Operationalizing National Road Design Guidelines: A Python Tool for Geometric Design Consistency Assessment

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Abstract. Geometric design consistency is a key principle in roadway design, reflecting the degree to which successive geometric elements promote smooth and predictable vehicle operation. Although national road design guidelines typically incorporate qualitative requirements for geometric harmony and operating speed continuity, they rarely provide computational procedures or tools to support systematic consistency evaluation during the design and assessment process. This paper presents a Python-based tool that operationalizes road design guidelines through a speed-based framework for geometric design consistency assessment.

The proposed methodology focuses on horizontal alignment and explicitly computes the 85th percentile operating speed (V_{85}) for tangents and circular curves using geometry-based relationships. Design consistency is evaluated by analyzing speed differentials (ΔV) between successive alignment elements and classifying consistency levels based on widely adopted threshold values. The approach enables the construction of continuous operating speed profiles and the automated identification of locations exhibiting potentially inconsistent geometric transitions. An application example is presented to demonstrate the tool's ability to support engineering judgement by highlighting critical locations along a roadway alignment. The approach is readily transferable to different regulatory contexts and provides a foundation for future extensions, including vertical alignment analysis and integration with advanced design and geographic information systems.

Keywords: Geometric design consistency · Operating speed (V_{85}) · Horizontal alignment · Speed-based assessment · Road design guidelines · Python-based tool

1 Introduction

Geometric design consistency is a fundamental principle in roadway design, reflecting the degree to which successive geometric elements support smooth and predictable vehicle operation. Inconsistent horizontal alignment may require abrupt speed adjustments, indicating a mismatch between roadway geometry and expected operating behaviour. As a result, speed-based measures, particularly those based on the 85th percentile operating speed (V_{85}), are widely used to quantify geometric design consistency and to identify potentially problematic transitions along road alignments.

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At the same time, national road design guidelines encode valuable but largely qualitative knowledge regarding geometric harmony, continuity, and acceptable speed variation. The absence of computational tools that translate these principles into automated evaluation procedures represents a critical gap between guideline-based design and modern computational practice. This paper addresses this gap by presenting a Python-based tool that operationalises road design guidelines through an explicit, speed-based geometric consistency assessment framework. By computing operating speed (V85) from horizontal alignment geometry and automatically evaluating speed differentials between successive elements, the proposed approach enables transparent, repeatable, and extensible consistency analysis, providing a foundation for integrating geometric design assessment into broader computational science and engineering applications.

The goal of this research is to bridge the gap between qualitative road design guidelines and computational evaluation by developing a Python-based tool for speed-based geometric design consistency assessment. The proposed approach enables automated, transparent, and repeatable evaluation of horizontal road alignment consistency through explicit computation of operating speed and speed differentials.

2 Literature Review

The geometric design of rural two-lane highways significantly influences traffic safety and operational efficiency (Gibreel et al., 1999). Engineers face challenges in balancing design criteria with budgetary and environmental factors. A critical aspect of this design is achieving consistency, which aligns roadway features with driver expectations, thereby preventing abrupt maneuvers and mitigating accident risks (Faghri & Harbeson, 1999; Messer, 1980). Geometric design consistency is fundamentally defined as the degree to which a highway's geometric and operational features conform to driver expectancy (Fitzpatrick et al., 2000; Hamilton et al., 2019; Wooldridge et al., 2003). It is generally understood as the alignment of a highway encouraging uniform driving behavior and meeting driver expectations (Messer, 1980). This concept is not limited to a single measure but can be applied across various conditions and measures of effectiveness, including horizontal alignment and intersections (Wooldridge et al., 2003). The underlying principle is that when drivers' expectations align with the actual road conditions, driving is considerably safer (Qin et al., 2020).

