocation at the district level) for future decision-making. This subsection presents the results of this analysis using bar and pie charts to display the number and percentage of curves in each GDOT district, and box plots to visualize the distribution of curves across various variables (i.e., curve radius, deviation angle, curve length, BBI, and estimated advisory speed) in each GDOT district.

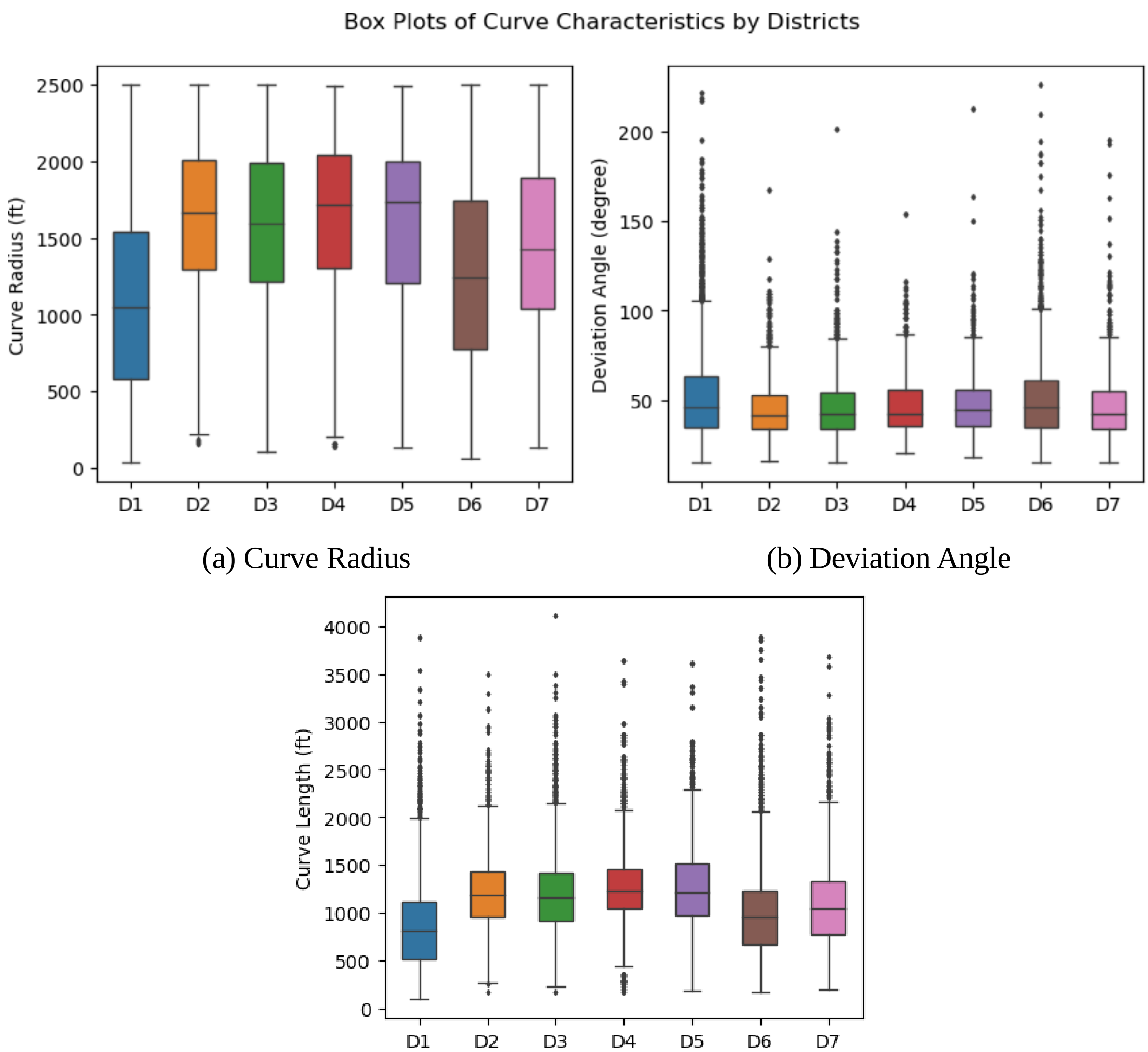
Figure 42 presents the results of the analysis of the curve inventory for Georgia's state-maintained routes by GDOT districts; it is based on nearly 18,000 centerline miles. **Figure 42 (a)** shows a bar chart that displays the number of curves identified in each district. **Figure 42 (b)** presents a corresponding pie chart that shows the percentage of curves in each district. District 1 has 4,190 curves, accounting for 31.59% of the total 13,264 identified curves. District 6 ranks second, with 2,434 curves (18.35% of the total). Notably, Districts 1 and 6 cover the mountainous areas in the north of Georgia, which explains the higher concentration of curves. Conversely, District 5 has the lowest number of curves, with 848 curves (6.39% of the total curves).



(a) Bar Chart (b) Pie Chart

Figure 42. Charts. Number of Extracted Curves on Georgia State-maintained Routes by GDOT Districts

Figure 43 presents box plots **(a)**, **(b)**, and **(c)** for curves in each district across curve radii, deviation angles, and curve lengths, respectively: **Figure 44 (a)** and **(b)** show box plots for curves in each district across the 95th BBI and the estimated advisory speeds. The box plots reveal that Districts 1 and 6, which cover mountainous areas, have a lower range of curve radii, a higher range of deviation angles, a lower range of curve lengths, a higher range of BBI, and a lower range of estimated advisory speeds. These trends follow the laws of mechanics. In contrast, Districts 2, 3, 4, and 5 exhibit similar trends of larger curve radii, smaller deviation angles, longer curve lengths, and higher estimated advisory speeds compared to Districts 1 and 6. District 7 falls in the middle of these trends.

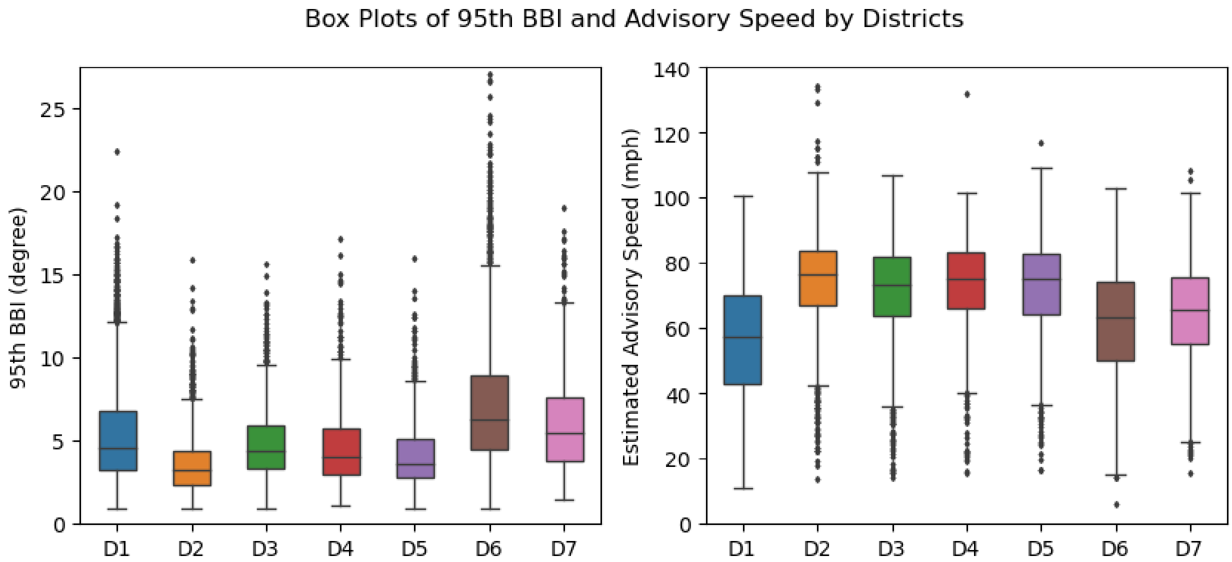


(a) Curve Radius

(b) Deviation Angle

(c) Curve Length

Figure 43. Charts. Box Plots of Curve Characteristics by GDOT Districts



(a) 95th BBI (b) Est. Advisory Speed

Figure 44. Charts. Box Plots of 95th BBI and Estimated Advisory Speed by Districts

Correlation Analyses Using Scatter Plots

Scatter plots have been employed to investigate the relationships between curve characteristics, such as radius, deviation angle, BBI, and estimated advisory speed. The purpose of this analysis is to identify potential impacts of curve characteristics on BBI and estimated advisory speed. **Figure 45** illustrates scatter plots for (a) curve radius vs. 95th BBI, (b) curve radius vs. estimated advisory speed, (c) deviation angle vs. 95th BBI, and (d) deviation angle vs. estimated advisory speed. Yellow areas on the plots indicate higher concentrations, while purple areas indicate lower concentrations. The results of this analysis reveal that higher curve radii are somewhat correlated with lower BBI values and strongly correlated with higher advisory speeds. However, deviation angle is not found to be strongly correlated with either BBI or advisory speed when the deviation angle ranges from 0-100 degrees. For deviation angles greater than 100 degrees, larger deviation angles tend to have larger BBI and lower advisory speed, but the distribution displays significant dispersion.

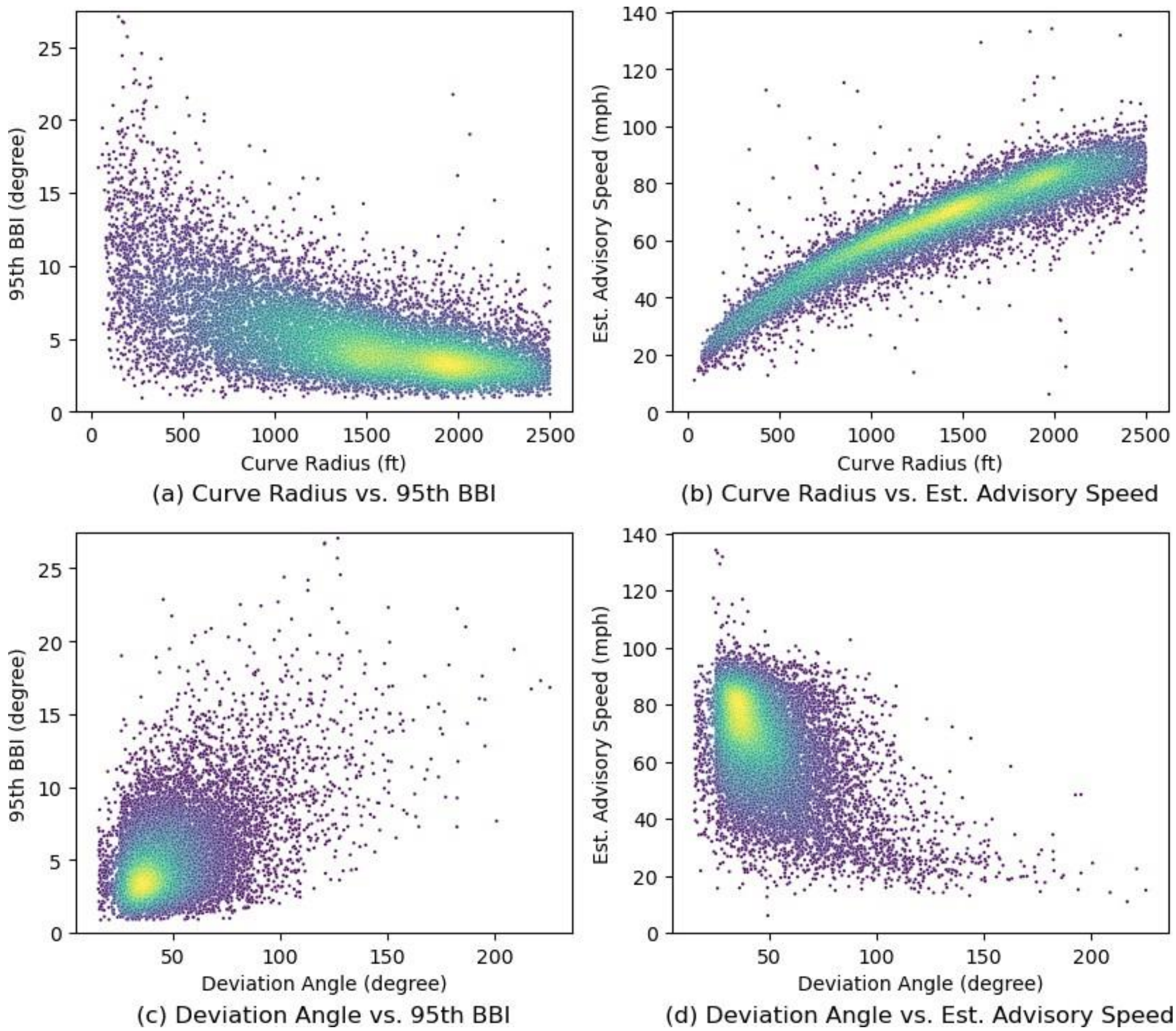


Figure 45. Charts. Scatter Plots for Analysing Correlations Between Curve Radius and Deviation Angle vs. 95th BBI and Est. Advisory Speed

