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Robustness-Oriented Geometric Assessment of Vehicle Turning Complexity for Rural Agricultural Transport and Emergency Response Planning

K Umadevi
School of Commerce, Guru Nanak College, Chennai, Tamilnadu, India

Abstract* - Reliable vehicle maneuverability is critical for rural transportation systems supporting agricultural freight and emergency response services. Rural road networks frequently contain sharp bends and irregular geometric alignments that may impede heavy vehicles and delay ambulances under time-sensitive conditions. This paper presents a computationally efficient geometric framework for assessing turning complexity using polyline-based road representations derived from Open Street Map. Turning angles are computed at each road vertex using vector-based geometry and transformed into a normalized GREEN robustness score. Turns are classified into GREEN (low complexity), AMBER (moderate complexity), and RED (high complexity) categories. The framework is implemented in Python, deployed via a Fast API web service, and integrated into open source QGIS for spatial visualization. The proposed system enables scalable screening of rural transport corridors and supports infrastructure prioritization for *agricultural logistics and emergency route planning.**

***Keywords:* Turning trajectory estimation, Vehicle trajectory analysis, Transportation network analysis, Uncertainty modeling, Geographic Information Systems (GIS), Road geometry analysis, Turning complexity classification,**

I. INTRODUCTION

Rural transport networks are fundamental to agricultural supply chains and emergency service accessibility. Agricultural produce must be transported efficiently from farms to markets, often through winding rural roads that were not designed for modern freight vehicles. Similarly, ambulances and fire services depend on predictable maneuverability across these networks to ensure rapid response. Unlike urban congestion challenges, rural mobility constraints are often geometric in nature. Sharp bends, narrow alignments, and irregular road geometry may reduce manoeuvrability, increase fuel consumption, and compromise safety. A detailed 'swept path' simulations are commonly used during road design but such approaches are not scalable for evaluating large regional networks.

This study introduces a geometric turning complexity assessment framework designed for scalable screening of rural road networks.

The framework:

1. Utilizes encoded polyline representations of road geometry;
2. Computes turning angles at each road vertex;
3. Converts geometric deviation into a GREEN robustness score;
4. Integrates with QGIS open source mapping software for spatial visualization.

The objective is to provide a computationally lightweight yet practical decision support tool for rural agricultural transport and emergency response planning.

II. METHODOLOGY

A. Road Geometry Representation

Road centerlines are represented using encoded polylines. Polylines are a compact ASCII string format widely employed in web-based mapping services. A polyline encodes latitude and longitude pairs using differential and variable-length encoding techniques. This enables efficient storage and transmission.

B. Turning Angle Computation

For each sequence of three consecutive points A, B, C, the turning angle at vertex B is calculated using vector operations.

Let $\overrightarrow{BA} = A - B$ and $\overrightarrow{BC} = C - B$.

The turning angle θ is computed as:

$$\theta = \text{Cos}^{-1}\left(\frac{\overrightarrow{BA}.\overrightarrow{BC}}{||\overrightarrow{BA}||\overrightarrow{BC}||}\right)$$

Angles greater than 165° are considered near-linear segments and excluded from classification. A threshold of 165° was selected to filter near-linear segments in order to retain mild curvature relevant to manoeuvring complexity. This helps ensure that very small, insignificant bends in the road are not wrongly identified as actual turns.

C. Turning Complexity Score
The turning complexity score is defined as:
Score = 180° - θ
This ensures that sharper turns produce higher complexity scores.

D. GREEN Robustness Classification
Turns are categorized as:
• GREEN (Score < 45°): Low geometric complexity
• AMBER (45° ≤ Score < 85°): Moderate complexity
• RED (Score ≥ 85°): High complexity

E. API-Based Architecture and QGIS Integration
The framework is implemented in Python and deployed via Fast API. The service accepts an encoded polyline and returns Geo JSON output containing angles, complexity scores, and classification labels. The output is visualized in QGIS open source mapping software using categorized symbology for GREEN, AMBER, and RED turning points.

F. QGIS Integration
The Geo JSON output is directly imported into QGIS. Categorized symbology is applied to render GREEN, AMBER, and RED turning points using distinct colours.
This integration enables planners to visualize geometric bottlenecks across rural transport corridors. A QGIS plugin has also been developed by the author for easy integration into QGIS.

FigI. Example visualization of turning complexity classification.

III. RESULTS

The framework was applied to representative rural routes derived from OpenStreetMap data. The system successfully identified and classified turning points according to geometric sharpness.

wkt_geom	theta_deg	green_score	category
Point (78.21517000000000053 10.0349699999999995)	164.85	15.15	GREEN
Point (78.21517000000000053 10.0349699999999995)	164.85	15.15	GREEN
Point (78.07193999999999789 10.04621000000000031)	164.79	15.21	GREEN
Point (78.07193999999999789 10.04621000000000031)	164.79	15.21	GREEN
Point (78.00302999999999543 10.07006999999999941)	164.79	15.21	GREEN
Point (78.07080000000000553 10.04651999999999923)	164.74	15.26	GREEN
Point (78.13052999999999315 10.04776000000000025)	164.74	15.26	GREEN

Point (78.20174000000000092 10.04420999999999964)	164.74	15.26	GREEN
Point (78.20673999999999637 10.03627000000000002)	164.74	15.26	GREEN
Point (78.20673999999999637 10.03627000000000002)	164.74	15.26	GREEN

Table 1. Example Values of turning complexity classification.

