USING GIS TO IDENTIFY AND CHARACTERIZE HORIZONTAL CURVATURE

2016 PA GIS Conference

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DATA Centric SERVICES

Putting Your Data To Work

PROJECT OVERVIEW

- Curves are roadway characteristics that are highly significant in terms of highway safety.
- Many state DOTs lack data for many of the curves on their roadways.
- Often, curve data exists on ROW or construction plans. But this is not a form which is useful for conducting highway safety analysis or other uses.
- This project examined a technique for using GIS roadway centerline data for automating the process of identifying and characterizing horizontal curves.

ROADWAY CURVES

- Roadway curves are design elements of roadways which serve as transition elements between two straight sections of roadway.
- There are two fundamental types of roadway curves:

Vertical Curves

- "A vertical curve provides a transition between two sloped roadways, allowing a vehicle to negotiate the elevation rate change at a gradual rate rather than a sharp cut." (2)
- There are two types:
  - Sag Curve – Change in grade is positive (valley)
  - Crest Curve – Change in grade is negative (hill)

Horizontal Curves

- "A horizontal curve provides a transition between two tangent strips of roadway, allowing a vehicle to negotiate a turn at a gradual rate rather than a sharp cut." (1)
- There are a number of different categories for horizontal curves:
  - Simple
  - Compound
  - Spiral
  - Reverse

HORIZONTAL CURVATURE AND HIGHWAY SAFETY

The crash rate for horizontal curves on 2-lane rural roads is 3X higher than on tangent road segments (Glennon et al., 1985)

3/4 of curve-related fatal crashes involve vehicles leaving the roadway and striking fixed objects or overturning (FHWA, 2016)

More than 25 % of fatal crashes are associated with a horizontal curve (FHWA, 2016)

The run-off-road crash rate is 4X higher on horizontal curves than on tangent segments (Glennon et al., 1985)

Crash frequency increases with decreasing horizontal curve radius (FHWA, 2016)

HIGHWAY SAFETY

- Improving highway safety and reducing fatalities is a key objective for state DOTs
- High risk sections or roadway need to be identified and prioritized. There are two general approaches:
  - Crash analysis
    - Use historic crash data to identify high risk roads
    - traditional reactive approach
  - Roadway analysis
    - Use roadway characteristics along with safety performance models to identify high risk roads
    - Proactive approach
- Once the top priority high risk roads are identified countermeasures can be implemented to reduce risk in these locations.

COUNTERMEASURES

Aimed at Keeping the Vehicle in its Lane

Centerline Rumble Strips

Chevrons

Delineators

Edge line Rumble Strips

High Friction Surface Treatment

8” Edge Line

COUNTERMEASURES

Aimed at Minimizing the Adverse Consequences of Leaving the Roadway

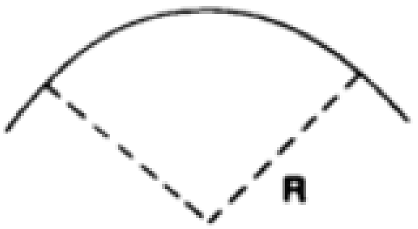
Removing Roadside Fixed Objects

Paving and / or Widening Shoulders

Crash Attenuation Barriers

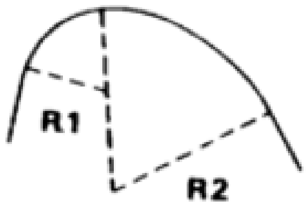
Shoulder Drop Off Elimination

TYPES OF HORIZONTAL CURVES



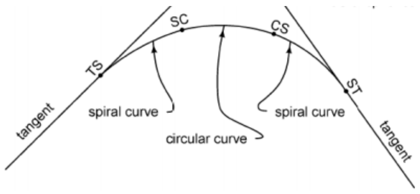
Simple Curves

- Uniform turning radius throughout
- Also known as circular arcs



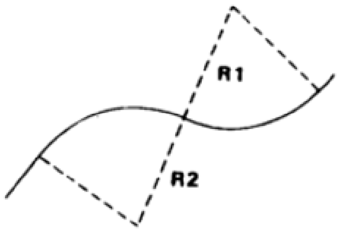
Compound Curves

- Two or more simple curves which are joined and turn in the same direction
- Most often used on interchange loops and ramps



Spiral Curve

- A curve where the radius is continuously getting longer or shorter.
- Spiral curves are generally used to provide a gradual change in curvature from a straight section of road to a curved section.

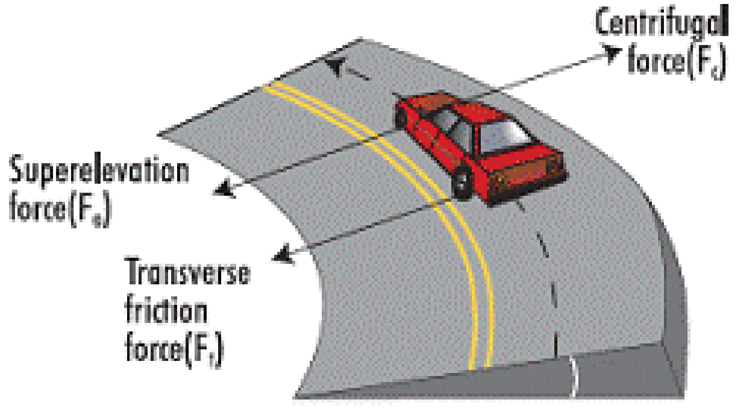


Reverse Curve

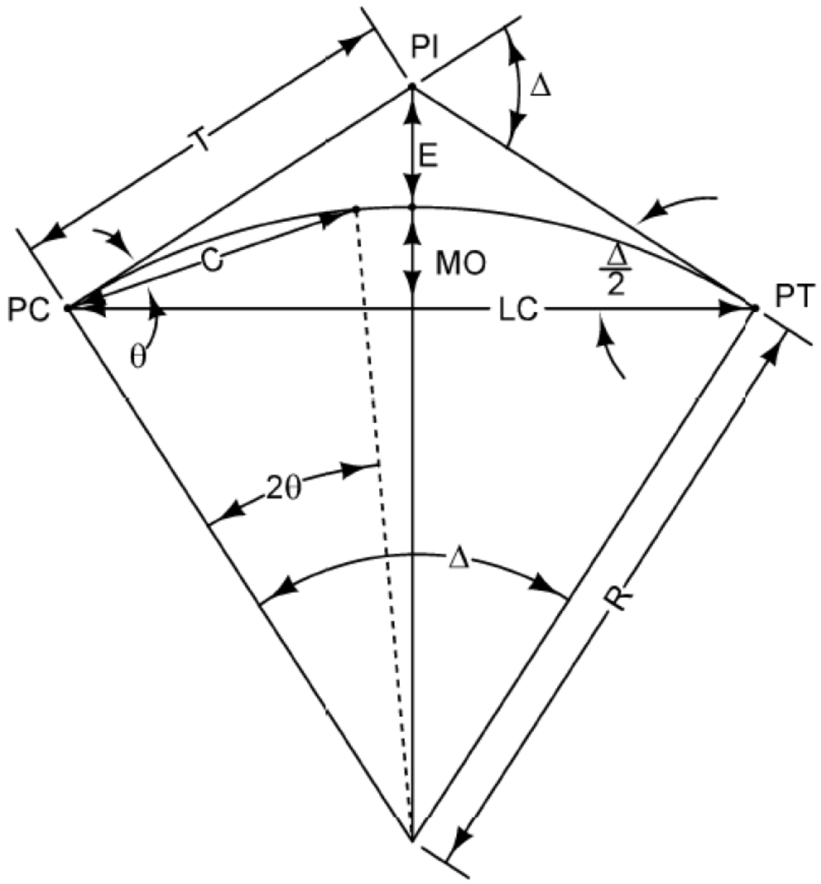
- A reverse curve consists of two simple curves joined together and turning is opposite directions.

SUPERELEVATION

- A car traveling around a curve has a number of forces acting on it:
  - Gravity
  - Centrifugal Force - Tendency of an object following a curved path to fly away from the center of curvature.
  - Centripetal Force - The force that keeps an object moving with a uniform speed along a circular path.
- The presence of superelevation on a curve allows some of the centripetal force to be countered by the ground, thus allowing the turn to be executed at a faster rate than would be allowed on a flat surface.



GEOMETRY OF A SIMPLE HORIZONTAL CURVE



Parameters

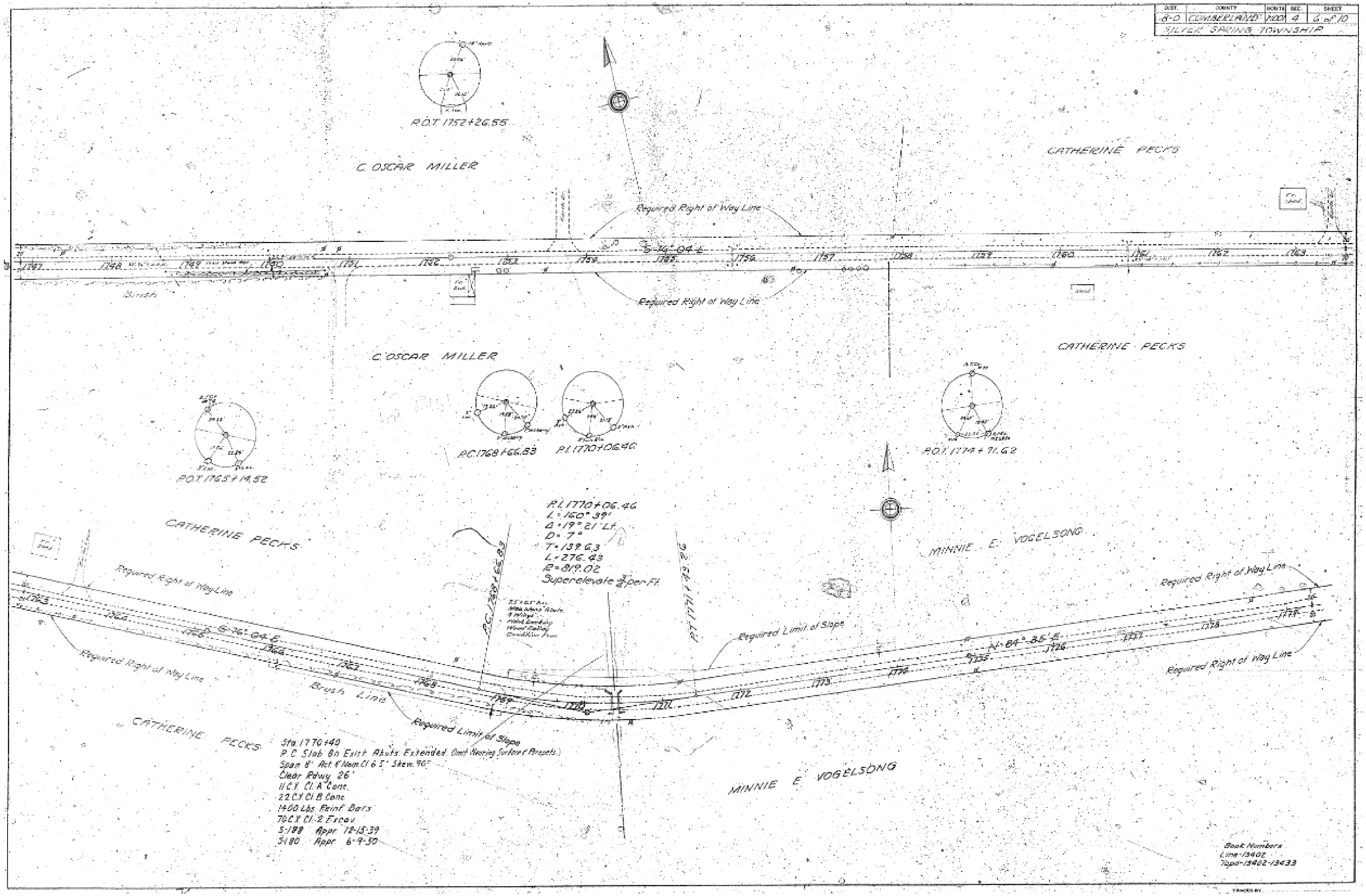
- PC – Point of Curvature
- PT – Point of Tangency
- PI – Point of Intersection
- Δ – Central Angle or Deflection Angle
- R – Radius
- E – External Distance
- MO – Middle Ordinate
- LC – Cord Length
- L – Curve Length (not labeled)
- Tangent Length

EVOLUTION OF A ROAD

- Many of today's roads were once paths.
- Since these roads were not designed, often there is little or no information about various roadway characteristics such as horizontal curves and grade.