RESULTS OF CURVE SIGN DESIGN

Table 12 presents the distribution of warning signs by type (out of a total of 29,054 signs designed in this study). It can be observed that chevrons were the most frequently designed sign, with over 12,000 left and right chevron signs each. Advisory signs were placed in 2,171 locations. The “curve (left)” and “curve (right)” signs were the next most common (nearly 600 each). The remaining types of warning signs had a smaller frequency, ranging from 60-200 signs.

Table 12. Number of Designed Curve Warning Signs on Georgia State-maintained Routes

Sign Figure							
Sign Code	w1-1_L	w1-1_R	w1-2_L	w1-2_R	w1-3_L	w1-3_R	
Sign Name	Turn (Left)	Turn (Right)	Curve (Left)	Curve (Right)	Reverse Turn (Left)	Reverse Turn (Right)	
# of Signs	**242**	**240**	**571**	**568**	**84**	**60**	
							
Sign Code	w1-4_L	w1-4_R	w1-5_L	w1-5_R	w1-8_L	w1-8_R	w13-1P
Sign Name	Reverse Turn (Left)	Reverse Turn (Right)	Winding Road (Left)	Winding Road (Right)	Chevron (Left)	Chevron (Right)	Advisory Speed (plaque)
# of Signs	**102**	**108**	**89**	**91**	**12364**	**12364**	**2171**

The map in **Figure 46** plots the locations of curve warning signs using small blue dots overlaid onto the previously generated map of curves (represented in red) and Georgia state-maintained routes (represented in grey). It is evident from this map that curve warning signs are primarily concentrated within the North Georgia and Atlanta metropolitan areas.

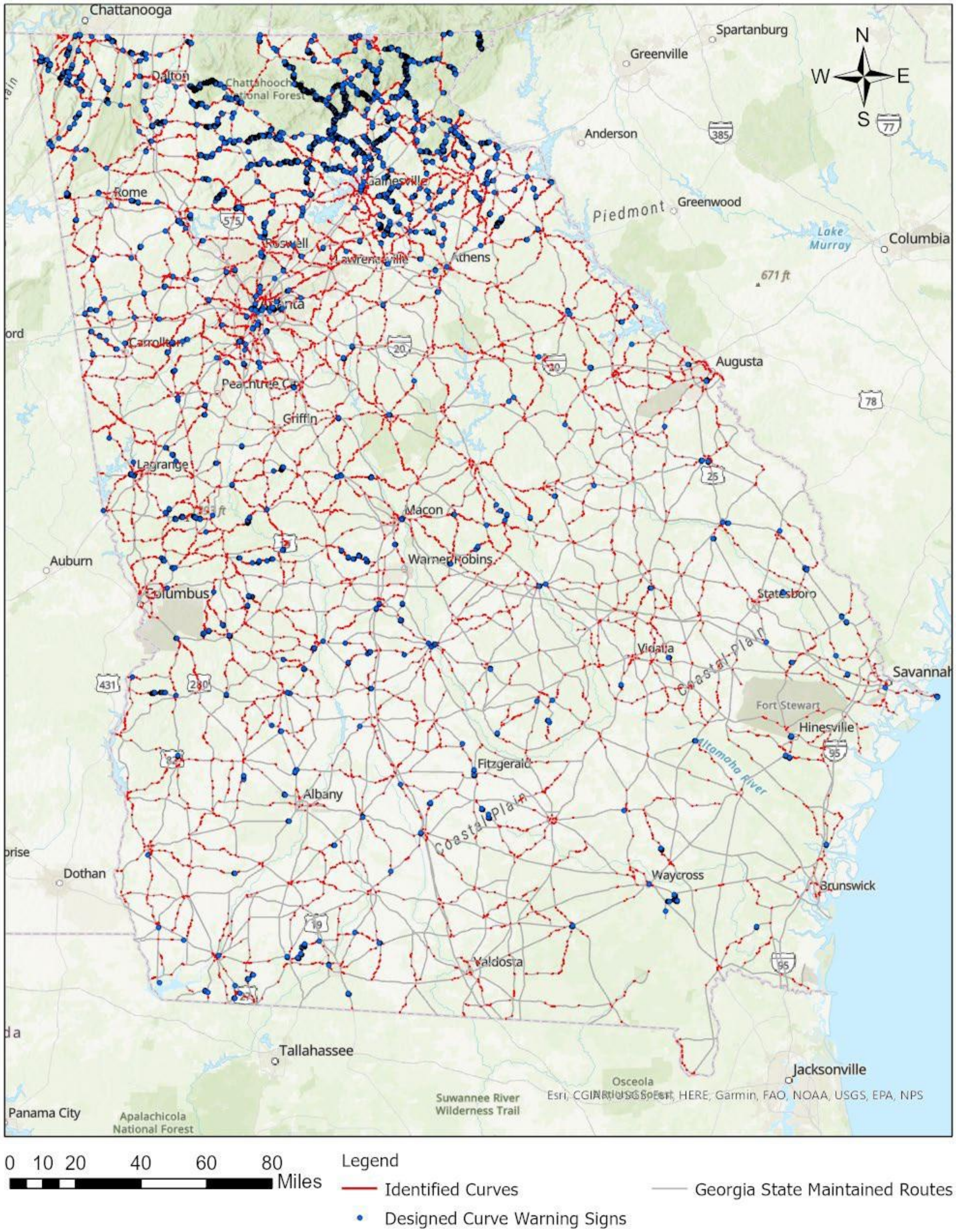
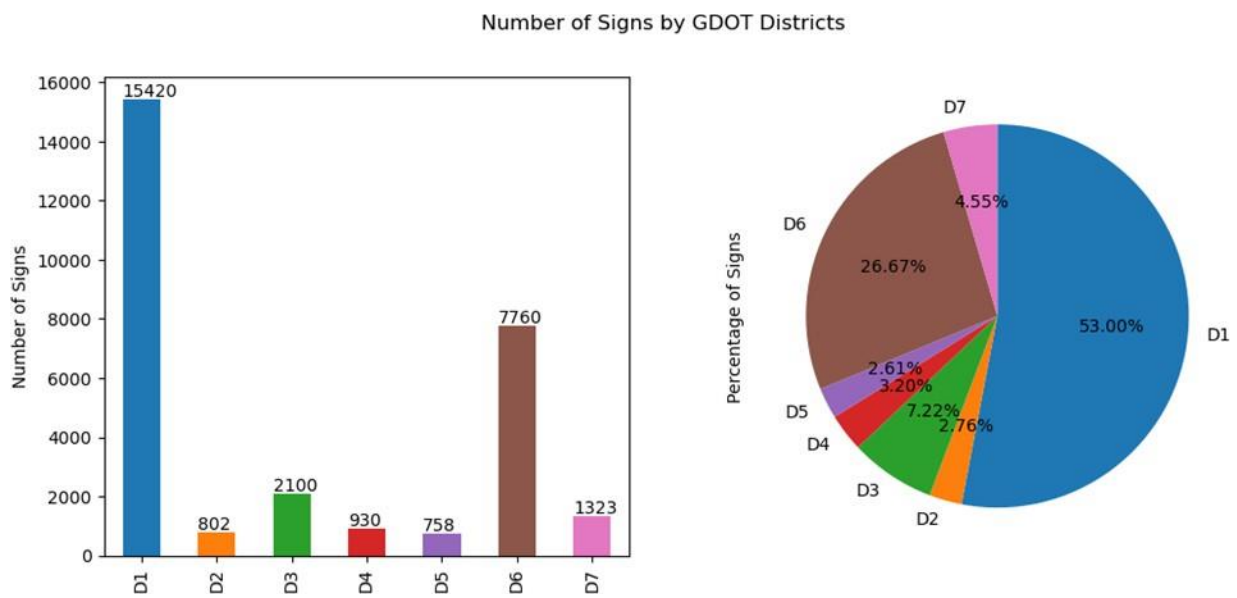


Figure 46. Plot. Designed Curve Warning Signs on Georgia State-maintained Routes

Figure 47 presents the distribution of designed warning signs in each GDOT district, depicted as **(a)** a bar and **(b)** pie chart. District 1 accounted for the largest number of signs, with 15,420 (53% of the total 29,093 designed signs). District 6 was the second largest, with 7,760 signs (26.67% of the total). These two districts, which cover the mountainous areas in the north of Georgia, required approximately 80% of all curve warning signs in Georgia. The remaining signs were distributed across the other districts (20.33% of the total designed signs). These results provide valuable insights for GDOT's future decision-making, including budget allocation at the district level.



(a) Bar Chart (b) Pie Chart

Figure 47. Charts. Number of Designed Curve Warning Signs on Georgia State-maintained Routes by GDOT Districts

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The objectives of this project are 1) to enhance GDOT's current curve sign design practice by refining and using the curve finder (Smart-Curve Information Extraction, Smart-CIE) and the MUTCD curve sign design computation algorithms, both already developed by Georgia Tech, 2) to process GDOT's already-collected CARS data more consistently, accurately, and efficiently on nearly 18,000 centerline miles of state-maintained routes, 3) to generate inventories of curves and MUTCD-compliant curve warning signs in both tabular and GIS formats to meet MUTCD curve sign design requirements and to support GDOT's sharp curve safety analysis using the AASHTOware Safety Powered by Numetric system. The following are the contributions and conclusions for this research project:

1) A critical review of existing GDOT practices for complying with the requirements of the MUTCD for curve warning signs review has been conducted to identify the existing challenges that the CARS method has and the enhancements that are needed, so the developed new method in this project can overcome these challenges and meet the requirements.

2) A procedure has been developed to prepare raw data acquired from CARS, including batch data downloading, missing data cleaning, data smoothing, data combining, spatial data selection, and data filtering. The prepared data is used to support curve inventory generation, advisory speed computation, and curve sign designs.

3) The curve finder computation algorithm (Smart-Curve Information Extraction, Smart-CIE, already developed by Georgia Tech) has been enhanced to increase accuracy (high recall and precision), improve reliability (no false negative), create better user control

(only three thresholds with physical meaning involved), and promote the capability of compound curve identification. Using selected curves with diverse characteristics on SR-2, 11, and 17 in GDOT District 1, the enhanced GT curve finder has been validated by comparing detected curves in GT curve finder with manual identified curves in CARS. The results demonstrate the promising results of generated curve inventory from GT curve finder.