The table 1 shows the longitude and latitude (wkt_geom) , the turning radius in degrees (theta_deg) , the computed Green Score (green_score) and classification of turning radius difficulty (category). The complete polyline analysed showed the following statistics:

Analyzed field	theta_deg
Count	239
Minimum value	0
Maximum value	164.85
Range	164.85
Mean value	149.3785
Median value	156.04
Standard deviation	21.57763

Table 2. Example polyline statistics.

category	count	percentage
GREEN	211	88.28%
AMBER	16	6.69%
RED	12	5.02%
Total	239	100.00%

Table 3. Example polyline category percentages.

Across the analyzed rural route, 239 turning vertices were detected. Of these, 211 (88.28% were classified as GREEN, 16 (6.69%) as AMBER, and 12 (5.02%) as RED.

RED turns were observed along winding rural corridors, while straight agricultural transport routes predominantly exhibited GREEN classification. Visualization within QGIS enabled clear identification of high-complexity segments.

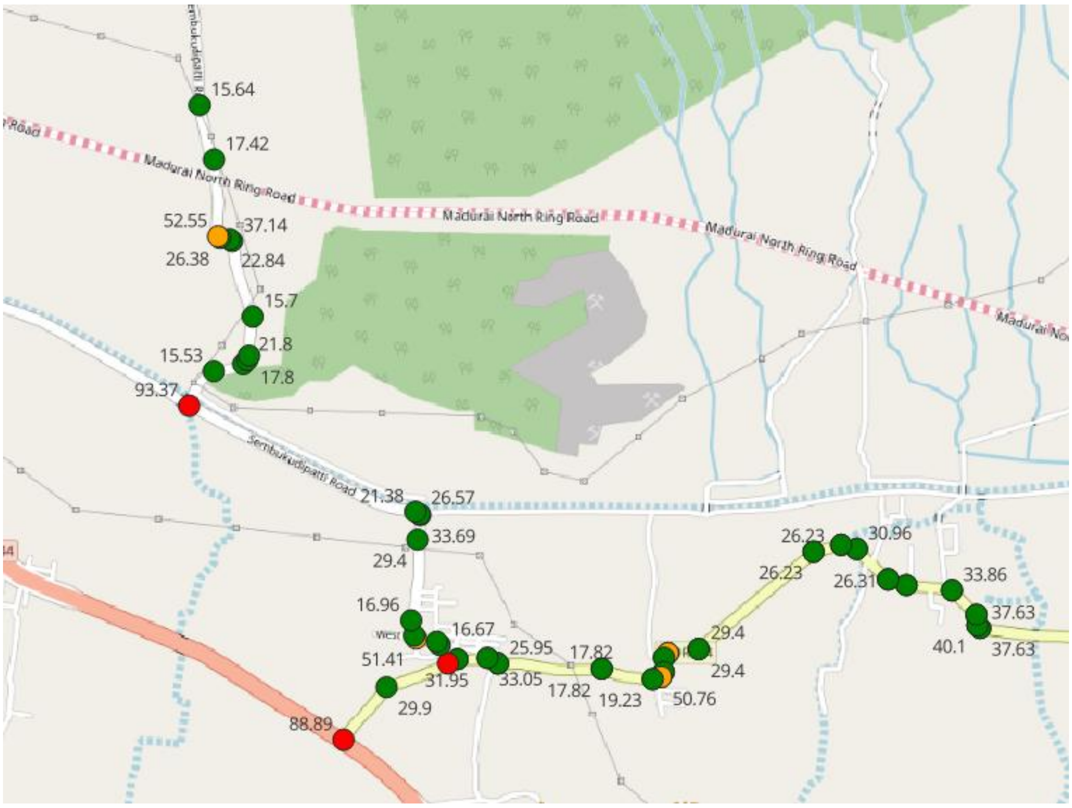

Figure 2. High-complexity turning points along a rural agricultural route.

IV. DISCUSSION

A. Implications for Agricultural Freight Transport

Agricultural logistics rely on predictable road performance. High-complexity turns may reduce vehicle speed, increase fuel consumption, and delay time-sensitive produce delivery. Identifying RED-classified turns allows targeted infrastructure interventions such as curve widening and shoulder reinforcement.

B. Implications for Rural Emergency Response
Emergency vehicles require reliable manoeuvrability under time-critical conditions. Sharp turns may reduce safe entry speeds and increase operational risk. Mapping turning complexity supports predefined safe routing and infrastructure prioritization.

C. Advantages and Limitations
The proposed framework offers scalability, computational efficiency, and compatibility with open-source GIS tools. However, it considers only geometric angle and does not incorporate full vehicle dynamics or road width parameters. The model uses a simplified kinematic constraint (single turning radius). Articulated vehicles and full 3D dynamics would require more complex modelling.

V. DATA AND CODE AVAILABILITY

The algorithms and processing workflows used in this study are publicly available in an online repository. The repository includes QGIS plugin scripts and instructions for reproducing the turning trajectory estimation and complexity classification described in this paper. The source code and example data can be accessed at the project repository on GitHub:
https://github.com/UMADEVIGNC/turningradiuscomplexity
The open source demo ‘Space’ is available at Hugging Face repository:
https://huggingface.co/spaces/KUMADEVI/turning_complexity

VI. CONCLUSION

This paper presented a scalable geometric turning complexity assessment framework for rural transport networks. By computing turning angles from polyline-based road geometry and transforming them into a GREEN robustness classification, the system provides a practical decision-support tool for agricultural freight optimization and emergency response planning.
The integration of Fast API-based computation with QGIS visualization demonstrates real world applicability. Incorporating geometric turning assessment into rural infrastructure planning can enhance both economic efficiency and public safety outcomes.

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