Driver expectancy refers to a driver's inclination, based on prior experience, to respond in a predictable manner to a given roadway or traffic situation (Torregrosa, 2015). Expectancies can be categorized as a) a priori - Based on a driver's accumulated long-term experience since obtaining their driving license, or b) ad hoc - Formed from the immediate experience of the road segment the driver is currently traversing (Torregrosa, 2015).

Therefore, a lack of consistency occurs when there are unexpectedly high driver workloads or sudden changes in highway alignment that do not meet these learned expectations (Fitzpatrick et al., 2000; Krammes et al., n.d.; Messer, 1980). Such inconsistencies can surprise drivers, leading to inappropriate speeds, increased workload, delayed responses, incorrect decisions, and ultimately, a higher likelihood of accidents (Messer, 1980; Torregrosa, 2015; Vukoje et al., 2012).

Early research by Messer, emphasizing driver behavior principles and empirical evidence, further developed methodologies for evaluating and improving geometric design consistency on rural non-freeway highways (Messer, 1980). Early research demonstrated that compliance with geometric standards does not necessarily ensure safe operating conditions, as accident occurrence was found to be more closely associated with changes in operating speed than with individual geometric elements [FHWA, 1999;].

The concept continued to gain greater acceptance in North America and globally, with research focusing on its integration into design practices (Gibreel et al., 1999; Hassan et al., 2001). Research commonly categorizes the factors influencing geometric design consistency on two-lane rural highways into speed, safety, and performance considerations (Gibreel et al., 1999).

Operating speed is a primary metric for evaluating design consistency, typically defined by the 85th percentile speed (V_{85}), under free-flow conditions (Gibreel et al., 1999). Variations in operating speed that deviate significantly from the design speed (V_e), or large differences in operating speeds between successive roadway elements, indicate design inconsistencies (Gibreel et al., 1999; Torregrosa, 2015). Studies have consistently identified the radius of horizontal curves as a dominant factor affecting operating speed prediction and models have been developed to predict operating speeds and assess consistency based on these speed differentials (Gibreel et al., 1999).

Operating speed profiles involve modeling operating speed profiles and comparing the design speed against operating speeds or analyzing the variation in operating speeds between successive highway elements (Gibreel et al., 1999; Torregrosa, 2015). Other methods also use the difference between the 85th percentile operating speed (V_{85}) of a road element and the inertial operating speed, defined as the average operating speed on the previous 1 km road segment (Cefalo et al., 2024). Operating speed consistency models can be local, assessing a single element or successive elements, or global, evaluating the entire road segment (Cefalo et al., 2024). The deviation of operating speed from design speed for each vehicle category at specific curve points (entry, mid-point, and exit) is also a criterion (Chaudhari et al., 2022).

Lamm et al. (1988) argued that operating at geometric features on two-lane rural highways with speeds significantly exceeding the allowable or design speed leads to geometric design inconsistencies. To address this issue, Lamm et al. (1988) introduced a consistency evaluation approach, referred to as *Safety Criterion I*, based on the speed differential between the 85th percentile operating speed and the design speed for individual geometric elements. This concept has also been adopted in the Greek road design guidelines as the **first safety criterion**, forming the basis for assessing global geometric harmony through the relationship between operating and design speeds. Within this framework, threshold values are used to classify geometric consistency as good, acceptable, or poor.

Criterion II is also a design consistency criterion, related to operating speed, and considers the differences in operating speeds on successive highway elements (Torregrosa, 2015). Like Criterion I, it is used to categorize the consistency of curves as good, fair, or poor (Chaudhari et al., 2022). The specific details of its calculation are implied to be part of the methodologies developed by Lamm et al. and Fitzpatrick et al. (Chaudhari et al., 2022).

Alignment indices such as the average radius, ratio of maximum to minimum radius, and average rate of vertical curvature, are used to characterize the general geometry of a road section and correlate with collision frequency (Cefalo et al., 2024; Torregrosa, 2015). The idea is that geometric inconsistencies arise when the general character of an alignment change significantly (Cefalo et al., 2024). Comparative analyses of European design standards shows that several countries have moved toward incorporating expected operating speeds and formal consistency rules to better manage driver expectations and improve safety (Brenac 1996). Comprehensive reviews of the literature have since consolidated these findings, consistently identifying operating-speed consistency as a critical prerequisite for safe and efficient traffic operation (Gibreel et al. 1999).