ROADWAY PLANS

When these data do exist, they typically reside on right of way or construction plans which can be many decades old.

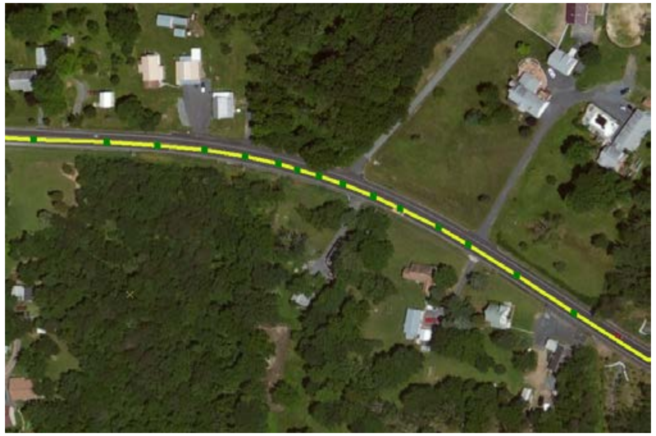


DATA SOURCES TO IDENTIFY AND CHARACTERIZE CURVES

Field Surveys

GPS Data

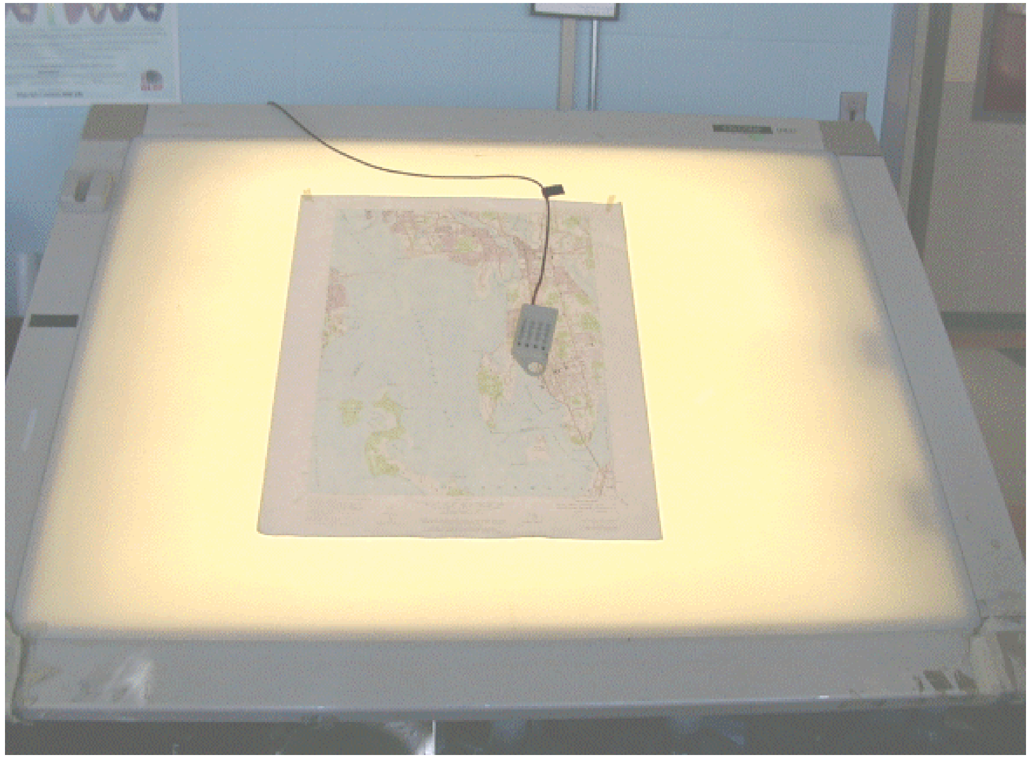
Satellite Imagery



GIS Data

DIGITIZING PA ROADWAYS

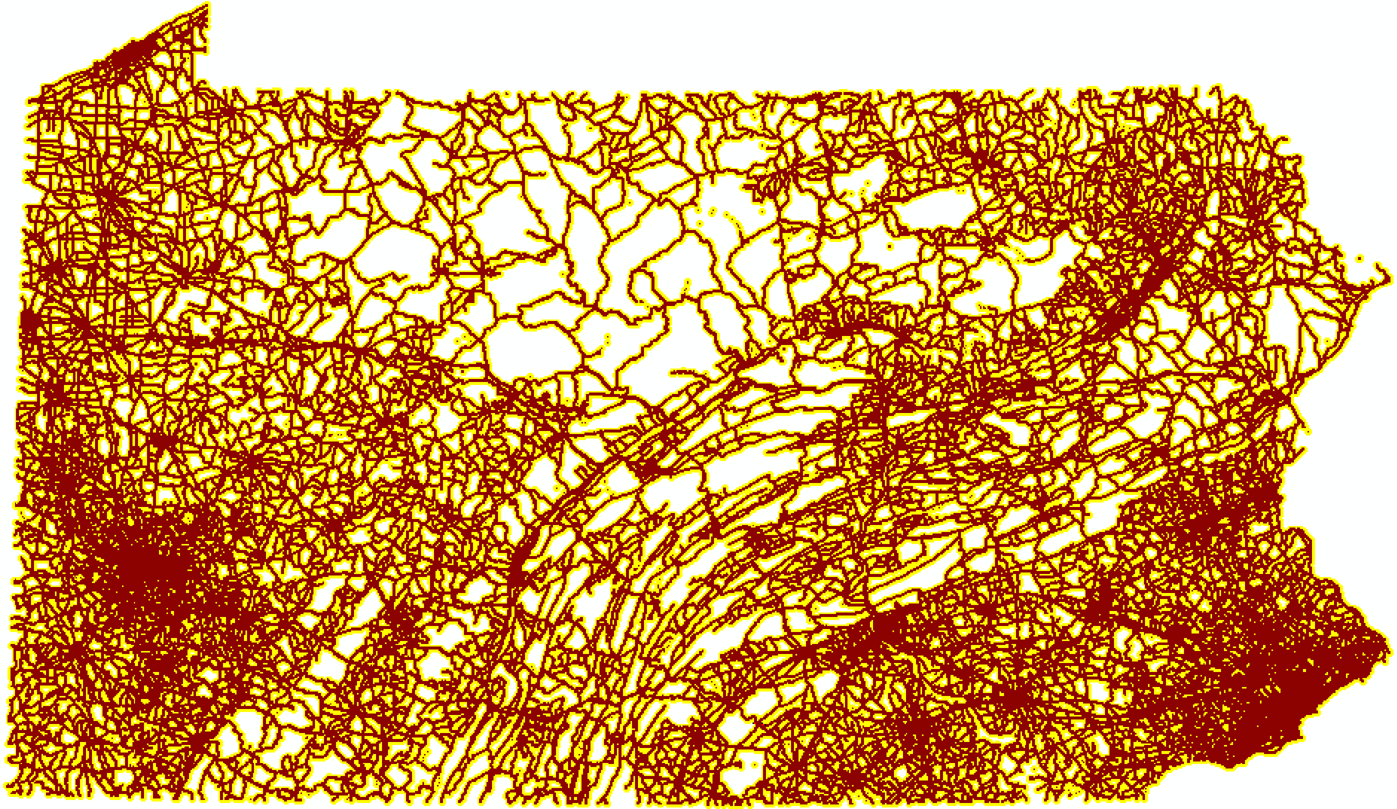
- Original Digitization (1:24,000 Ortho-photography)
  - 35,000 person hours spanning 3 years
- Realignment (1:2,000 Ortho-photography)
  - 33,000 person hours spanning 13 years
- Annual Maintenance
  - 2,000 person hours / year



PENNSYLVANIA'S ROAD NETWORK

PENNSYLVANIA HIGHWAY SYSTEMS	LINEAR MILES	DVMT
TOTAL SYSTEM	120,039	273,648,047
Rural	73,918	98,387,066
Urban	46,121	175,260,981
FEDERAL AID SYSTEM	28,221	229,268,160
National Highway System	7,217	146,755,616
Interstate System	1,867	67,904,906
NON-FEDERAL AID SYSTEM	91,817	44,379,887
TOTAL STATE OWNED	41,103	223,757,168
PennDOT Owned	39,770	205,468,504
Pennsylvania Turnpike Commission	554	16,305,216
Other PA State Agencies	779	1,983,448
TOTAL NON-STATE OWNED	78,935	49,890,879
Total Local Municipal Owned	78,120	47,025,412
Federal Agency Owned	800	2,035,491
Toll Bridge/Ferry	15	829,976

* 2014 Pennsylvania Highway Statistics



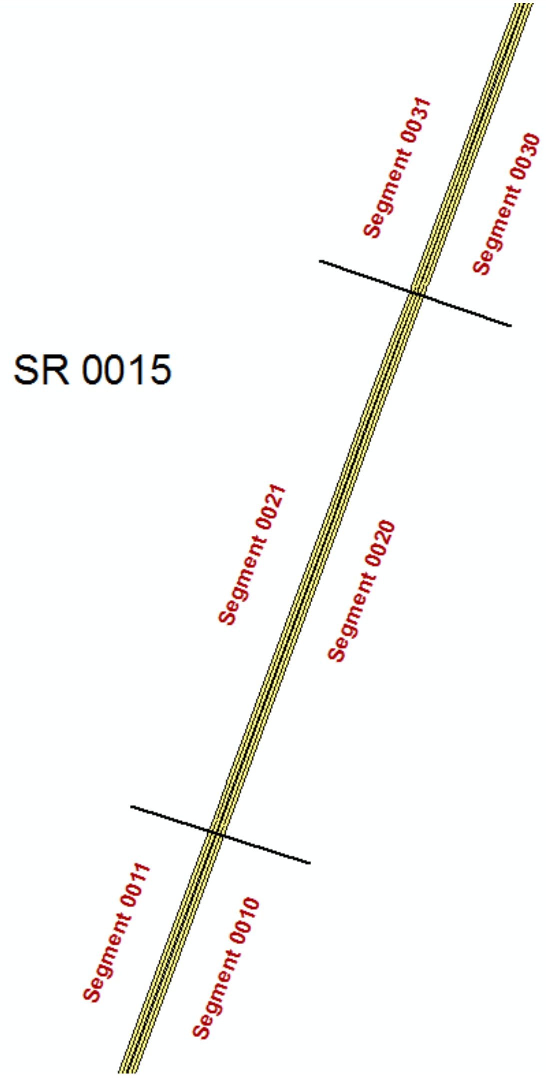
STATE ROUTES AND SEGMENTS

State Routes

- Are identified by a 4 digit number (e.g. SR 0030).
- State route number are unique within a county.
- 0001-0999 are traffic routes
- 1000-4999 are fully contained within a county
- A route can be divided into any number of segments

Segments

- Segments are continuous sections of roadway which are typically about a half mile in length.
- Segments increase in a north or east bound direction typically in increments of 10
- Divided highways have segments in both directions. In the north or eastbound direction the segment number is even and in the opposite direction it is odd.
- The position along a segment is designated as an offset typically specified in feet.