4) The MUTCD curve sign design computation algorithm (already developed by Georgia Tech) has been enhanced to efficiently process curve warning sign design automatically at the network-level and to have the capability to handle reverse curve and winding road signs by grouping adjacent curves and analyzing their relationships. The enhanced GT curve sign design computation algorithm has been validated by comparing its curve sign design results with the outcomes derived using CARS. The results demonstrate the promising results of designed curve signs from GT curve sign design computation algorithm.

5) The enhanced curve finder and MUTCD-compliant curve warning sign design computation algorithm have been used to successfully process nearly 18,000 miles Georgia state-maintained routes. A total of 13,264 curves have been identified and 29,054 signs have been designed. These generated inventories of curves and the MUTCD-compliant curve signs have been delivered as tabular and GIS formats to GDOT. GDOT has already successfully implemented and used these outcomes for its sharp curve safety analysis and safety improvement planning.

6) Descriptive statistics have been produced on generated curves and curve sign inventory to

summarize research outcomes. GIS maps have been plotted to visualize identified curves and designed signs according to location. Summary statistics (such as mean, median, and standard deviation) have been provided to help understand the characteristics of generated curve inventory. Histograms have been created to identify patterns and trends in the curve inventory, such as the frequency of curves with different radii, deviation angles, lengths, BBI values, and advisory speeds. Bar and pie charts and box plots have been created to identify distributions of curve inventory (including their characteristics) and warning signs by GDOT districts, which can be used to improve future decision-making (such as budgeting at district-level). Finally, a correlation study has been conducted to examine potential relationships between variables (such as curve radius, deviation angle, BBI, and advisory speed). Findings from the descriptive statistics are summarized as follows:

a. Areas in the north of Georgia, particularly in the mountainous regions (Districts 1 and 6), as well as the Atlanta metropolitan area (District 7), have higher concentrations of curves and curve warning signs that may require additional safety measures.

b. The district with the highest number of curves is District 1, with 4,190 curves, accounting for 31.59% of the 13,262 identified curves. District 6 ranks second, with 2,434 curves, which represents 18.35% of the total. Both Districts 1 and 6 are situated in the mountainous northern region of Georgia. Conversely, District 5, which covers the coastal regions, reports the lowest number of curves, with only 848 curves identified, representing just 6.39% of the total curves.

c. Districts 1 and 6, which cover mountainous areas, have observed lower values of curve radii, higher values of deviation angles, lower values of curve lengths, higher BBI values, and lower values of estimated advisory speeds in the box plots. These trends follow the laws of mechanics among curve radius, deviation angle, curve length, BBI, and estimated advisory speed.

d. Correlation analyses find that higher curve radii are somewhat correlated with lower BBI values and strongly correlated with higher advisory speeds. However, deviation angle is not found to be strongly correlated with either BBI or advisory speed when the deviation angle ranges from 0-100 degrees. For deviation angles greater than 100 degrees, larger deviation angles tend to have larger BBI values and lower advisory speeds, but the distribution displays significant dispersion.

e. District 1 accounted for the largest number of signs, with 15,420 (53%) of the total 29,093 designed signs. District 6 was the second largest, with 7,760 signs (26.67% of the total). These two districts, which cover the mountainous areas in the north of Georgia, require approximately 80% of all curve warning signs in Georgia. The remaining signs (20.33%) were distributed across the other districts.

The following are the recommendations for future work:

1) **Low-cost data collection method to establish a sustainable and systemic curve safety assessment:** It is recommended that the cost of data collection (currently done by Rieker devices) be reduced by introducing low-cost mobile devices (e.g., smartphones and dash cameras) and/or using intra-agency crowdsourcing techniques. Considering that the

Rieker device is proprietary, it is recommended to explore non-proprietary alternatives, particularly these low-cost mobile devices.

2) **GPS correction using roadway centerline geometry**: It is recommended to develop a method to correct/calibrate disrupted GPS or GPS with offsets using roadway centerline geometry data. Therefore, these GPS data can be salvaged to minimize data re-collection.

3) **Confidence level of estimated advisory speed**: To enhance the reliability of the estimated advisory speed, a model that provides a confidence level should be developed. This confidence level, categorized as high, medium, or low, will serve as an indicator of the reliability of the computed advisory speed based on the data collected using either the Rieker device or other low-cost mobile devices from multiple runs (i.e., repeated tests). This will provide a means for transportation agencies to differentiate good and bad data that can be used to target roadway segments (with low confidence) from which data must be re-collected. This will significantly improve the reliability of agencies' safety decision-making and the productivity of data re-collection.

4) **Enhanced web-based data management tool with well-structured database and flexible data query capabilities:** It is recommended that an advanced web-based tool for managing data from low-cost mobile devices be developed. This tool would offer functionalities like data uploading, manipulation, and visualization (e.g., missing data, confidence level, curve geometry, locations). It would identify routes with sufficient data coverage and routes requiring more data collection, thereby optimizing the data collection process. Given the large data volume, a well-structured database is essential for efficient and flexible data querying and review. Flexible query features, such as click-based route

selection or keyword searches (e.g., route name, county code), are recommended for accessing relevant data.

5) **Automated MUTCD compliance checking system:** It is recommended to develop a low-cost, frequent, and automatic system that uses low-cost mobile devices with video log data capture capabilities (e.g., smartphones and dash cameras) and machine learning (ML) technologies to perform MUTCD compliance checking for curve warning signs. This system will include 1) roadway image/video data collection using low-cost mobile devices, 2) an automated curve sign detection model, 3) an automated MUTCD-compliant curve sign design (expected to be developed in this study) method, and 4) an automated MUTCD compliance checking model that compares designed curve sign with real-world existing signs. Therefore, missing curve warning signs can be identified promptly by examining existing signs with designed MUTCD-compliant curve signs.

6) **Refinement of MUTCD by incorporating reverse curve and winding road sign design procedures into MUTCD:** The current version of the MUTCD advises users to employ engineering judgment for determining curve warning sign designs on continuous curves; however, this method is subjective and lacks detailed specifications. To address this issue, it is recommended to include the procedures for designing reverse curve signs and winding road signs by grouping adjacent curves and analyzing their relationships, which have been developed in this study, into the MUTCD. This will provide more objective, consistent and comprehensive guidelines for the design of curve warning signs.

7) **Enhanced comprehensive curve safety assessment and improvements using comprehensive risk factors:** It is recommended to use this project as a base to establish

an enhanced curve safety assessment and improvement/treatment planning by comprehensively considering and examining the following risk factors: 1) BBI, 2) curve characteristics (e.g., curve radius, deviation angle, curve length), 3) vertical slope, 4) super elevation, 5) side friction, 6) estimated advisory speed, 7) speed difference between advisory speed and speed limit, etc. Besides curve sign compliance checking, other safety improvements, such as high-friction surface treatment, shoulder widening, curve realignment, rumble strips, guardrails, and line marking improvement, etc., can be applied using the extracted comprehensive risk factors that are previously difficult to obtain.

8) **Identifying contributing factors and establishing more accurate SPFs for curve crashes using detailed curve characteristics and historical crashes:** It is recommended to further leverage detailed curve characteristics (in the extracted curve inventory) and historical crashes to achieve the following goals: 1) identify contributing factors to curve crashes by correlating individual variables (e.g., curve radius, deviation angle, curve length, BBI, and advisory speed) with historical curve crashes, 2) establish more accurate safety performance functions (SPFs) for curve crash prediction using multiple variables, including data (e.g., curve radius, deviation angle, curve length, BBI, and advisory speed) that were previously difficult to collect at the network-level. To achieve this level of analysis, accurate spatial locations (latitude and longitude) from historical crash reports are crucial. However, obtaining this information has been a continuing challenge. For example, if the police move the vehicles involved in an accident to a safe location out of the curve and then report the GPS location, it does not accurately represent where the

actual crash occurred. Therefore, it is recommended to establish a standard operating procedure or methodology for capturing more accurate locations of crashes.

APPENDIX A. DATA DICTIONARY

This appendix describes the data items included in the generated inventories of sharp curves and designed curve warning signs using **Table 13** and **Table 14**, respectively. Three sets of data items are included in **Table 13**. The first set of the data (e.g., **g_**xxx) inherit the road unique identifier, type, and location characteristics information from GIS shapefile of "**G**eorgia's road base map" that GDOT uses for sharp curve analysis using AASHTOware Safety Powered by Numetric. The second set of the data (e.g., **c_**xxx) includes the generated "**C**urve characteristics" data items derived from Georgia Tech. The third set of the data (e.g., **p_**xxx) include "**P**rocessed" data items using raw CARS data collected by GDOT using Rieker devices. Two processed BBI data items: 1) max BBI, and 2) 95th percentile BBI, are used to represent the worst case of BBI on each curve. Compared to max BBI, 95th percentile BBI is more representative of worst case BBI especially because that max BBI may include extreme value caused by sudden driving change and bias the curve safety analysis. Three altitude data items, including 1) altitude of PC, 2) altitude of PT, and 3) altitude of middle point between PC and PT, to see if the curve is flat, sag or with peak, have been extracted to represent each curve.

In addition, improvements have been made to ensure the accuracy of a generated curve inventory, such as the following:

- **Use of the 95th percentile BBI:** Experimental tests were conducted to determine the use of the 95th percentile BBI instead of the maximum BBI value when recording BBI to the curve inventory. This avoids extreme BBI values from probable sensor signal error. It should be noticed that the 95th percentile BBI is recorded in the curve inventory for supporting curve safety analysis, while the moving averaged BBI (mentioned in Module 2, Step 2) is used during in the computation of advisory speed computation.

- **Voting method for inconsistent posted speed values:** A voting method was used to deal with inconsistent posted speed values collected in multiple data collection runs, improving data reliability for curve sign design and data recording in curve inventory. The voting method resolves inconsistent speed limit values collected over multiple runs by selecting the speed limit with the most votes as the final posted limit. In the event of a tie, the higher speed value is chosen.

In **Table 14**, most data fields included in the curve warning sign inventory starts with "**s_**" (e.g., **s_xxx**), which denotes "**S**ign selection and placement" data. The warning sign inventory also inherit two **"c_xxx"** fields to indicate the curve that the sign is located.

Table 13. Data items (presented as "Field Name") and dictionary in curve inventory (Data name: "SharpCurvesDX")

Field Name	Unit/Type	Description
FID	Number (Int)	GIS internal data field used as the unique ID for current attribute table
Shape*	Text (String)	GIS internal data filed used to explain the type of feature
c_segid	Text (String)	Processing route segment ID
c_sectid	Number (Int)	Curve section ID. A curve section can be a simple curve or constituted by multiple split curves (i.e., compound or spiral curves).
c_id	Number (Int)	Unique curve identifier per processing segment
c_type	Text (String)	Curve types that can be "simple" or "split". A split curve is part of a compound or spiral curve.
c_radius	Feet (Double)	Curve radius (in feet)
c_devangle	Degree (Double)	Curve deviation angle (in degree)
c_length	Feet (Double)	Curve length from PT to PC (in feet)
c_pc_x	Decimal degree (DD) (Double)	Longitude of point of curve (PC)
c_pc_y	DD (Double)	Latitude of point of curve (PC)
c_pt_x	DD (Double)	Longitude of point of tangent (PT)
c_pt_y	DD (Double)	Latitude of point of tangent (PT)
g_rcd	Number & alphabet (String)	Unique inventory route ID in Georgia and combine with c_id and c_segid to be able to uniquely identify a curve in the state. Formatted as (XXXAYYYYBBz)
g_rte_typ	Text (String)	Route Type (A in the G_RCD) (Code 1: State Route, 2: County Road, 3: City Street)
g_rte_cod	Text (String)	Route Code (XXXX in the G_RCD)
g_rte_numb	Text (String)	Route Number (YYYY in the G_RCD)
g_rte_suff	Text (String)	Route Suffix (BB in the G_RCD)
g_spd_limt	Miles per hour (mph) (Double)	The posted speed limit of the curve from AASHTOware Safety Powered by Numetric data
p_bbi_max	Degree (Double)	The maximum BBI value at the same curve among different data collection runs
p_bbi_95th	Degree (Double)	The 95th percentile of BBI values at the same curve among different data collection runs
p_pc_alti	Feet (Double)	The altitude of the point of curve (PC)
p_mid_alti	Feet (Double)	The altitude of the point in the middle of PC and PT
p_pt_alti	Feet (Double)	The altitude of the point of tangent (PT)
p_spd_limt	Miles per hour (mph) (Double)	The posted speed limit of the curve from CARS
p_adv_sped	Miles per hour (mph) (Double)	The estimated advisory speed in decimal.