To operationalize these concepts, several models and tools have been developed to evaluate design consistency in practice. Geometric design consistency assessment is commonly supported through a combination of dedicated safety analysis tools, design software environments, and research-oriented computational workflows. Among the most widely used platforms, the Interactive Highway Safety Design Model (IHSDM), developed by the FHWA, incorporates operating speed prediction and consistency evaluation modules within a standardized analytical framework. While such tools are robust and well established, they offer limited flexibility for methodological adaptation and are typically aligned with specific national design practices. Design software environments, such as Autodesk Civil 3D and alignment analysis tools developed by Transoft Solutions, provide detailed geometric modelling capabilities but generally lack built-in, guideline-specific consistency assessment indices tailored to every country roadway design guideline. In several countries, this limitation has been partially addressed through the development of custom add-ins or toolkits integrated into design software platforms. Other tools focus on predicting operating speed levels, performing optical analyses of the road, and determining available sight distance using 3D models (Dell'Acqua et al., 2016). Additionally, advanced techniques like **artificial neural networks** and fuzzy logic are employed in artificial intelligence modeling to analyze the safety impacts of diverse highway geometries on traffic accidents (Garnaik et al., 2023).

However, despite the existence of well-defined national design criteria addressing geometric harmony and speed consistency, such computational tools are not available in the Greek context. As a result, consistency evaluation in practice relies largely on manual checks, spreadsheets, or locally developed scripts, limiting automation, reproducibility, and systematic application during the design process.

3 Methodology

3.1 Conceptual Framework

The proposed methodology provides a computational framework for assessing geometric design consistency. The approach focuses on horizontal alignment and evaluates consistency through explicit estimation of the operating speed (V_{85}) and the analysis of speed differentials between successive geometric elements. The methodology is intended to support automated and repeatable consistency assessment during roadway design and evaluation.

The overall workflow consists of four main stages: (i) representation of roadway geometry, (ii) estimation of operating speed for each alignment element, (iii) computation of geometric consistency metrics, and (iv) classification of consistency levels based on predefined thresholds (Fig. 1).