PENNDOT'S LRS

Every position on a Pennsylvania roadway can be identified with an LRS Key.

01400900400348

County

Route

Segment

Offset

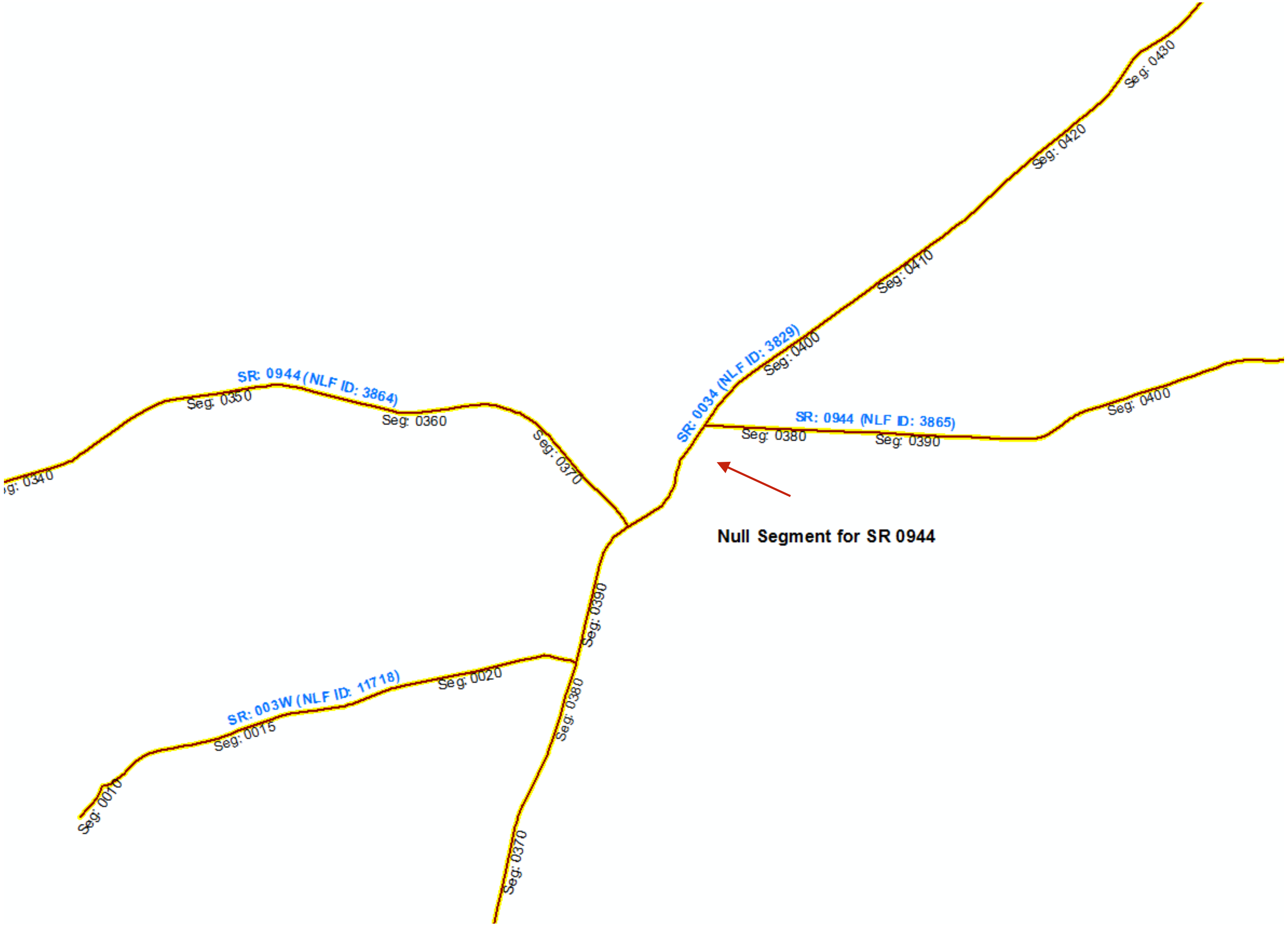
LINEAR REFERENCING SYSTEM (LRS)

- A system of spatial referencing where objects (e.g., signs, guiderail), occurrences (e.g., crashes) or attributes (e.g., speed limit, traffic volume, pavement type) are located in terms of measurements along a linear feature.
- Collectively, these objects, occurrences and attributes are referred to as events.
- An LRS is used in linear networks such as roads, railways, waterways, oil and gas pipelines and power and data transmission lines.
- Dynamic segmentation is a powerful process made possible through the implementation of an LRS.

NETWORK LINEAR FEATURE (NLF)

A null segment is used to represent a discontinuity, or interruption, in a road alignment.

The normal order of precedence is Interstates, followed by U.S. Traffic Routes, then PA Traffic Routes, and finally, other state routes. Within each of these categories, generally the lower numbered route takes precedence

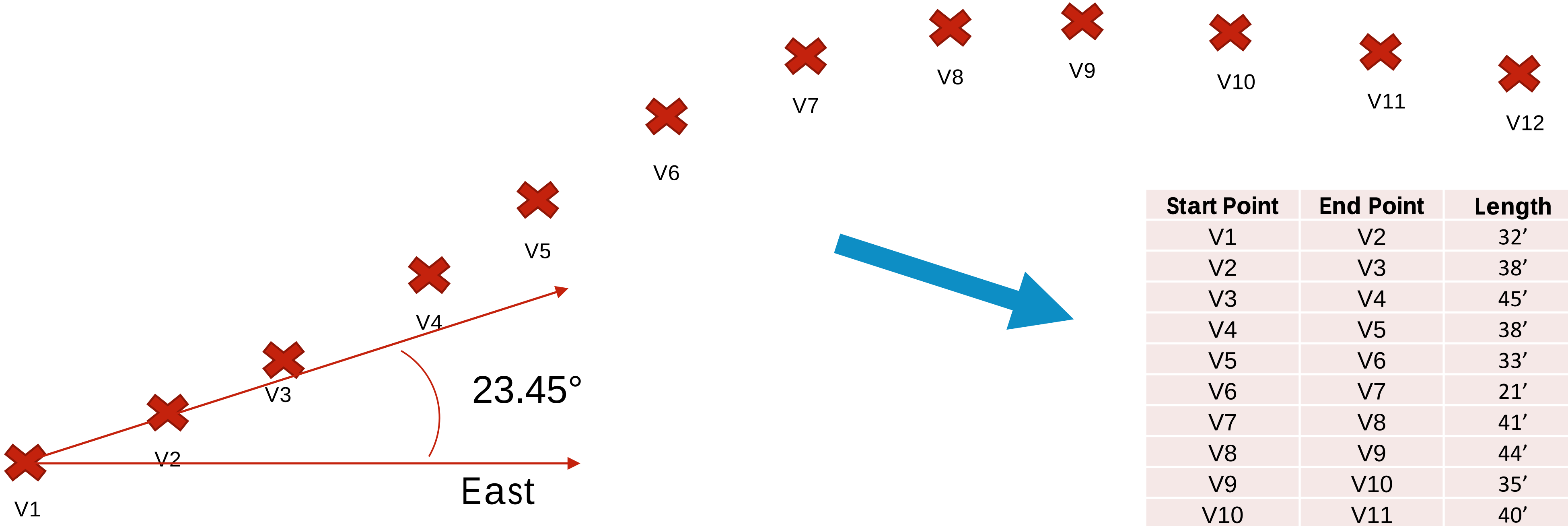


APPROACH

The Happy Path

Step 1

Deconstruct the roadway feature into 2-vertice linear sections and for each section determine its bearing angle with respect to due east (Φ_B).



Start Point	End Point	Length	Φ_B
V1	V2	32′	23.45°
V2	V3	38′	27.22°
V3	V4	45′	35.29°
V4	V5	38′	35.55°
V5	V6	33′	35.18°
V6	V7	21′	29.73°
V7	V8	41′	15.76°
V8	V9	44′	3.34°
V9	V10	35′	-12.45°
V10	V11	40′	-20.26°
V11	V12	39′	-20.21°

APPROACH

The Happy Path

Step 2

A. For each section (n), calculate the difference in the bearing angle for the section ($\Phi_{B(n)}$) in comparison to the bearing angle for the prior section ($\Phi_{B(n-1)}$) and the bearing angle for the next section ($\Phi_{B(n+1)}$).

B. If the changes in bearing angle (Φ_P and Φ_N) both exceed a threshold value (Φ_T), flag the section as being part of a curve and indicate the direction of change.