(continued)

p_sped_dif	Miles per hour (mph) (Double)	The computed speed differential that is calculated using posted speed limit (from CARS, which is "p_spd_limt", or from GDOT center line dataset, which is "g_spd_limt", when speed limit is not available from CARS) to minus the estimated advisory speed.
p_colldate	Text (String)	BBI data collection date. Formatted as (YYYY-MM-DD)
p_note	Text (String)	This field contains notes from GT data processing. The notation used in this field are code names which are defined in following: **NONE**: no special notation. **ASV_XX+**: high advisory speed variability flag, curves that belong to a reverse or winding curve group that shows high advisory speed variability among the individual curves. Recommended for review by GDOT engineers to make single case judgement. • ASV_5+: advisory speed variability greater than 5 MPH and less than 10 MPH. • ASV_10+: advisory speed variability greater than 10 MPH and less than 15 MPH. • ASV_15+: advisory speed variability greater than 15 MPH. **NO_VALID_DATA**: no valid/proper BBI data collection to estimate advisory speed. There are several reasons: 9) No CARS data collection. 10) CARS data do not cover the curve path properly. If data collection vehicle traveled less than 70% or more than 130% of curve centerline length, this data collection run is filtered out. 11) Speed of data collection is too low. If minimum data collection speed lower than 5 MPH, this run of data collection is filtered out.

Table 14. Data items (presented as "Field Name") and dictionary in curve warning sign inventory

Field Name	Unit/Type	Description
FID	Number (Int)	GIS internal data field used as the unique ID for current attribute table
Shape*	Text (String)	GIS internal data filed used to explain the type of feature
c_segid	Text (String)	Processing segment ID
c_id	Number (Int)	Unique curve identifier per processing segment
s_id	Number (Int)	Unique sign identifier per processing segment
s_code	Text (String)	MUTCD sign code.
s_label	Number (Int)	Advisory speed number that will be printed on W13-1P signs, this field will be "0" for all other sign types.
s_dir	Decimal degree (DD) (Double)	Direction which the sign is facing.
s_required	Text (String)	Sign requirement based on MUTCD, can be "OPTIONAL", "RECOMMENDED", or "REQUIRED".
s_mp	Number (Double)	Mile Post number of the sign
g_rcd	Number & alphabet (String)	Unique inventory route ID in Georgia and combine with C_ID to be able to uniquely identify a curve in the state. Formatted as (XXXAYYYYBBz)
s_long	Number (Double)	Longitude of the sign
s_lat	Number (Double)	Latitude of the sign

APPENDIX B. CARS DATA ACQUISITION AND PREPARATION

This appendix describes the detailed procedures to acquire and prepare CARS data.

Step 1: Download Raw Data from CARS Portal

This step batch downloads the GPS, BBI and posted speed limit data as separated files in SQL format from CARS portal. Bulk data export function in CARS portal is used to download the raw data, as shown in the **Figure 48**. The raw GPS, BBI and the posted speed limit data are packaged in the data session file, so we only select "Collected data session file data" for downloading. The output data format we selected is ".sql" file rather than ".csv" file, because the ".sql" file has higher decimal accuracy for the GPS data (x, y coordinates). As of July 2020, there are 10,828 sessions of data stored on CARS portal (nearly 1.8 GB data in the zipped file), which indicates there are total 10,828 runs of data collected had been conducted in the past several years by GDOT people.

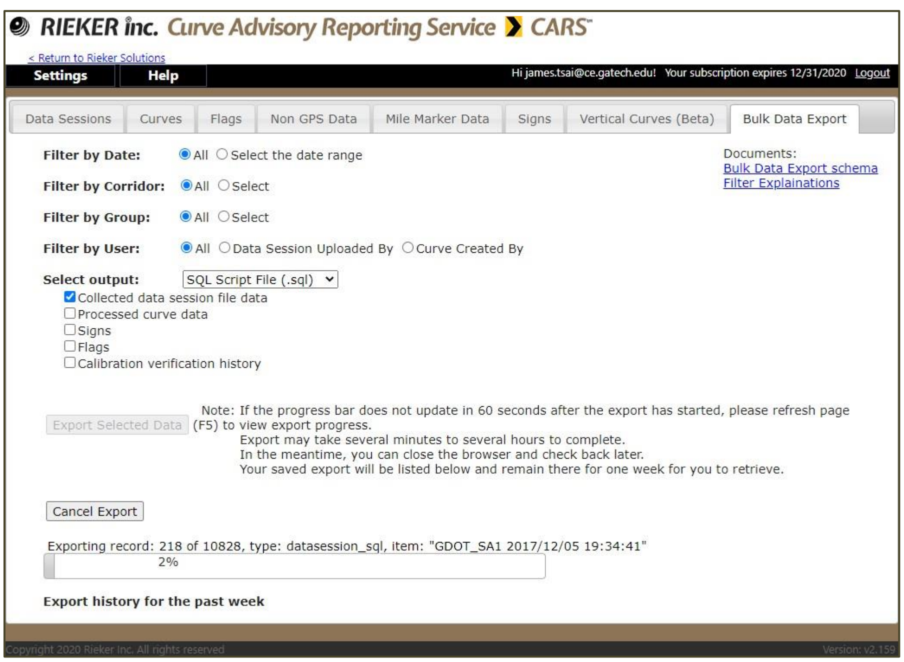


Figure 48. Screenshot. The "Bulk Data Export" function in CARS portal

The downloaded "Collected data session file data" is a zip file, which contain four ".sql" file, including 1) BBI samples, 2) GPS samples, 3) Speed Limit Samples, and 4) Export Data File, as shown in the following **Figure 49**. The BBI samples data session data contains the inclination value timestamps; GPS samples data session data contains latitude, longitude, altitude, heading, velocity information along with timestamps; Speed limit samples data contains speed limit information along with timestamps; and Export Data File csv file contains the basic folder name, uploader, and uploading time information of each session of data. We will only use 1) BBI samples, 2) GPS samples, and 3) Speed Limit samples data in the following data preprocessing steps; and they will transmit from the ".sql" file format to the ".csv" file format for easier reading and processing. Noticed that the additional text information in the ".sql" file format will be removed, so the data size shrunk, as shown in **Figure 50**.

Name	Date modified	Type	Size
SpeedLimitSamples.sql	6/28/2020 9:59 PM	SQL File	3,270 KB
GPSSamples.sql	6/28/2020 10:04 PM	SQL File	7,810,319 KB
ExportDataFile.sql	6/28/2020 9:59 PM	SQL File	2,267 KB
BBISamples.sql	6/28/2020 9:59 PM	SQL File	10,447,148 KB

Figure 49. Photo. The ".sql" files contained in the downloaded zipped file

Name	Date modified	Type	Size
GPS_SQL_Data.csv	6/29/2020 12:46 AM	Microsoft Excel C...	3,204,820 KB
BBI_SQL_Data.csv	6/29/2020 12:51 AM	Microsoft Excel C...	3,320,007 KB
SPD_SQL_Data.csv	6/29/2020 12:51 AM	Microsoft Excel C...	880 KB

Figure 50. Photo. The transmitted ".csv" files of GPS, BBI and Posted Speed Limit data

GPS Samples Data

There are eight columns/fields in the "GPS Sample" data, including File ID, Velocity, Heading, Sample Timestamp, DOP, Latitude, Longitude, and Altitude. The file ID is unique for each of the data sessions, which is referred to one run of data collection. As previously mentioned, there is total 10,828 data sessions collected by GDOT people using CARS system as of July 2020; it will have 10,828 different File ID in this “GPS Sample” file. The duration of each run of data collection is different, so the data length (number of rows) of different File ID varies. In total, there are nearly 33 million rows of GPS points, so the average number of GPS points for each data collection run is nearly 3,050. From the “Sample Timestamp”, we noticed the frequency of GPS data collection is nearly 5 samples/second (5Hz). Therefore, we got the average data collection duration for each session is nearly 10 minutes. The following **Table 15** shown the example of “GPS Sample” data.

Table 15. Example of the "GPS Samples" data

FileID	Velocity	Heading	Sample Timestamp	DOP	Latitude	Longitude	Altitude
24351	40.7	179	07/18/2016 15:58:18.440	1.79	32.96436	-82.8092	472
24351	40.3	179	07/18/2016 15:58:18.648	1.79	32.96432	-82.8092	472
24351	40.3	179	07/18/2016 15:58:18.852	1.67	32.96429	-82.8092	473
24351	40.3	179	07/18/2016 15:58:19.056	1.67	32.96426	-82.8092	474
24351	40.3	179	07/18/2016 15:58:19.240	1.67	32.96422	-82.8092	474
24351	40.3	179	07/18/2016 15:58:19.440	1.79	32.96419	-82.8092	475
24351	40.4	179	07/18/2016 15:58:19.648	1.79	32.96416	-82.8092	475
24351	40.5	179	07/18/2016 15:58:19.844	1.67	32.96413	-82.8092	475
24351	40.5	179	07/18/2016 15:58:20.036	1.67	32.96409	-82.8092	475
24351	40.6	179	07/18/2016 15:58:20.236	1.67	32.96406	-82.8092	475
24351	40.8	179	07/18/2016 15:58:20.436	1.67	32.96403	-82.8092	475
24351	40.8	179	07/18/2016 15:58:20.641	1.67	32.96399	-82.8092	475
24351	40.7	179	07/18/2016 15:58:20.837	1.67	32.96396	-82.8092	476
…	…	…	…	…	…	…	…

BBI Samples Data

There are three columns/fields in the "BBI Samples" data, which are File ID, Sample Timestamp and Inclination. The File ID of BBI and GPS data for the same data collection session is the same. Therefore, when combining the BBI and GPS data, we use the FileID to match the same data collection session. However, the BBI has higher data collection frequency, nearly 14 samples/second (14 Hz), than GPS' 5 samples/second (5 Hz). In total, nearly 85 million BBI data points are collected compared to 33 million GPS data points. Therefore, we will assign the BBI values to the corresponding GPS points by matching their Sample Timestamp.

Table 16. Example of "BBI Samples" data

FileID	SampleTimestamp	Inclination
24351	07/18/2016 15:58:18.572	-0.12
24351	07/18/2016 15:58:18.648	-0.97
24351	07/18/2016 15:58:18.720	-0.55
24351	07/18/2016 15:58:18.804	-1.16
24351	07/18/2016 15:58:18.876	-2.68
24351	07/18/2016 15:58:18.956	-1.67
24351	07/18/2016 15:58:19.020	-0.81
24351	07/18/2016 15:58:19.116	-0.55
24351	07/18/2016 15:58:19.188	-0.82
24351	07/18/2016 15:58:19.264	-1.39
…	…	…

Posted Speed Limit Data

There are four columns/fields in the “Speed Limit Samples” data, which are Filed Id, Sample Timestamp, Speed and Unit. The posted speed limit data is manually recorded by the GDOT personnel in the tablet system at the beginning of their run and whenever they noticed the posted speed limit changed. There might only be several speed limit recordings for a data session with a long duration gap between two speed limit recordings. In summary, there are only 23,994 recordings of posted speed limits. So, the speed limit data also needs to be assigned to the GPS by matching the File Id and Sample Timestamp. To be notified that some runs did not have any speed limit recordings, which might because there are no posted speed limit signs been noticed during the short data collection.