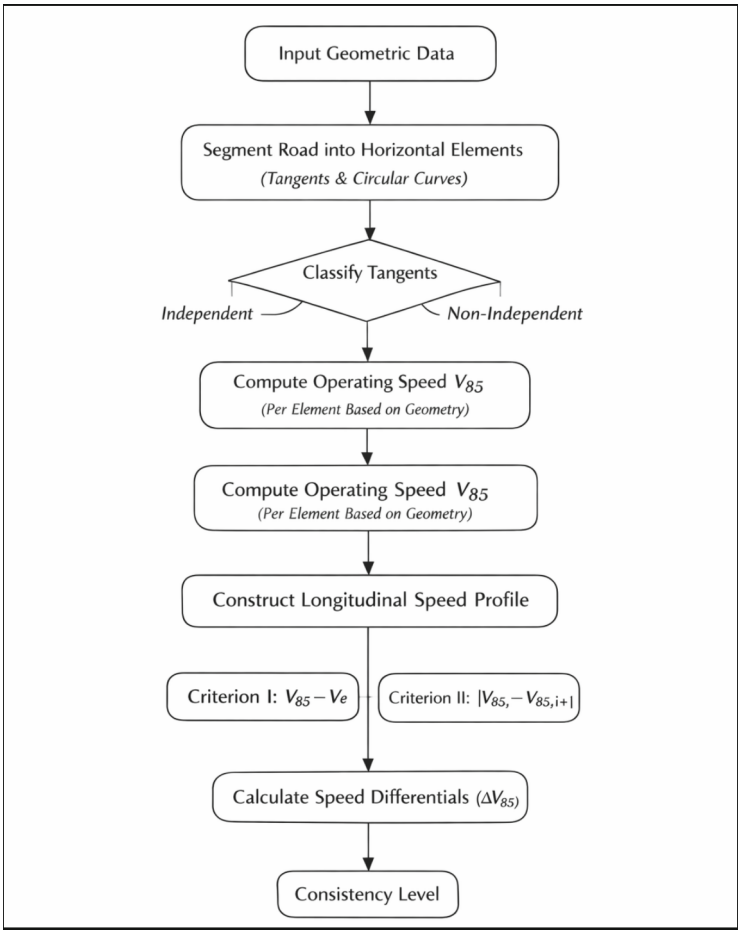

Fig. 1. Methodological flow chart of the proposed speed-based geometric design consistency assessment framework.

3.2 Input Data and Roadway Representation

The roadway alignment is represented as an ordered sequence of horizontal geometric elements, consisting of tangents and circular curves. Each element is characterized by its length and, where applicable, its radius. The road is assumed to belong to a single functional category, and a corresponding design speed (V_e) is assigned based on national

road design guidelines. The analysis assumes homogeneous geometric and operational conditions within the examined segment. Vertical alignment, cross-sectional characteristics, and roadside features are not considered in the present study, in order to isolate the effect of horizontal alignment on geometric consistency.

Each horizontal alignment element (tangent or circular curve) is represented using a set of geometric and operational parameters. The required input data and the corresponding estimated (derived) data used in the consistency assessment are summarized below.

- Total length of horizontal alignment element: Length of the tangent or circular curve.
- Chainage at start/end of design element: Chainage corresponding to the beginning/end of the element.
- Radius of circular curve: Radius of the curve; for tangents, an infinite radius is assumed.
- Lane width: Width of the traffic lane, used as a parameter in operating speed estimation.
- Longitudinal grade in the direction of increasing chainage (s): Average longitudinal slope of the element, expressed as a percentage.
- Deflection angle: Angular change in alignment direction for circular curves; equal to zero for tangents.

Based on the input geometric characteristics, the following quantities are computed:

- **Degree of deflection:** A curvature-related parameter derived from the horizontal geometry, used to characterise the intensity of deflection (gon/km) for each single element.
- **Operating speed (V_{85})** Estimated for each element as a function of geometric characteristics (radius, curvature measure, lane width, and longitudinal grade).

Case 1: Longitudinal grade $s \leq 5\%$, or $s > 5\%$ with element length $L < 250$m

$$V_{85} = \frac{10^6}{10150,10 + 8.529K_E} + [(b - 3.5) \times 20]$$

where:

- $K_E$is the degree of curvature of the alignment element,
- b is the lane width (m).

Case 2: Longitudinal grade $s > 5\%$ and element length $L \geq 250$m(independent of lane width)

For $5\ \% < s \leq 7\%$**:**

$$V_{85} = 73,260 - 0.015K_E$$

For $7\ \% < s < 10\%$**:**

$$V_{85} = 69,456 - 0.0140 \cdot K_E$$

The resulting speed profile represents the expected variation of operating speed due solely to horizontal geometric characteristics and forms the basis for consistency assessment.

In this paper, tangent is a distinct design element influencing operating speed behaviour. Therefore, each tangent is characterized as non-independent or independent tangent. Non-independent tangent are described tangent sections whose length is insufficient to allow drivers to significantly adjust their operating speed between successive horizontal curves. In contrast, this paper adopts the concept of independent tangents to describe tangent sections of sufficient length to permit drivers to accelerate or decelerate and stabilise their operating speed independently of the adjacent horizontal curves.

Thus (Lamm),

- Tangents are regarded as non-independent design elements and the sequence curve-to-curve controls the design process, and
- Tangents are regarded as independent design elements and the sequence tangent-to-curve controls the design process.