Start Point	End Point	Length	Φ_B
V1	V2	32’	23.45°
V2	V3	38’	27.22°
V3	V4	45’	35.29°
V4	V5	38’	35.55°
V5	V6	33’	35.18°
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V8	V9	44’	3.34°
V9	V10	35’	-12.45°
V10	V11	40’	-20.26°
V11	V12	39’	-20.21°

Step 2A. $\Phi_P = \Phi_{B(n)} - \Phi_{B(n-1)}$

$\Phi_N = \Phi_{B(n+1)} - \Phi_{B(n)}$

Start Point	End Point	Length	Φ_B	Φ_P	Φ_N
V1	V2	32’	23.45°		3.77°
V2	V3	38’	27.22°	3.77°	8.07°
V3	V4	45’	32.29°	8.07°	3.26°
V4	V5	38’	35.55°	3.26°	-0.37°
V5	V6	33’	35.18°	-0.37°	-5.45°
V6	V7	21’	29.73°	-5.45°	-13.97°
V7	V8	41’	15.76°	-13.97°	-12.42°
V8	V9	44’	3.34°	-12.42°	-15.79°
V9	V10	35’	-12.45°	-15.79°	-7.81°
V10	V11	40’	-20.26°	-7.81°	0.05°
V11	V12	39’	-20.21°	0.05°	

Step 2B. If $|\Phi_P| > \Phi_T$ AND $|\Phi_N| > \Phi_T$ then Curve=“Yes”

Start Point	End Point	Length	Φ_B	Φ_P	Φ_N	Curve	Direction
V1	V2	32’	23.45°		3.77°	No	
V2	V3	38’	27.22°	3.77°	8.07°	Yes	Left
V3	V4	45’	32.29°	8.07°	3.26°	Yes	Left
V4	V5	38’	35.55°	3.26°	-0.37°	No	
V5	V6	33’	35.18°	-0.37°	-5.45°	No	
V6	V7	21’	29.73°	-5.45°	-13.97°	Yes	Right
V7	V8	41’	15.76°	-13.97°	-12.42°	Yes	Right
V8	V9	44’	3.34°	-12.42°	-15.79°	Yes	Right
V9	V10	35’	-12.45°	-15.79°	-7.81°	Yes	Right
V10	V11	40’	-20.26°	-7.81°	0.05°	No	
V11	V12	39’	-20.21°	0.05°		No	

APPROACH

The Happy Path

Step 3

Pass through the array and construct curve features from consecutive curve sections aggregating the changes in bearing angle to yield the central angle (Δ)and aggregating the length of the sections to determine curve length and NLF offsets for the start of the curve and the end of the curve.

Start Point	End Point	Length	Φ_B	Φ_P	Φ_N	Curve	Direction
V1	V2	32’	23.45°		3.77°	No	
V2	V3	38’	27.22°	3.77°	8.07°	Yes	Left
V3	V4	45’	32.29°	8.07°	3.26°	Yes	Left
V4	V5	38’	35.55°	3.26°	-0.37°	No	
V5	V6	33’	35.18°	-0.37°	-5.45°	No	
V6	V7	21’	29.73°	-5.45°	-13.97°	Yes	Right
V7	V8	41’	15.76°	-13.97°	-12.42°	Yes	Right
V8	V9	44’	3.34°	-12.42°	-15.79°	Yes	Right
V9	V10	35’	-12.45°	-15.79°	-7.81°	Yes	Right
V10	V11	40’	-20.26°	-7.81°	0.05°	No	
V11	V12	39’	-20.21°	0.05°		No	

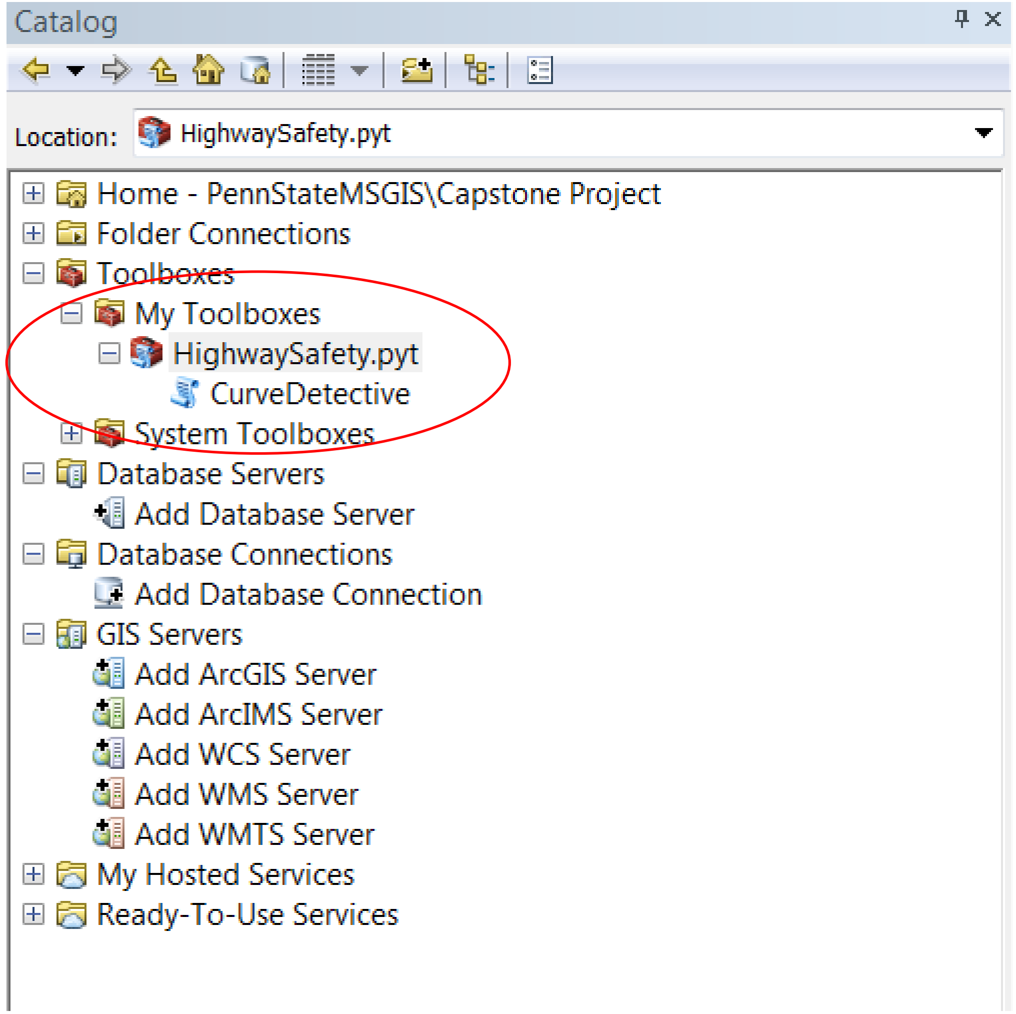
Array of 2-Vertice Linear Sections

Δ	Length	Radius	NLF	Start Offset	End Offset	Direction
15.10°	83’	32’	1581	32’	115’	Left
55.44°	141’	38’	1581	186’	327’	Right

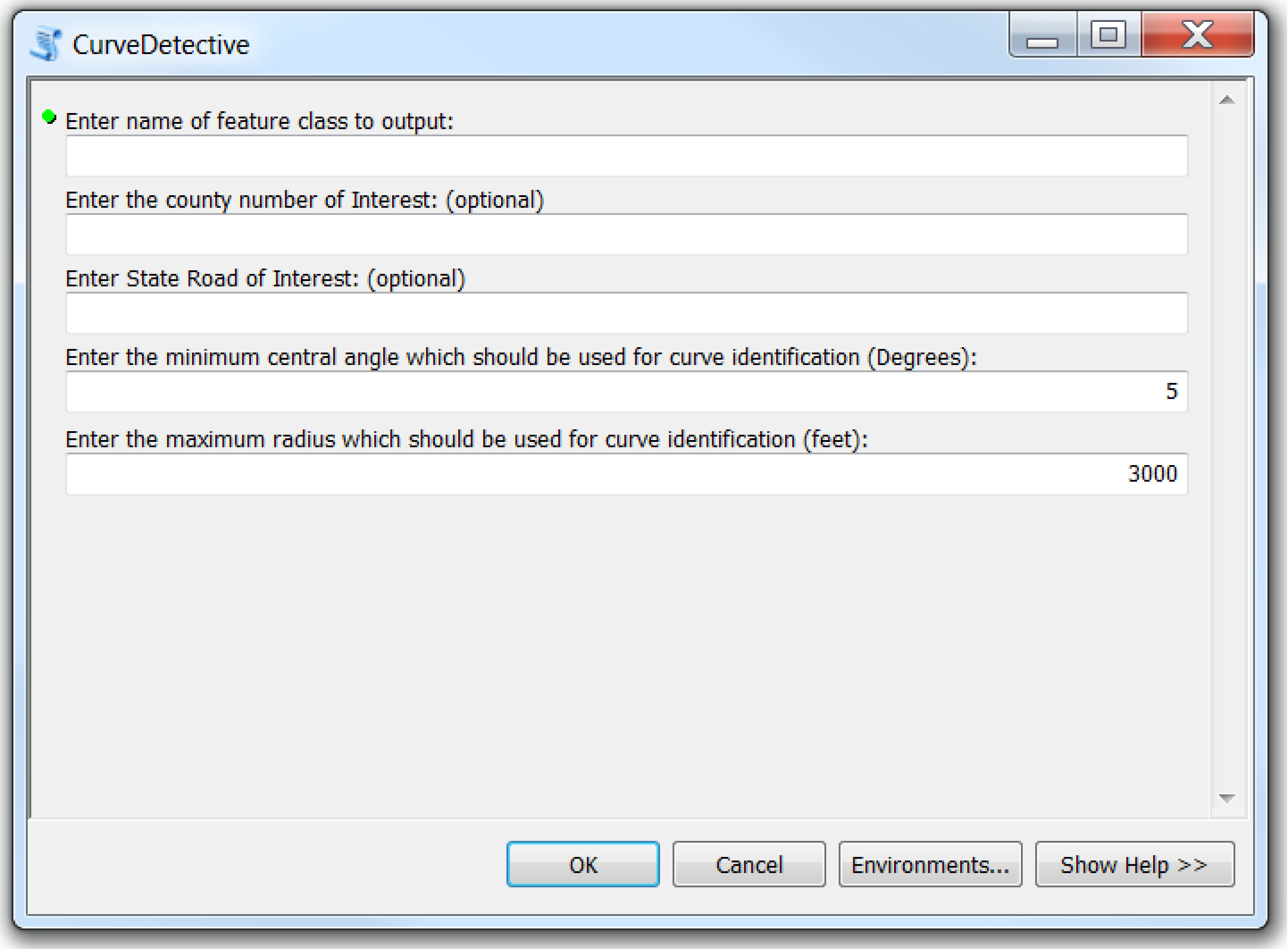
Curve Feature Class

AUTOMATING THE APPROACH

A custom Python toolbox in ArcGIS was developed which uses roadway centerline data to identify and characterize horizontal curves.