Table 17. Examples of "Speed Limit Samples" data

FileID	SampleTimestamp	Speed	Units
24501	07/21/2016 10:29:04.803	45	MPH
24501	07/21/2016 10:29:43.851	0	MPH
24538	07/22/2016 10:48:01.022	35	MPH
24538	07/22/2016 10:51:35.570	45	MPH
24538	07/22/2016 10:52:15.612	35	MPH
…	…	…	…

Step 2: Clean the Raw Data

GPS data with latitude and longitude is used to determine the actual location of data collection in the real word. ArcGIS is used later to plot the GPS points on the map. While, after reviewed the

GPS, BBI and Posted Speed Limit data, we found BBI and Posted Speed Limit are using File ID and Sample Timestamp to match with GPS. And we noticed that the BBI data has higher sampling frequency than GPS data while the Speed Limit data has much lower sampling frequency than GPS data.

Therefore, the strategy for combining the GPS, BBI and Posted Speed Limit data is using GPS data as the base data format and then assign/join the BBI and Posted Speed Limit data to it according to the File ID and Timestamp. In case of the missing data of GPS or BBI data, we will first inventory the number of GPS, BBI, and Speed Limit samples for each data session to check and remove the sessions with absolutely no GPS and BBI data. Noticed that if a session with no Speed Limit data, it will still be kept.

A Python script is developed to go through all the GPS, BBI and Speed Limit data to generate the inventory checking list. The following **Table 18** is an example of the generated inventory checking list. For each data session, the number of GPS data points, BBI data points and Speed Limit data points are listed. Meanwhile, the data samples ratio of BBI and GPS are calculated to check whether the data is normal or not. In summary, there are 73 over 10,828 data sessions with zero number of GPS points. These sessions will be removed before the data combining step. And there are 113 others than these 73 data sessions with the abnormal “BBI/GPS Sample Ratio” (lower than 2.4 or greater than 2.7). This abnormal data will be checked later in detail. In a word, there are less than 2% of missing or abnormal data.

Table 18. Example of the generated inventory checking list

ProcessID	FileID	#GPS_Points	#BBI_Points	#SpeedLimit Points	BBI/GPS Sample Ratio
1	24351	1070	2757	0	2.6
2	24352	423	1090	0	2.6
3	24353	303	783	0	2.6
…	…	…	…	…	…
133	39145	0	8117	0	0
…	…	…	…	…	…
530	76658	7933	20480	11	2.6
531	76659	24672	63141	16	2.6
532	76728	59092	148202	56	2.5
…	…	…	…	…	…

Step 3: Apply Moving Average Filter to BBI data

This step applies a moving average filter (with a window size of 7 points to the BBI data), to smooth out any erratic readings. **Figure 13** in Chapter 3 shows data before and after applying the moving average filter on a sample of BBI data.

Step 4: Combine GPS, BBI and Speed Limit Data to a single file

This step aligns the GPS data (collected at 5 Hz), BBI data (collected at 14 Hz), and posted speed limit data using the closest timestamps. The resulting combined data is referred to as "trajectory data" in subsequent steps. The following subsections describes the detailed procedures.

Assign BBI values to GPS points (more to one data join)

Since the BBI has higher data collection frequency (14 Hz) than GPS (5 Hz), we will match each GPS sample to a BBI sample by finding the closest Sample Timestamp. As shown in the following Figure 51, the two yellow-colored timestamps in a row are matched; the left side are

GPS data, while the right side are BBI data. So, for a certain period, there are more BBI samples than GPS samples because of the lower sampling frequency of GPS, so it will have gaps for GPS data after the matching. In other words, each GPS data point corresponds to multiple BBI data points (normally are two or three). So, we will find the extreme BBI value for assigning to the GPS point, as shown in the red colored boxes and the arrows in **Figure 51**.

GPS Data										BBI Data (After Moving Average)		
FileID	Velocity	Heading	SampleTimestamp	DOP	Latitude	Longitude	Altitude	Inclination		FileID	SampleTimestamp	Inclination
212414	20.9	207.2	2021-06-16**14:04:39.20**43603	1.53	33.763665	-84.432928	955.71	-0.99		212414	2021-06-16**14:04:39.18**87338	-0.99
										212414	2021-06-1614:04:39.2668648	0.23
										212414	2021-06-1614:04:39.3449958	-0.59
212414	20.9	206.2	2021-06-16**14:04:39.40**74949	1.53	33.763650	-84.432937	955.71	-0.75		212414	2021-06-16**14:04:39.40**74949	-0.75
										212414	2021-06-1614:04:39.4856227	-0.47
212414	20.9	205.4	2021-06-16**14:04:39.61**06301	1.53	33.763635	-84.432945	955.71	0.08		212414	2021-06-16**14:04:39.57**93825	0.08
										212414	2021-06-1614:04:39.6575058	-0.04
										212414	2021-06-1614:04:39.7356352	-0.43
212414	20.9	204.7	2021-06-16**14:04:39.81**37677	1.53	33.763620	-84.432953	955.38	1.10		212414	2021-06-16**14:04:39.81**37677	1.10
										212414	2021-06-1614:04:39.8762691	2.62
										212414	2021-06-1614:04:39.9543978	1.92
212414	21.4	204.2	2021-06-16**14:04:40.00**12742	1.53	33.763605	-84.432963	955.38	0.65		212414	2021-06-16**14:04:40.03**25257	0.65
										212414	2021-06-1614:04:40.1106536	0.00
212414	20.5	204.0	2021-06-16**14:04:40.20**44072	1.53	33.763588	-84.432972	955.38	0.33		212414	2021-06-16**14:04:40.20**44072	0.33
										212414	2021-06-1614:04:40.2825374	0.58
										212414	2021-06-1614:04:40.3450418	-0.95

Figure 51. Table. Example of Assigning BBI values to GPS base data

Assign Speed Limit values to GPS points (one to more data join)

Speed Limit data has lesser data points than GPS. So, the Speed Limit data will be first matched to GPS data based on the closest Sample Timestamps. Then, a certain period of GPS data points, from one matched timestamp (as start) to the next matched timestamp (as end), will be assigned the matched Speed Limit values (the start matched one), as the red colored boxes and arrows shown in the **Figure 52**. Noticed that if the speed limit data is not available, the assigned speed limit will be 0. This situation usually happened when data collection is just started before encountered the first speed limit sign.

GPS Samples Data										Speed Limit Samples Data			
FileID	Velocity	Heading	SampleTimestamp	DOP	Latitude	Longitude	Altitude	Asg. SpeedLimit		FileID	SampleTimestamp	Speed	Units
79220	12.4	40	12/04/2017 13:30:30.423	1.59	34.09096	-83.9996	1024	0					
79220	13	40	12/04/2017 13:30:30.627	1.59	34.09097	-83.99959	1024	0					
79220	13.7	39	12/04/2017 13:30:30.830	1.59	34.09098	-83.99958	1024	0					
79220	14.2	39	12/04/2017 13:30:31.033	1.59	34.09098	-83.99957	1024	0					
79220	14.5	40	12/04/2017 13:30:31.236	1.59	34.09099	-83.99956	1024	0					
79220	15.2	39	12/04/2017 13:30:31.424	1.59	34.091	-83.99956	1025	0					
79220	15.4	39	12/04/2017 13:30:31.627	1.59	34.09101	-83.99954	1025	40		79220	12/04/2017 13:30:31.642	40	MPH
79220	15.7	39	12/04/2017 13:30:31.830	1.59	34.09102	-83.99954	1025	40					
79220	16.3	39	12/04/2017 13:30:32.033	1.59	34.09103	-83.99953	1025	40					
79220	16.6	39	12/04/2017 13:30:32.236	1.59	34.09104	-83.99952	1025	40					
...	...	...	...	...	...	...	...	...					
79220	31.7	322	12/04/2017 13:35:15.034	1.57	34.11494	-84.00764	1166	40					
79220	31.2	322	12/04/2017 13:35:15.221	1.57	34.11496	-84.00766	1167	40					
79220	31.1	322	12/04/2017 13:35:15.424	1.57	34.11498	-84.00768	1168	30		79220	12/04/2017 13:35:15.378	30	MPH
79220	30.8	322	12/04/2017 13:35:15.628	1.57	34.115	-84.0077	1168	30					
79220	30.7	322	12/04/2017 13:35:15.831	1.57	34.11503	-84.00772	1169	30					
79220	30.6	323	12/04/2017 13:35:16.034	1.57	34.11505	-84.00773	1169	30					
...	...	...	...	...	...	...	...	...					

Figure 52. Table. Example of assigning Speed Limit value to GPS base data

Combined trajectory data and its format

The following **Figure 53** shown the combined data format, which attached two addition columns of BBI and Speed Limit data on the original GPS data. The ProcessID as the first column is added after generated the inventory checking list; this is for an easier QA/QC. Since there are a total of 10,828 data sessions, the ProcessID starts from 1 and end at 10,828.

ProcessID	FileID	Velocity	Heading	SampleTimestamp	DOP	Latitude	Longitude	Altitude	A_Inclination	A_SpeedLimit
1	24351	40.7	179	07/18/2016 15:58:18.440	1.79	32.96436	-82.8092	472	-0.12	0
1	24351	40.3	179	07/18/2016 15:58:18.648	1.79	32.96432	-82.8092	472	-1.16	0
1	24351	40.3	179	07/18/2016 15:58:18.852	1.67	32.96429	-82.8092	473	-1.67	0
1	24351	40.3	179	07/18/2016 15:58:19.056	1.67	32.96426	-82.8092	474	-0.82	0
1	24351	40.3	179	07/18/2016 15:58:19.240	1.67	32.96422	-82.8092	474	-0.87	0
1	24351	40.3	179	07/18/2016 15:58:19.440	1.79	32.96419	-82.8092	475	-0.51	0
1	24351	40.4	179	07/18/2016 15:58:19.648	1.79	32.96416	-82.8092	475	-0.67	0
1	24351	40.5	179	07/18/2016 15:58:19.844	1.67	32.96413	-82.8092	475	-0.88	0
1	24351	40.5	179	07/18/2016 15:58:20.036	1.67	32.96409	-82.8092	475	-1.03	0
1	24351	40.6	179	07/18/2016 15:58:20.236	1.67	32.96406	-82.8092	475	-0.32	0
1	24351	40.8	179	07/18/2016 15:58:20.436	1.67	32.96403	-82.8092	475	-0.74	0
1	24351	40.8	179	07/18/2016 15:58:20.641	1.67	32.96399	-82.80919	475	-0.58	0
1	24351	40.7	179	07/18/2016 15:58:20.837	1.67	32.96396	-82.80919	476	0.1	0
1	24351	40.7	179	07/18/2016 15:58:21.041	1.67	32.96393	-82.80919	476	-0.74	0
1	24351	40.9	179	07/18/2016 15:58:21.257	1.67	32.96389	-82.80919	476	-1.31	0
1	24351	40.9	179	07/18/2016 15:58:21.461	1.67	32.96386	-82.80919	476	-0.3	0
1	24351	40.7	179	07/18/2016 15:58:21.641	1.67	32.96383	-82.80919	477	0.35	0
1	24351	41.1	179	07/18/2016 15:58:21.837	1.67	32.96379	-82.80919	477	-0.56	0
...	...	...	...	...	...	...	...	...	...	...

Figure 53. Table. The format of the finalized data combination

Instead of combining all the GPS, BBI and Speed Limit data into a super big single file, we artificially separate it to multiple files by each one million data samples. This is considering the reading speed and the computer memory (RAM) when conduct the "selection by location" in ArcGIS for the following step. The **Figure 54** shown the 33 ".csv" files for storing all combined data. Then, the ".csv" formatted trajectory data will be plotted and stored as 33 shapefiles using the ArcGIS software for the later data selection, which is shown in **Figure 55**.