CURVE DETECTIVE INTERFACE

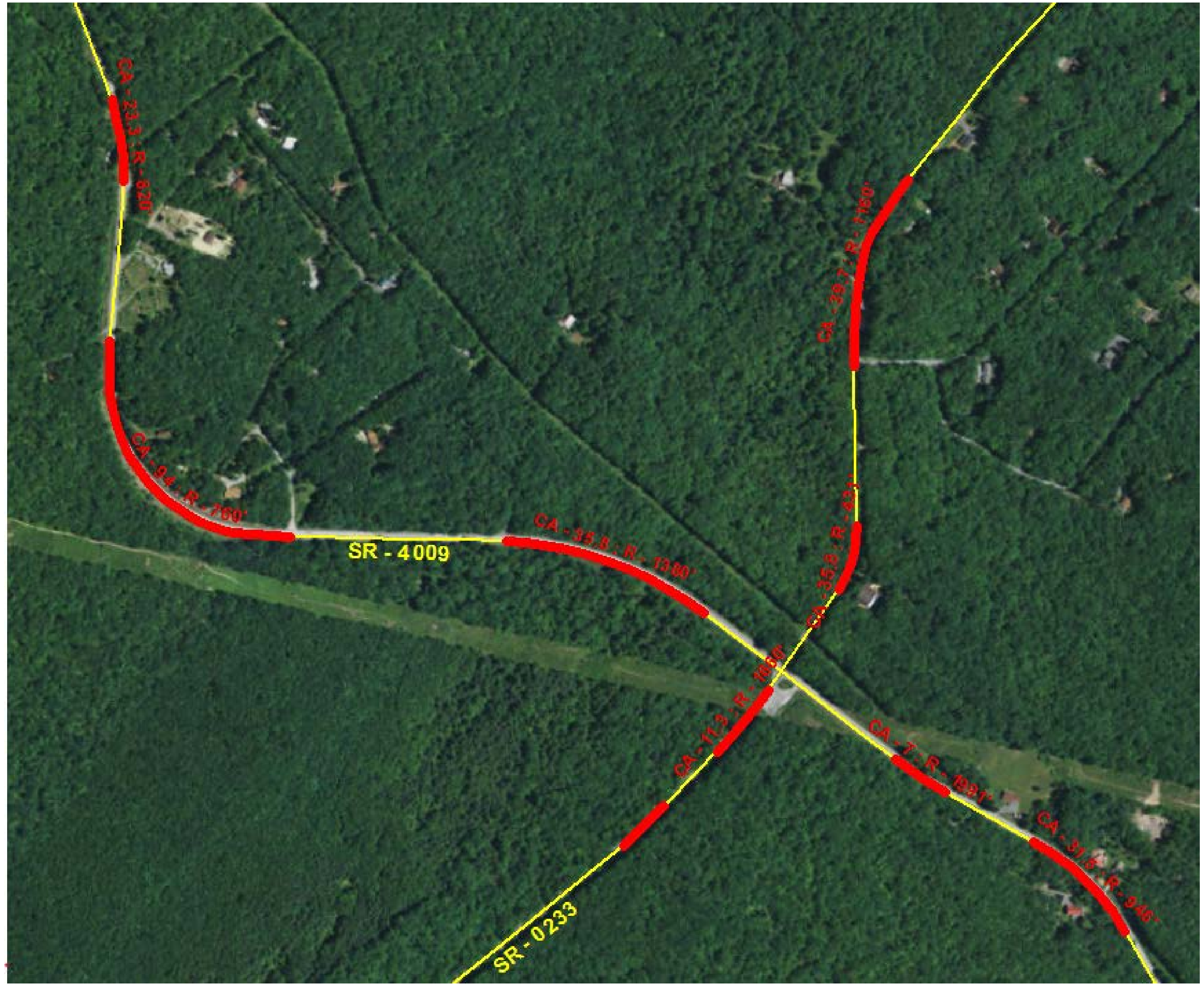


- Curve Detective was written in Python.
- It can be added to ArcGIS as a custom tool.
- If an SR is not specified, the entire county will be processed.
- If a county isn’t specified, the entire state will be processed.

TOOL OUTPUT

The tool output is a horizontal curve feature class with the following attributes:

- Central Angle
- Radius
- Curve Length
- Direction of turn
- NLF ID
- NLF Begin Offset
- NLF End Offset



STATEWIDE ANALYSIS

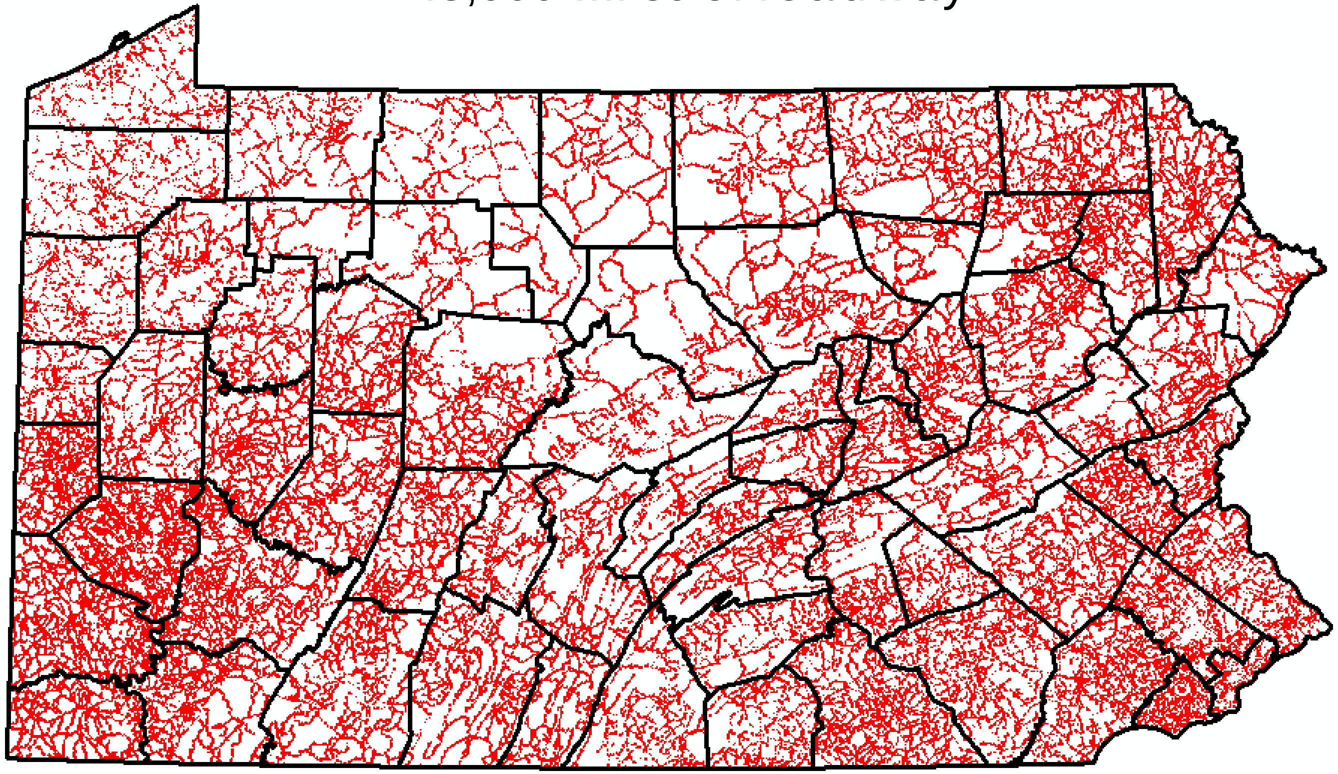
45,000 miles of roadway

Parameters:

- Central Angle > 5°
- Radius < 3000’

Results:

- 2 hours to process
- 169,222 curves



Table

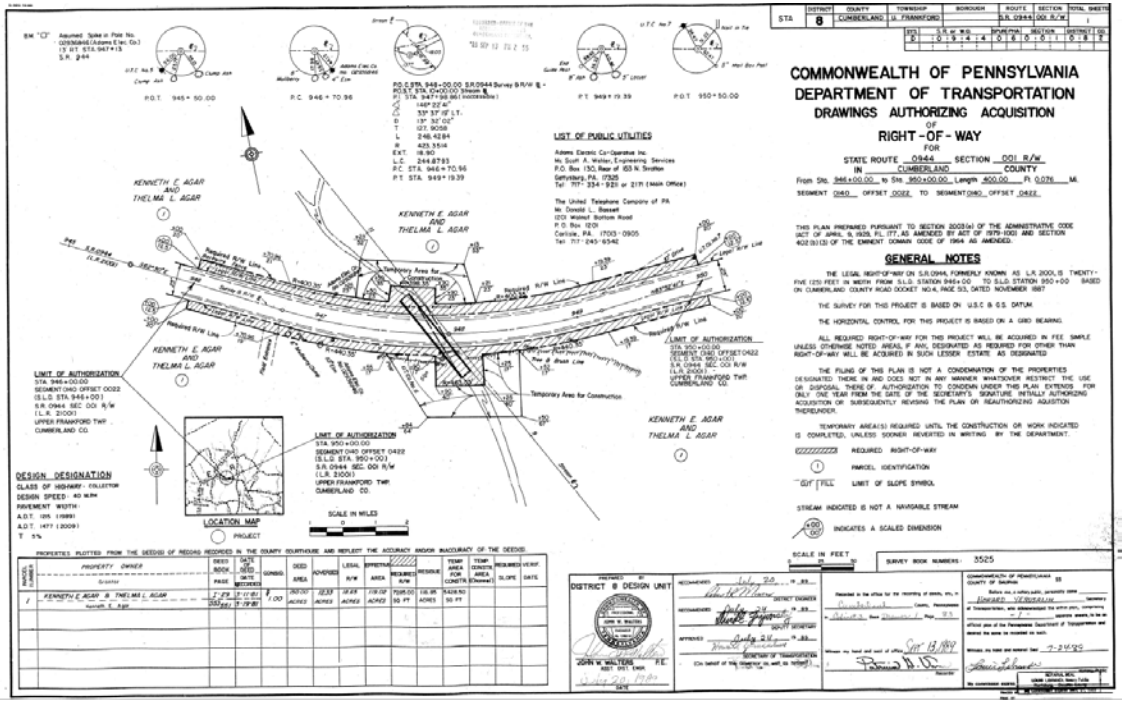
StatewideHC

OBJECTID *	Shape *	Shape_Length	Radius	CentralAngle	Length	NLF_ID	NLF_CNTL_B	NLF_CNTL_E	Reverse	Direction	Verticies
1	Polyline	1695.415565	2481	39.14874	1695	1	5329	7028		R	16
2	Polyline	1552.79122	2779	32.01065	1553	1	12487	14040		L	13
3	Polyline	118.438401	1212	5.599602	118	1	41174	41292		L	2
4	Polyline	164.062778	1510	6.226431	164	1	47588	47752		L	2
5	Polyline	118.344097	1195	5.675139	118	1	59286	59404		L	2
6	Polyline	184.415822	2113	5.000508	184	1	92241	92426		R	2
7	Polyline	257.824586	1740	8.487478	258	1	100699	100957		L	3
8	Polyline	722.848508	2097	19.74918	723	1	101119	101842		L	7
9	Polyline	489.783942	1835	15.29247	490	1	113659	114149		R	5
10	Polyline	440.03538	1635	15.41679	440	1	118643	119083		R	5
11	Polyline	221.451068	2028	6.256175	221	1	124693	124914		L	3
12	Polyline	280.620579	2351	6.840353	281	1	125202	125483		L	3
13	Polyline	122.366832	1340	5.233905	122	1	125721	125844		L	2
14	Polyline	327.526142	2209	8.49439	328	1	127758	128077		R	4
15	Polyline	218.183709	1822	6.860234	218	1	128262	128480		R	3