Combined_File_1.csv	Combined_File_2.csv	Combined_File_3.csv
Combined_File_4.csv	Combined_File_5.csv	Combined_File_6.csv
Combined_File_7.csv	Combined_File_8.csv	Combined_File_9.csv
Combined_File_10.csv	Combined_File_11.csv	Combined_File_12.csv
Combined_File_13.csv	Combined_File_14.csv	Combined_File_15.csv
Combined_File_16.csv	Combined_File_17.csv	Combined_File_18.csv
Combined_File_19.csv	Combined_File_20.csv	Combined_File_21.csv
Combined_File_22.csv	Combined_File_23.csv	Combined_File_24.csv
Combined_File_25.csv	Combined_File_26.csv	Combined_File_27.csv
Combined_File_28.csv	Combined_File_29.csv	Combined_File_30.csv
Combined_File_31.csv	Combined_File_32.csv	Combined_File_33.csv

Figure 54. Photo. The combined trajectory data stored in 33 separate files

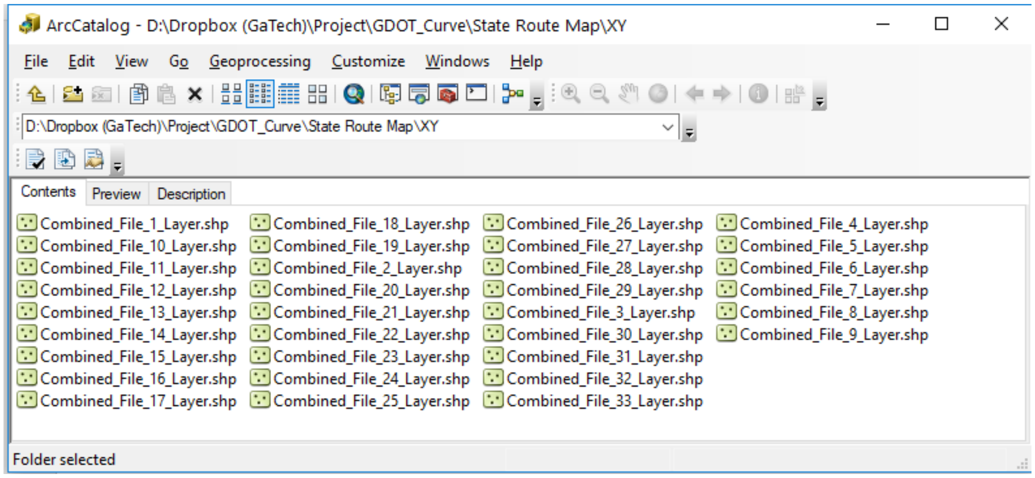


Figure 55. Photo. The shapefile format of 33 combined trajectory data

Step 5: Spatial Query Trajectory Data According to State-maintained Routes

The trajectory data was collected fragmentally by local GDOT officers. This step spatial queries the trajectory data by 75 ft distance to state-maintained routes and saves the queried results as GIS shapefile for each state-maintained roadway. The ArcGIS software was used to select the combined data by individual State Highways (e.g., SR2, SR3). The reasons for splitting the data by route is because we considered generating the curve inventory and design curve signs for each individual state highway. Therefore, we will first acquire the GIS shapefile of all Georgia's State Highways as the base map, then split this shapefile of all Georgia's State Highways to multiple separate shapefiles for each individual highway (i.e., there are 337 state highways in Georgia). After this splitting, each individual shapefile of a highway will as the input feature for selecting the combined trajectory data.

The GIS shapefile of all State Highways

The GIS shapefile base map of the whole Georgia's Highways is acquired from GDOT, as shown in the following Figure 56. In summary, there are 19,878 centerline miles of highways (State

Routes) in the whole Georgia, which are consisted by 337 individual highways.

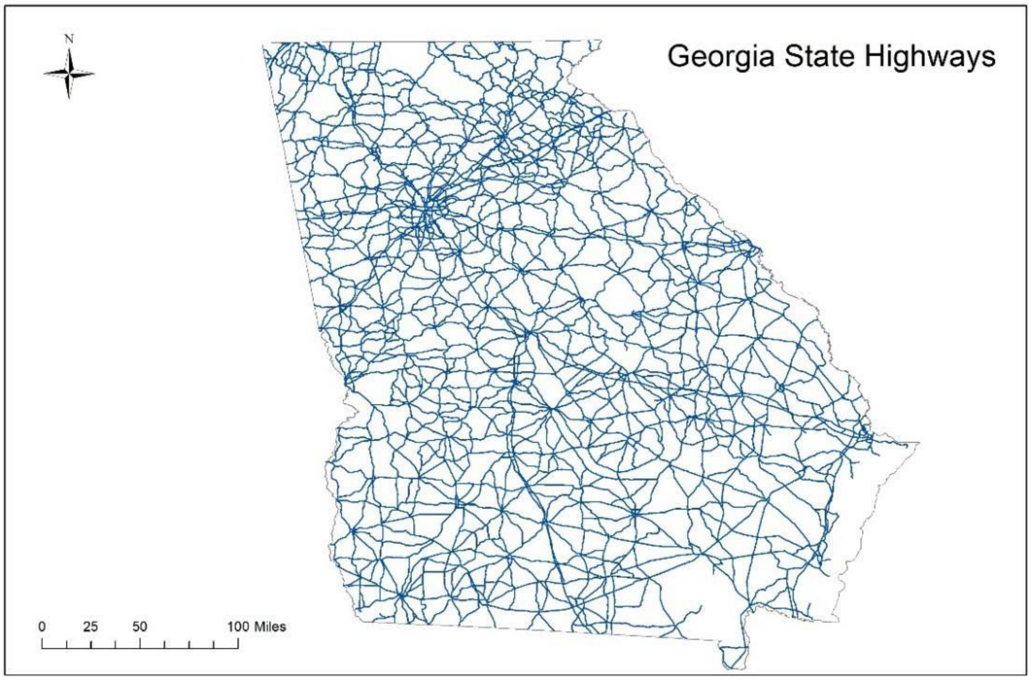


Figure 56. Photo. GIS shapefile of Georgia's State Highways

Split the Highways to individual routes

Considering later in this project that we need to generate the curve inventory and design the curve signs based on each individual state route; So, we need to select the all-trajectory data (i.e. the combined GPS, BBI and Speed Limit data) by each individual state route as well. For this reason, we will split the Highways to individual routes, which gives us 337 individual state routes, as shown in the following **Figure 57**. With the split shapefiles for individual state routes, we can flexibly plot any numbers of state routes. The plotting of state route 1 to 10 is shown in **Figure 58**.

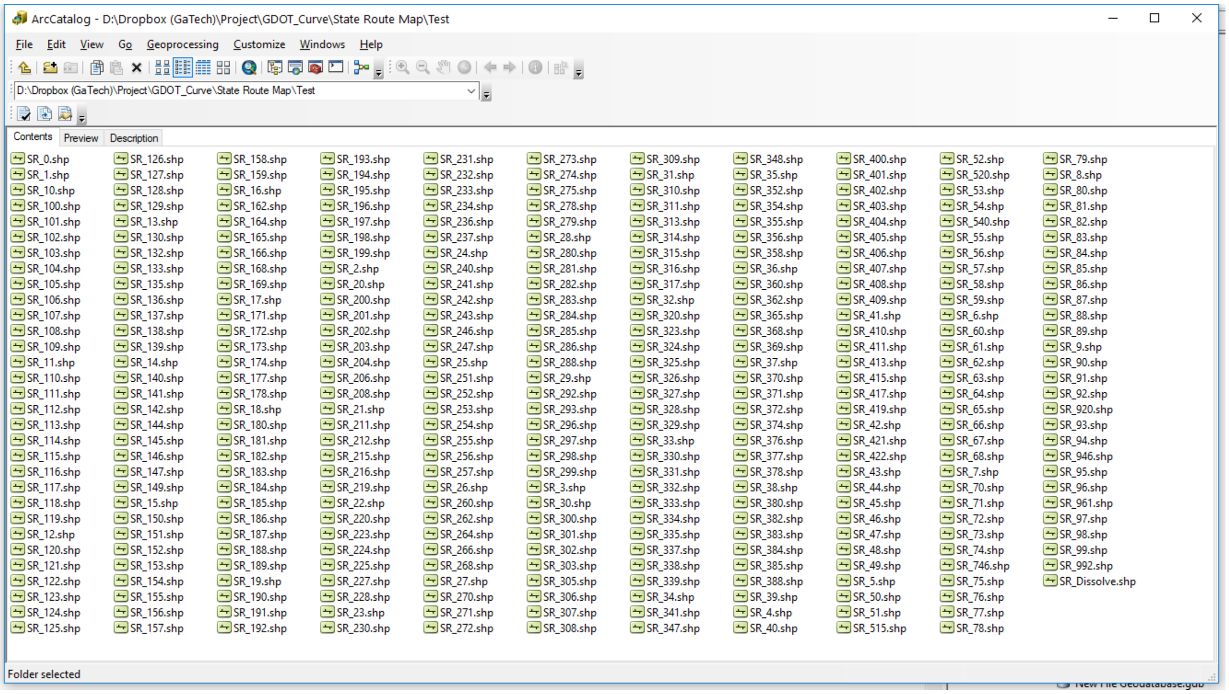


Figure 57. Photo. The 337 split individual state routes

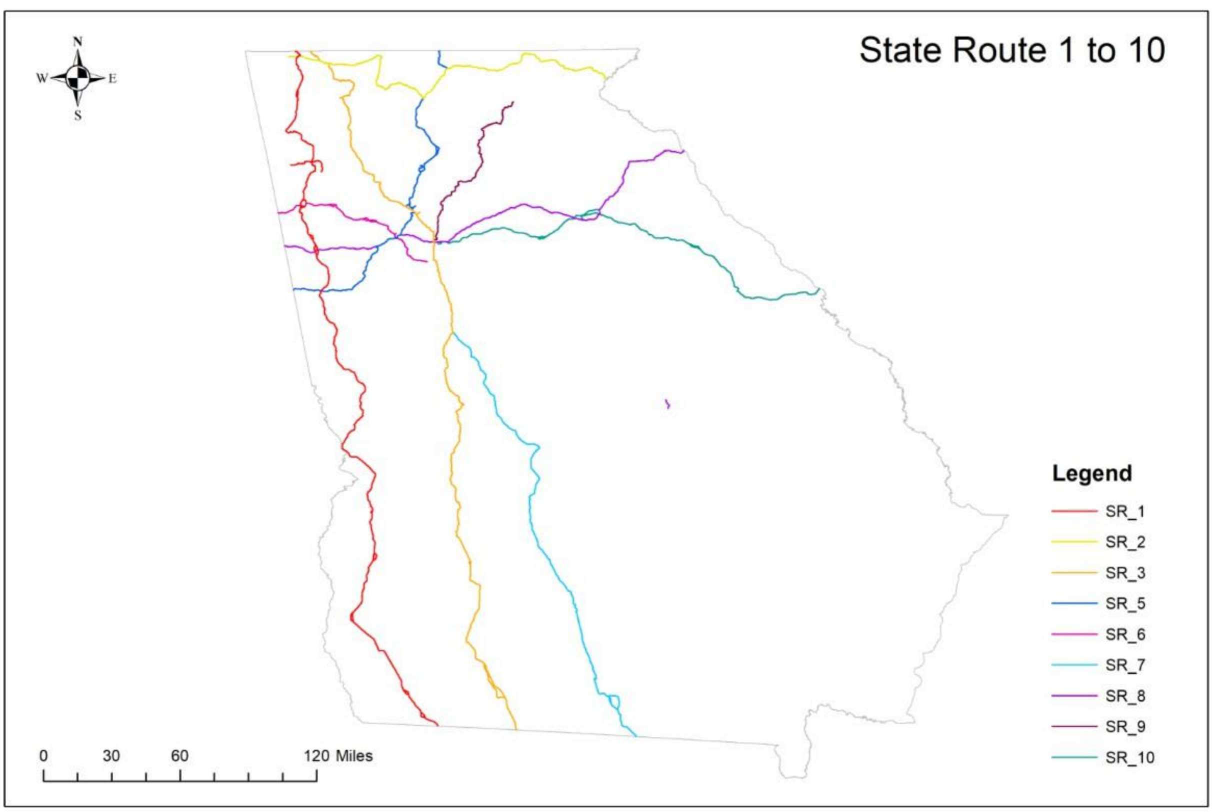


Figure 58. Photo. The GIS plotting of state route 1 to 10

Select trajectory data by route

Using the split individual route as the input feature and the all trajectory data (i.e. the combined GPS, BBI and Speed Limit data) as the target layer for running the "select by location" function in ArcGIS software with a "25 meters" search distance and the "intersection" as the spatial selection method, we can select the trajectory data points that are within the 25 meters range of the base line of the route. The following Figure 59 shown the examples of selected trajectory points of state route 1 to 5.

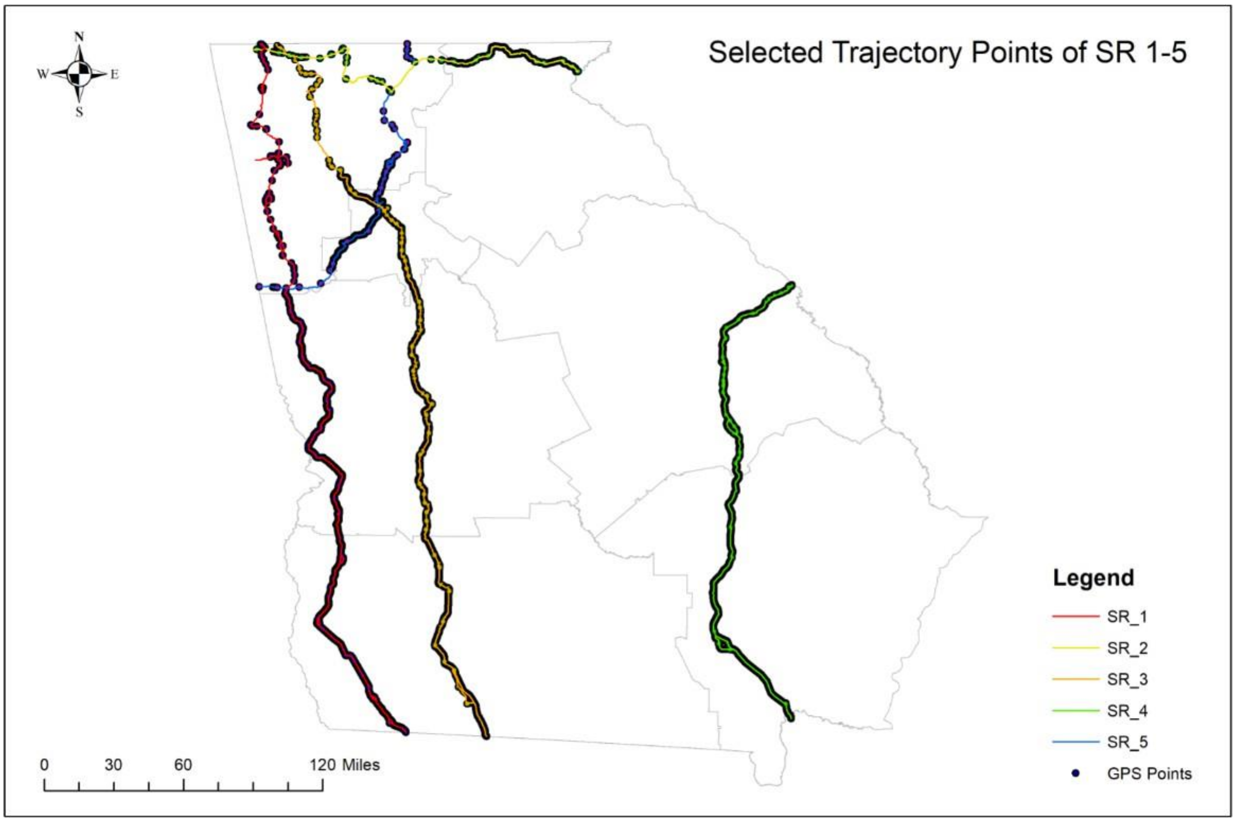


Figure 59. Photo. Selected trajectory points of state route 1 to 5

From the plotting of the selected trajectory points of state route 1 to 5, we found there are only few scatter points had been selected in the District 6, which is the district at the left top corner of

Georgia. To confirm the reason why only scattered points in the District 6, we zoomed in to check the selected trajectory points of State Route 2 in the following section.

Zoom in checking of the selected trajectory points of SR2

Figure 60 shown the zoom in checking of the selected trajectory points of SR 2. From this plotting, we found the trajectory data in the right-side district (District 1) fully covered the whole baseline but the left side district (District 6) is nearly no data covering the base line. To check whether the data of District 6 is missed by not uploading to the CARS portal or missed by our preprocessing problem, the **Figure 61** shown the SR 2 data plotted by CARS portal in District 6. We found many roads nearby the SR 2 are collected but only SR-2 has no data. So, this checking confirmed that the data might not been uploaded to the CARS portal.

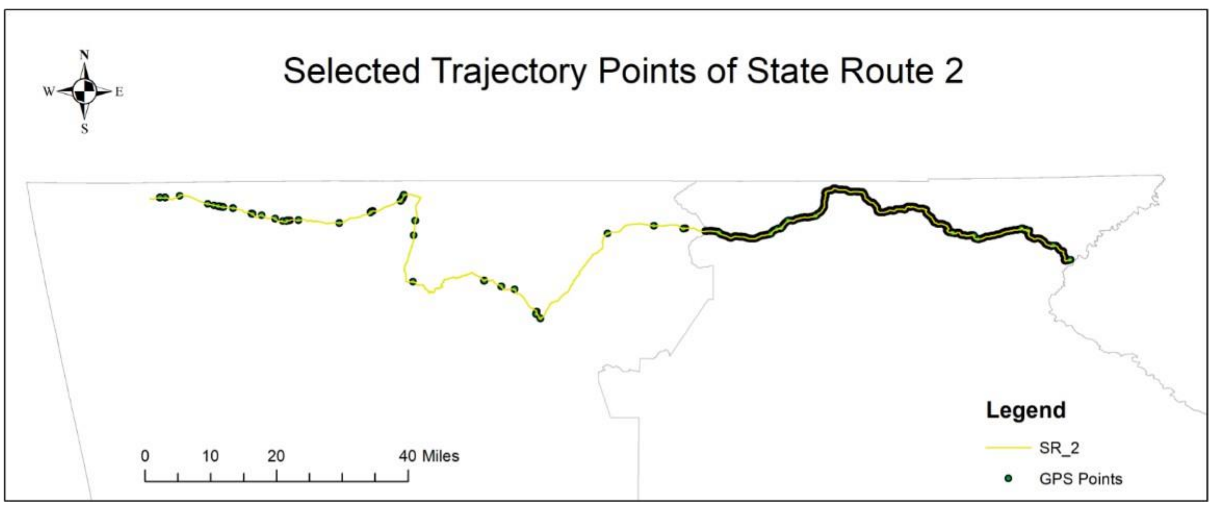


Figure 60. Photo. Zoom in checking of the selected trajectory points of SR 2

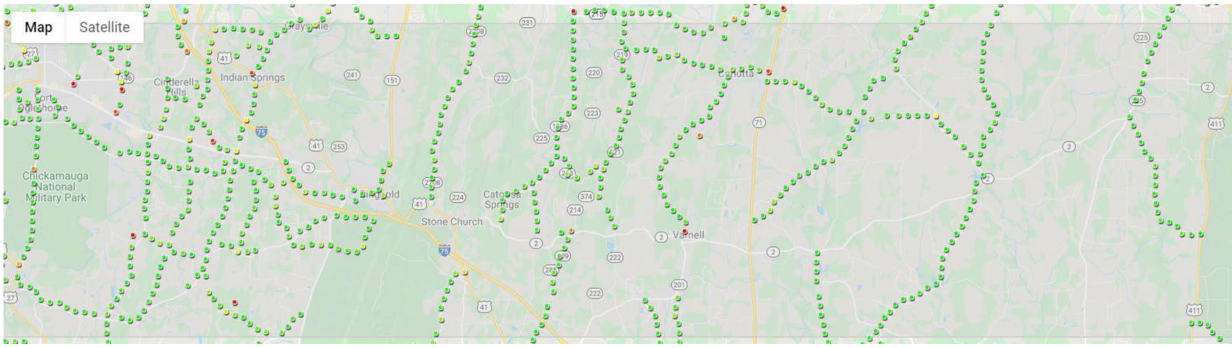
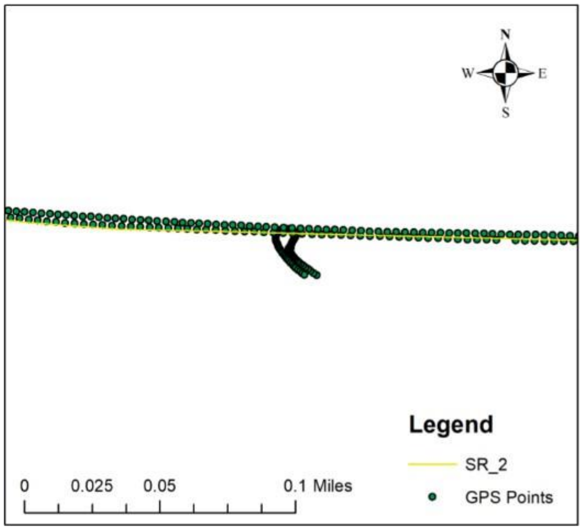


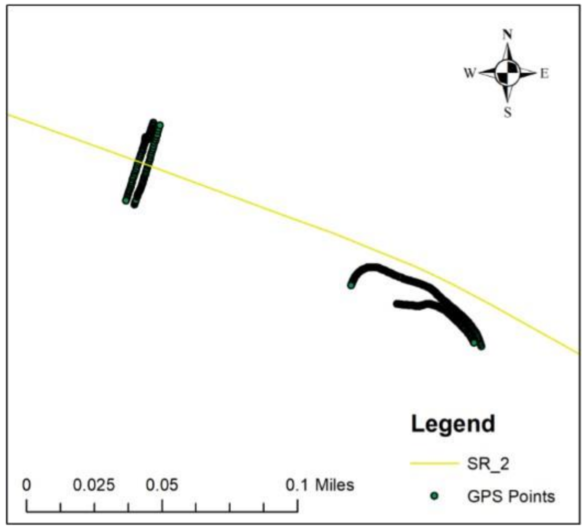
Figure 61. Photo. The missing data of SR2 in District 6 from CARS portal

Step 6: Filter Out the Duplicate and Wrongly Selected Data

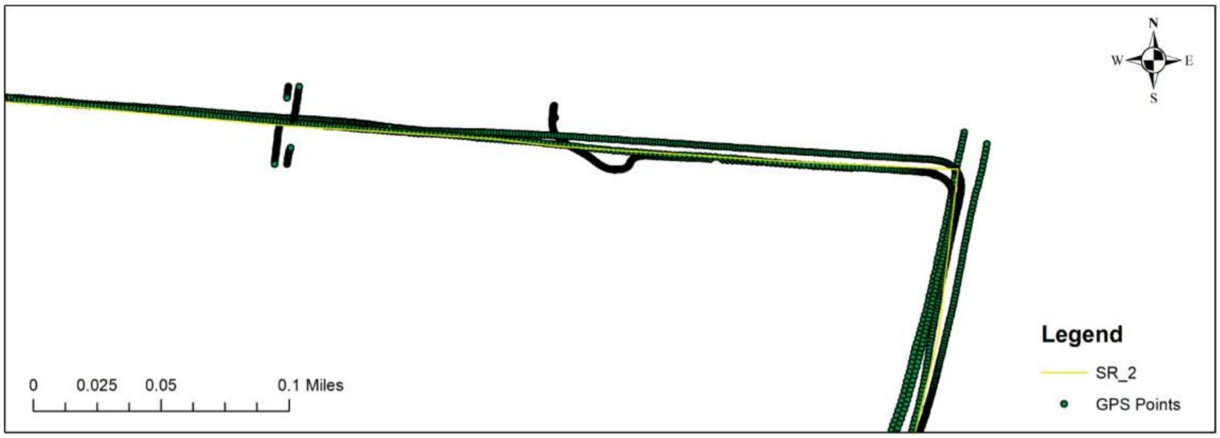
Since the trajectory data selection for each route is based on the spatial relationship (e.g., within 50 meters) of the GPS points and the base line, there are many duplicated and wrongly selected condition happened, as shown in the following **Figure 62**. The wrongly detected trajectory data is from other nearby trips, such as the crossing of other trips, and the duplicated trajectory data is occurred as another wrongly selection condition.