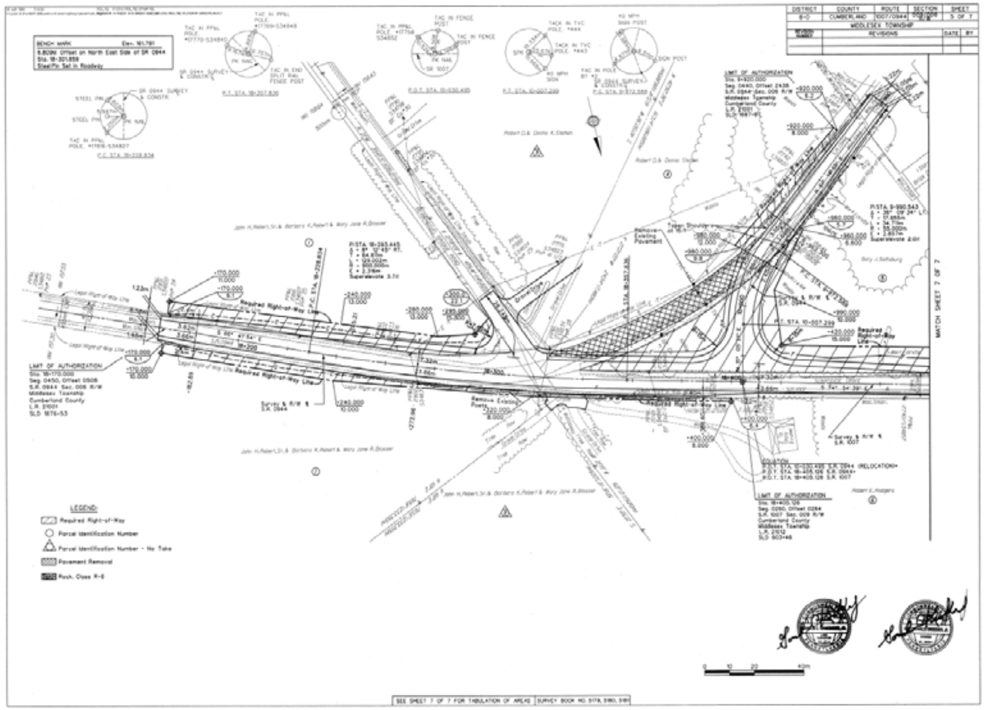
1 (0 out of 169222 Selected)

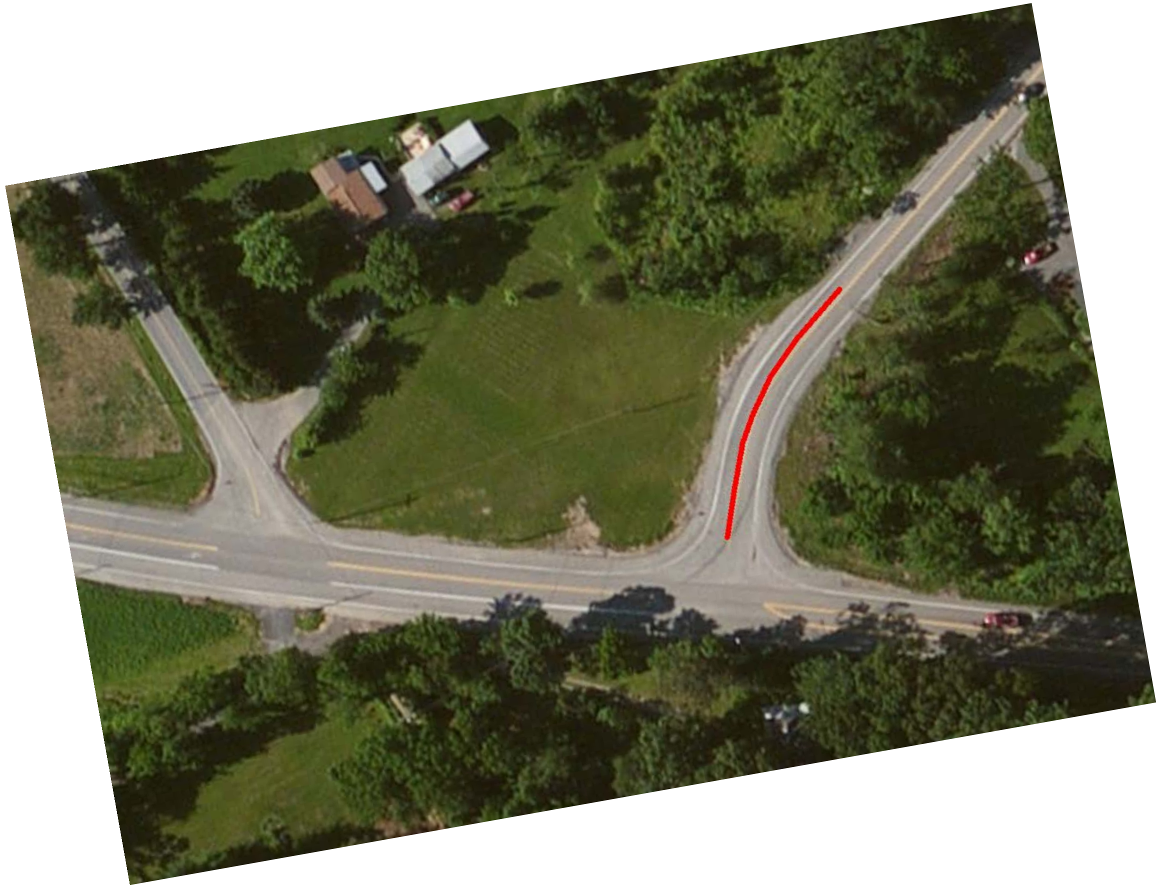
StatewideHC

CUMBERLAND COUNTY
SR 0944 : SEGMENT 140



CUMBERLAND COUNTY SR 0944 : SEGMENT 440





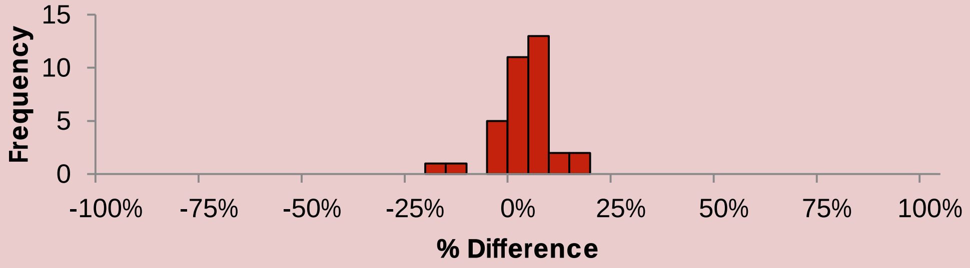
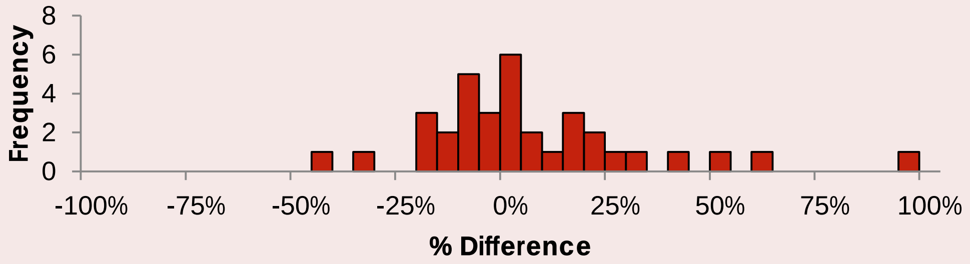
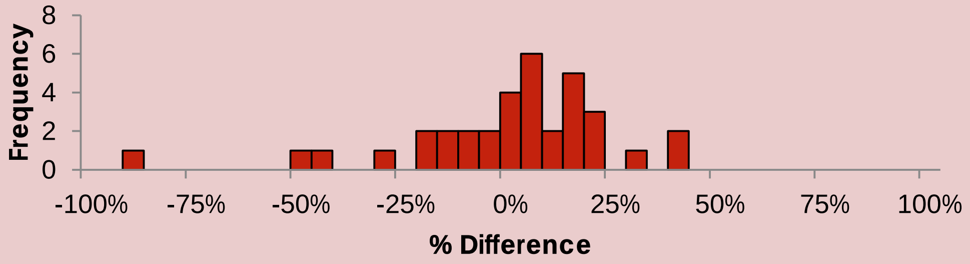
VALIDATION OF RESULTS

- Curve data was manually extracted from ROW and Construction plans. Some challenges in doing this:
  - Finding plans with curvature information
  - Translating legislative route designations to State Route designations
  - Determining segment – offset from project stationing designations used on drawings
- Central angle, length and radius values were compared to the output of Curve Detector.
- Total number of curves compared was 35

Characteristics of Selected Curves

Parameter	Range
Central Angle	8° - 102°
Length	114 ft – 1124 ft
Radius	180 ft – 2953 ft

VALIDATION OF RESULTS

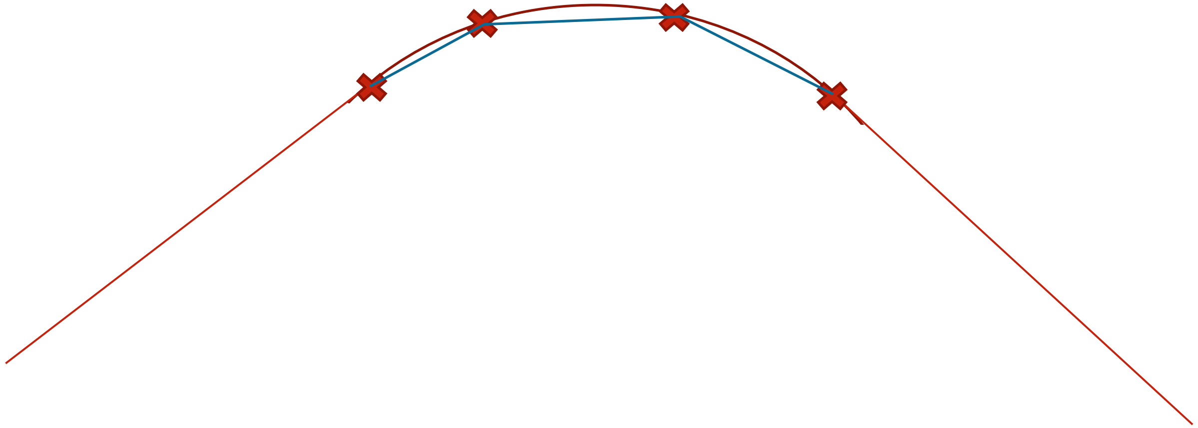
Parameter	Avg % Difference (%D)	SD	Histogram
Central Angle	-1%	6%	
Length	2%	26%	
Radius	-3%	25%	

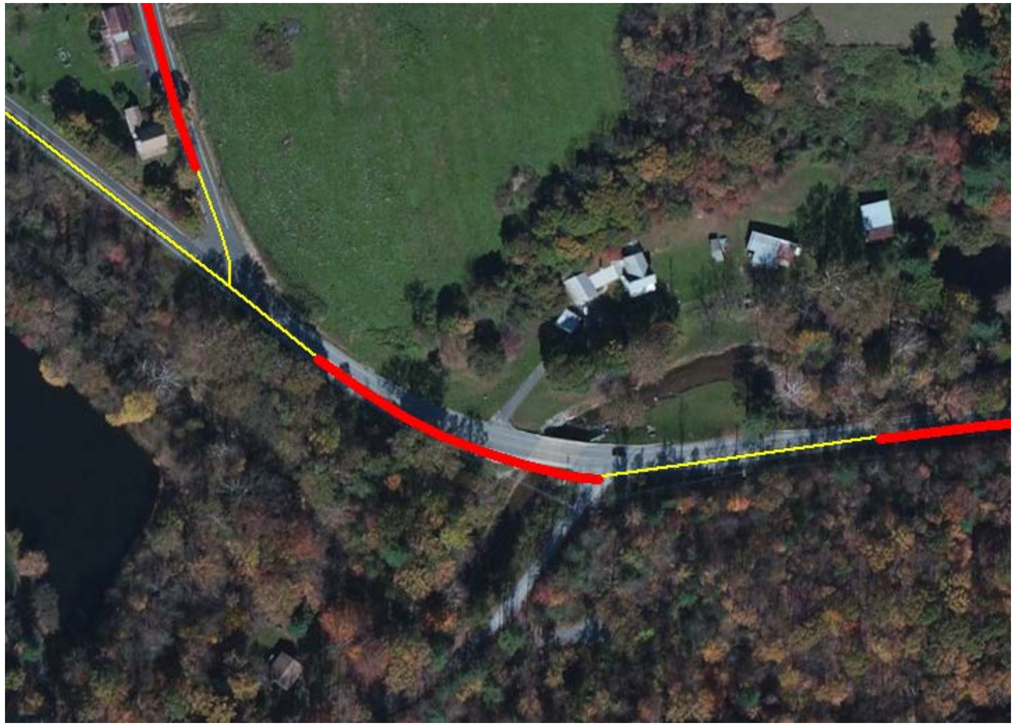
"T" AND "Y" INTERSECTIONS

CURVE SPANNING SEGMENT BOUNDARIES

POTENTIAL SOURCES OF ERROR

- Identification of PC and PT
- Cord Length vs. Arc Length
- Spacing of Vertices
- Inaccuracies in Centerline Data

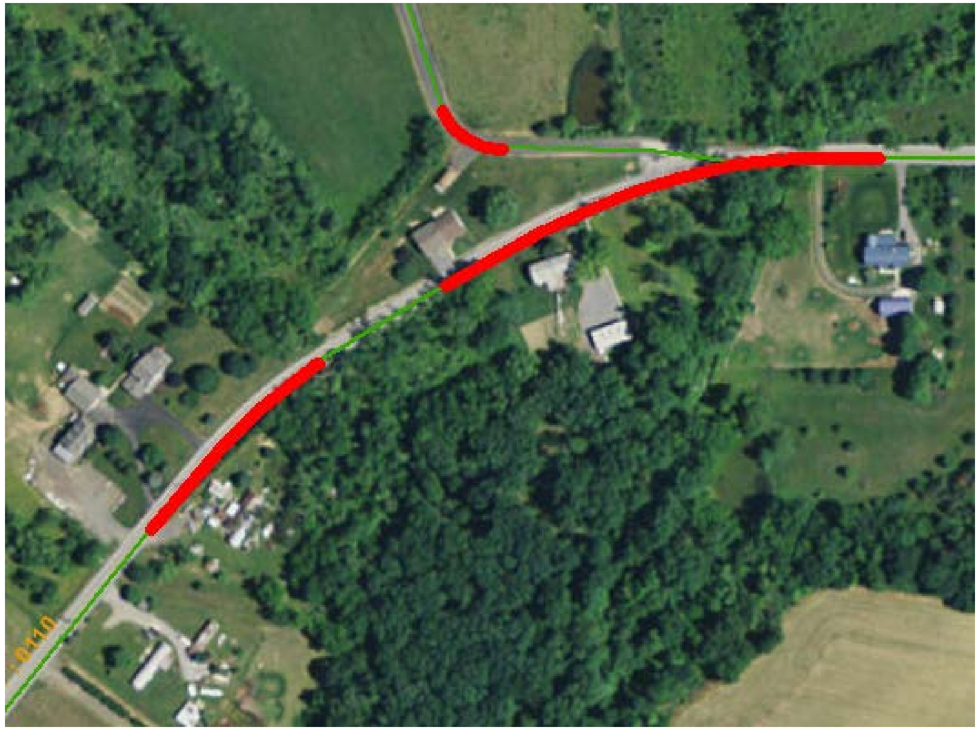




Parameter	Construction Drawing	Curve Detective
Central Angle	45.61°	46.95°
Length	480’	363’
Radius	603’	443’

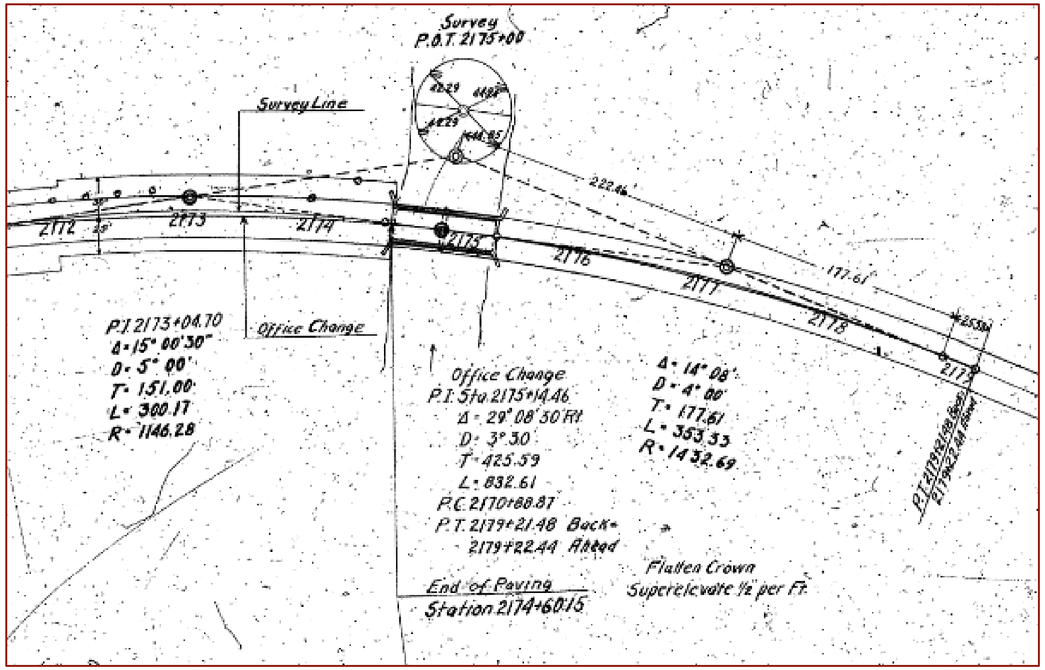
SPLIT CURVES

Adams County SR 4008 Segment 0020-0030

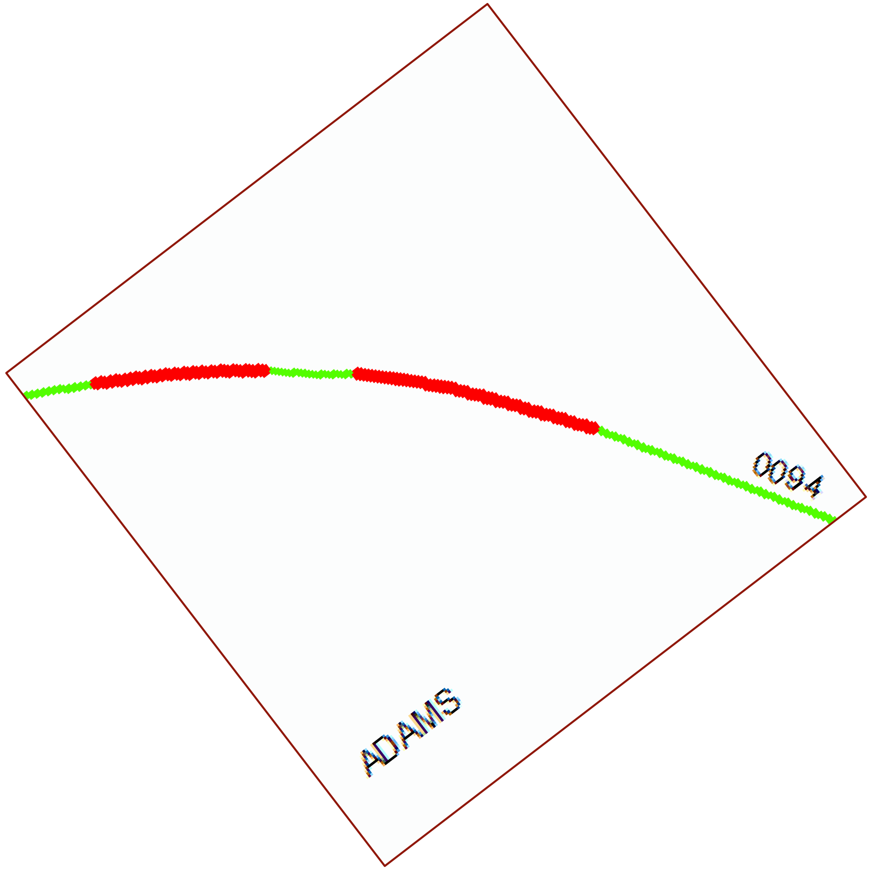


Cumberland County SR 0977 Segment 0110-0120

SUBJECTIVE DECISIONS



1929 Construction Drawing



CRASH ANALYSIS

<u>Crash Data</u>

- 2010 – 2014 (5 Years)
- 44,546 miles of roadway
- 449,081 crashes
- 5,224 fatalities
- 12,786 major injuries
- 49,567 moderate injuries
- 161,268 minor injuries