(a) Incorrectly selected U-turn



(b) Incorrectly selected crossing drives



(b) Incorrectly selected crossing and overlapping drives

Figure 62. Photo. The examples of the duplicate and wrongly selected data

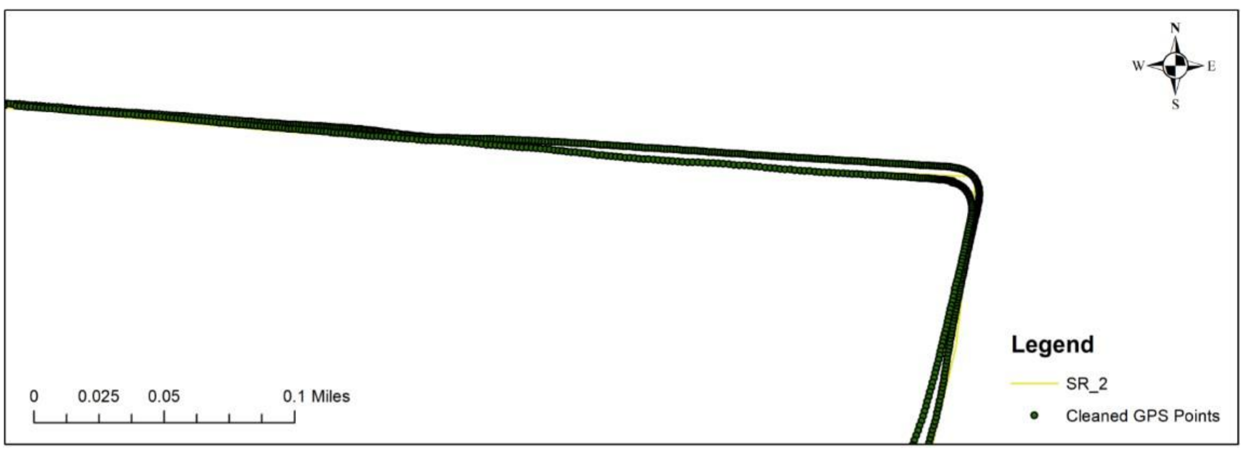
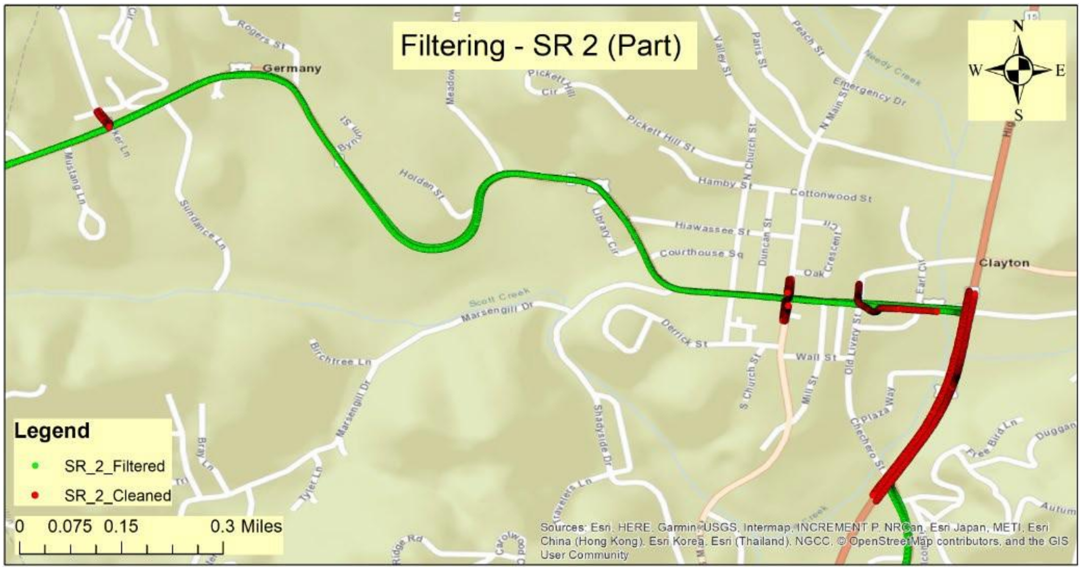
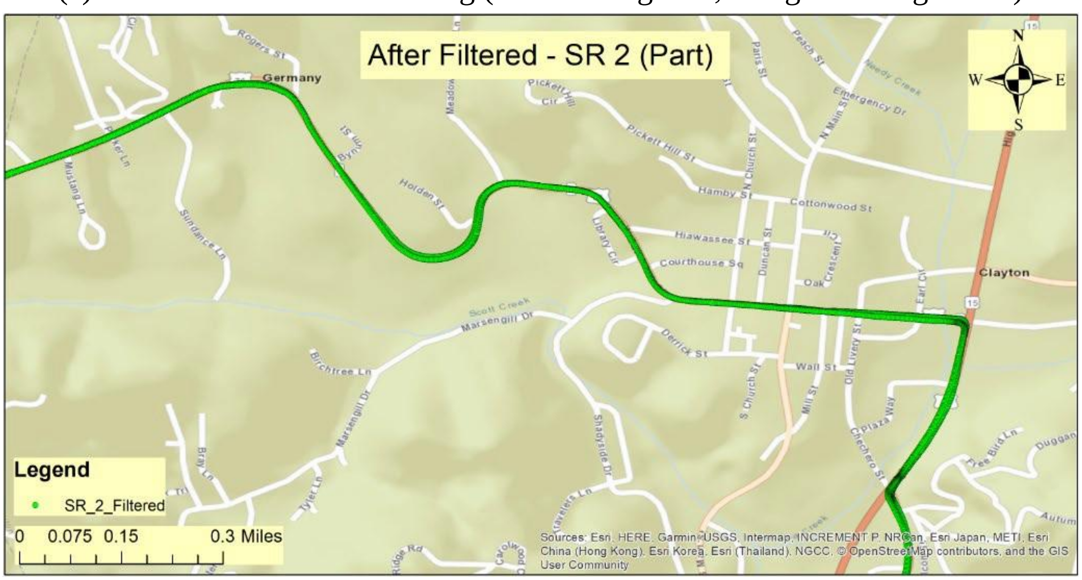


Figure 63. Photo. Filtered out trajectory data

However, these wrongly selected data usually is very short compared to the target data collection trip. Therefore, we removed these wrongly selected data sessions according to their number of trajectory data points. In our python script, we set up 2000 points as the minimum threshold for removing the wrongly collected small sessions, which works well. The **Figure 63** shown the data after filtering out the wrongly selections of **Figure 62 (c)**. And the following **Figure 64 (a)** shown data before filtering and **Figure 64 (b)** shown data after filtering.



(a) Part of SR 2 data for filtering (red is wrong data, and green is right data)



(b) Part of SR 2 after filtered

Figure 64. Photo. Filtering of part of SR 2 trajectory data

APPENDIX C. PRELIMINARY STUDY TO DETERMINE SHARP CURVE

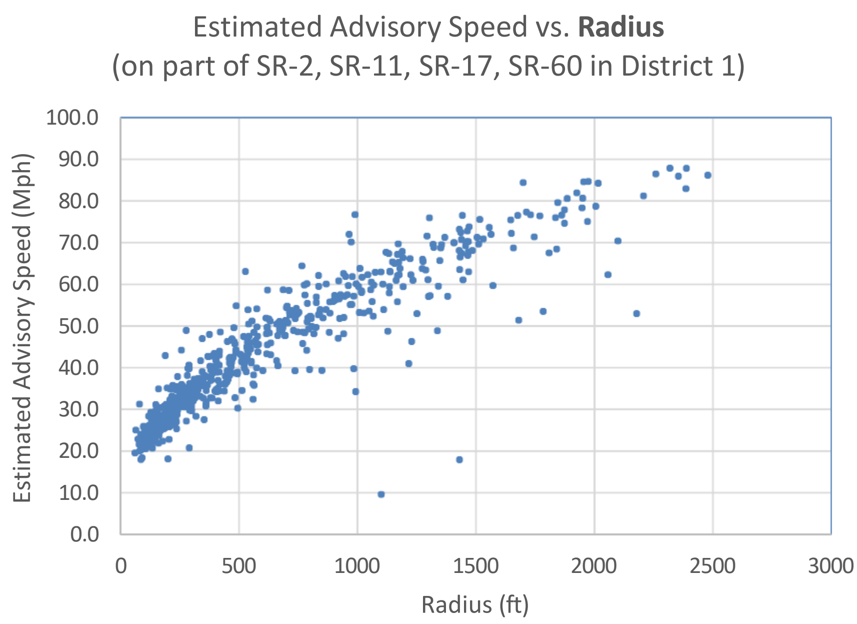


Figure 65. Graph. Estimated Advisory Speed vs. Radius

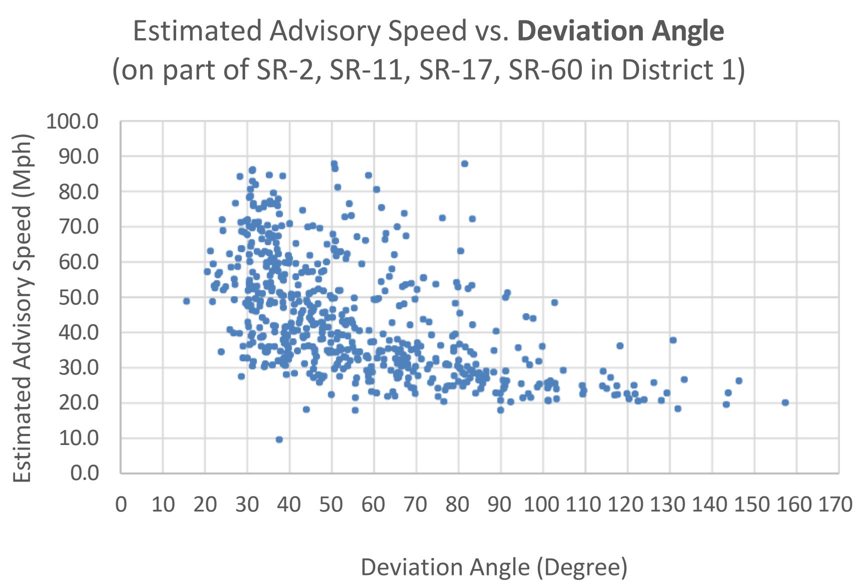


Figure 66. Graph. Estimated Advisory Speed vs. Deviation Angle

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