- 384 billion vehicle miles traveled

CRASH RATES

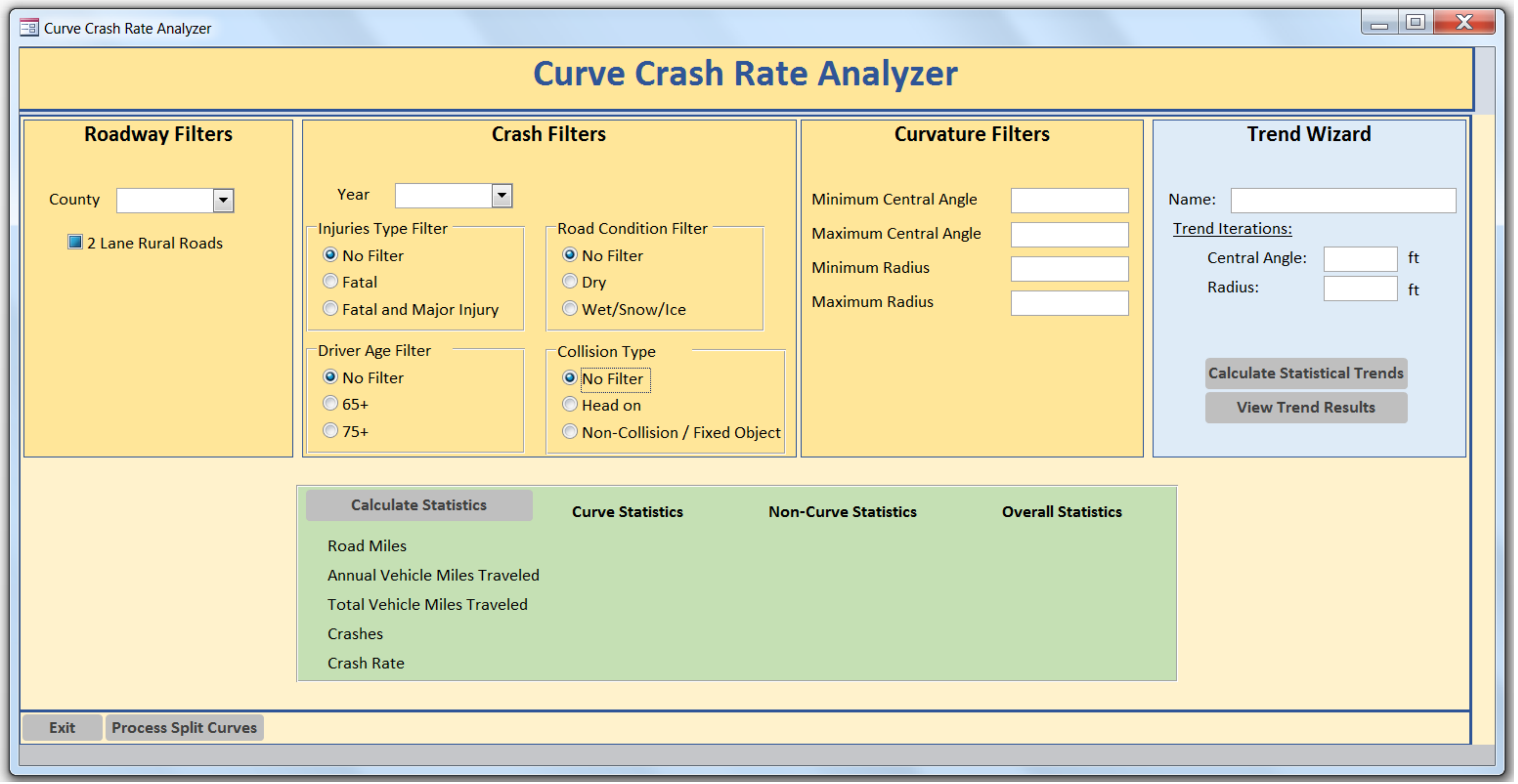
Crash rates are typically reported as crashes per million vehicle miles traveled.

$$R = \frac{C \times 100{,}000{,}000}{V \times 365 \times N \times L}$$

R – Crash rate (crashes per million vehicle miles)
C – Total number of crashes
V – Traffic volume (AADT)
N – Number of years of data
L – Length of roadway in miles

(See Reference 7)

CURVE CRASH RATE ANALYZER



CRASH RATES ANALYSIS 1

Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: All
- Road condition types: All
- Driver types: All
- Collision types: All
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000’

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Crashes	31,560	90,622
Crash Rate	1.8262	0.7804

Finding: Crash Rate on curves is 2.34 times the crash rate on roadway with a straight alignment.

CRASH RATES ANALYSIS 2

Fatal Crash Rates

Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: Fatal
- Road condition types: All
- Driver types: All
- Collision types: All
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000’

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Fatal Crashes	1,899	4,516
Crash Rate	0.1099	0.0389

Finding: Fatal crash rate on curves is 2.83 times the crash rate on roadway with a straight alignment.

Conclusion: Not only are crashes more likely to occur on curves, crashes on curves are more likely to result in fatalities.

CRASH RATES ANALYSIS 3

Crash Rates for Older Drivers

Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: All
- Road condition types: All
- Driver types: 75+
- Collision types: All
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000'

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Crashes (Driver 75+)	1,236	4,792
Crash Rate	0.0715	0.0413

Finding: For drivers over 75, the crash rate on curves is 1.73 times the crash rate on roadway with a straight alignment.

Conclusion: While the crash rate for drivers over 75 increases on curves it doesn't increase as much as it does for all drivers.

CRASH RATES ANALYSIS 4

Slippery Conditions

Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: All
- Road condition types: Wet / Snow / Ice
- Driver types: All
- Collision types: All
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000'

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Crashes (Slippery Conditions)	11,959	29,366
Crash Rate	0.6920	0.2529

Finding: In wet or slippery conditions, the crash rate on curves is 2.73 times the rate on straight roadway alignments. By comparison, in dry conditions the curve crash rate is 2.13 times the rate on straight roadway alignments.

Conclusion: In wet or slippery conditions, the risk of a crash along curved alignments increases more than it does along straight alignments.

CRASH RATES ANALYSIS 5

Run Off Road Crashes

Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: All
- Road condition types: All
- Driver types: All
- Collision types: Run Off Road
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000'

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Run Off Road Crashes	22,265	47,871
Percentage of Total	71%	53%

Finding: A substantially higher percentage of crashes on curves are due to the vehicle leaving the road than on straight roadway alignments.

CRASH RATES ANALYSIS 6

Head On Collisions

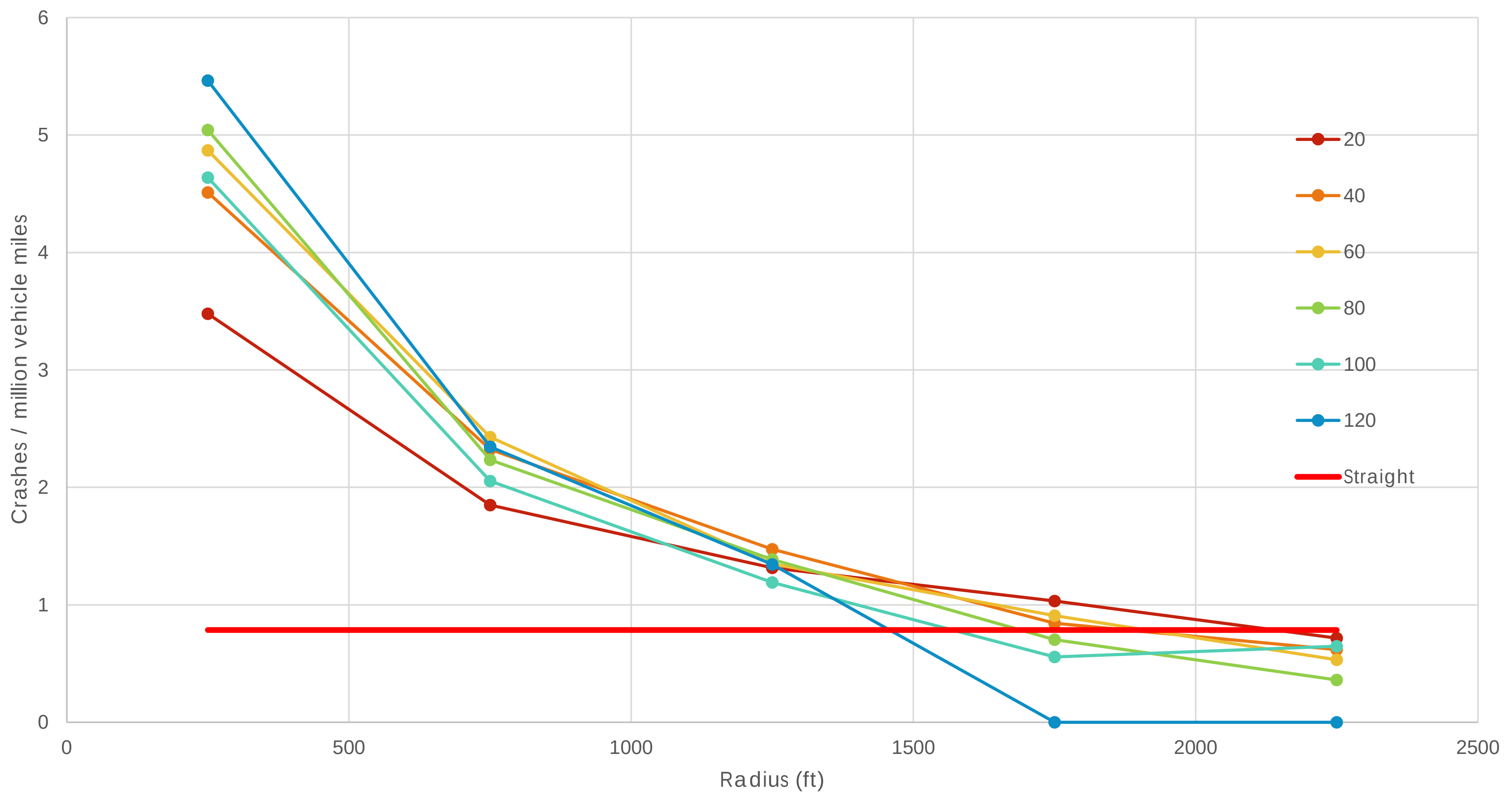
Analytical Parameters:

- Roadway Type: 2 Lane Rural Roads
- Region: Statewide
- Crash Data Period: 2010-2014
- Injury types: All
- Road condition types: All
- Driver types: All
- Collision types: Head On Collisions
- Curve Central Angle: ≥ 10°
- Curve Radius: ≤ 2000’

Alignment	Curve	Straight
Vehicle Miles (billions)	17.3	116.1
Head On Crashes	1,134	2,485
Percentage of Total	3.6%	2.7%

Finding: A higher percentage of crashes on curves are due to head on collisions than on straight roadway alignments.

CRASH RATE VS. RADIUS



POTENTIAL REFINEMENTS

- Adjustments to the algorithms to further minimize the occurrence of split curves.
- Extrapolate pre and post curve tangents to identify the PI and improve the estimate of the PC and PT.
- Develop a standard format of roadway centerline data as an input to the tool so that it could be more readily used by other state DOTs.

CONCLUSIONS

- Extracting roadway horizontal curve data from roadway centerlines is very rapid and cost effective.
- The methodology can be applied to both state and local roadways since PennDOT has centerline data for both. GPS data is not available for local roads.
- Comparisons with survey data is quite accurate. The average %D for the central angle and radius were1% and -3% respectively.
- The standard deviation of the %D was 6% for the central angle and 25% for the radius.
- An analysis of crash rates indicated:
  - Crash rates increase substantially as the radius decreases below 2000 feet.
  - Roadway departure crashes are much more common on curves (71% vs. 53%)
  - Crashes on curves are more likely to result in fatalities.
  - Slippery conditions increase the risks on curves more than on straight roadway alignments.

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QUESTIONS