3.3 Geometric Design Consistency Metrics

Geometric consistency is evaluated using speed-based indicators, consistent with the principles of OMOE-X Safety Criteria I and II. According to the Greek road design guidelines (OMOE-X), Safety Criterion I is concerned with the achievement of overall harmony and continuity in roadway design through the alignment of design speed (V_e) and operating speed (V_{85}). The criterion establishes that the selected geometric parameters—such as curve radii, tangent lengths, and transition elements—should be compatible with the intended design speed so that the resulting operating speeds do not deviate significantly from it. In this context, consistency is treated as a design-quality requirement, ensuring that successive geometric elements form coherent sequences rather than arbitrary combinations of minimum or maximum values. Criterion I therefore governs the global relationship between geometry and expected operating behaviour, promoting uniformity of design speed over sufficiently long roadway sections and discouraging abrupt changes in geometric standards.

Safety Criterion II focuses more explicitly on the continuity of operating speed (V85) along the alignment and the dynamic interaction between successive horizontal elements. The guideline emphasises that abrupt variations in operating speed between adjacent tangents and curves, or between successive curves, should be avoided, as they may lead to undesirable driving manoeuvres. To this end, OMOE introduces the concept of controlling speed differentials (ΔV_{85}) and prescribes acceptable relationships between successive curve radii through diagrams and qualitative classifications. Criterion II thus addresses local geometric transitions, ensuring that changes in curvature and alignment characteristics lead to gradual and predictable speed adaptation. While the guideline provides graphical and descriptive guidance for assessing these relationships, it does not define a computational procedure, highlighting the need for automated tools capable of translating these principles into quantitative consistency evaluation (Table 1).

These metrics directly quantify the degree of speed adaptation required between elements and provide an objective measure of geometric consistency.

These thresholds are applied consistently across all assessed elements and are considered compatible with the design philosophy of OMOE-X, which emphasizes gradual variation of geometric characteristics and avoidance of abrupt speed changes.

Table 1. Quantitative Ranges for Safety Criteria I to III for Good, Fair, and Poor Design Classes

Consistency level	Good	Acceptable	Poor
Criterion I – Design harmony	$\lvert V_{85i} - V_e \rvert \leq 10$ km/h	10 km/h $\leq \lvert V_{85i} - V_e \rvert \leq 20$ km/h	$\lvert V_{85i} - V_e \rvert > 20$
Criterion II – Speed continuity	$\lvert V_{85i} - V_{85i+1} \rvert \leq 10$ km/h	10 km/h $\leq \lvert V_{85i} - V_{85i+1} \rvert \leq 20$ km/h	$\lvert V_{85i} - V_{85i+1} \rvert > 20$

3.4 Description of the Proposed Tool

The tool will be developed using Python due to its versatility, extensive libraries for data manipulation and numerical computation, and its ability to integrate with other systems. While specific Python libraries for this exact application might need to be custom-developed, existing libraries can aid in data processing and analysis. For instance, Python can interact with geometric data, potentially even through CAD-related Python APIs if detailed geometric models are used (Becker et al., 2022; Heidari & Iosifidis, 2024).

The system is designed around three logical layers:

- **Input layer** – responsible for reading and structuring geometric data.
- **Computation layer** – responsible for operating speed estimation and consistency calculations.
- **Output layer** – responsible for reporting, visualisation, and classification results.
- **(i) Data Processing Module**
  Handles the import of alignment data (e.g., from CSV or Excel format), performs validation checks, and organises the data into element-wise structures (e.g., pandas DataFrames). Each horizontal alignment element is tagged as a tangent or curve and prepared for subsequent analysis.
- **(ii) Tangent Classification Module**
  Implements the logic for distinguishing independent from non-independent tangents based on geometric length criteria. This module determines whether consistency evaluation follows a curve–curve or tangent–curve control sequence.
- **(iii) Operating Speed Computation Module**
  Applies the OMOE-X equations to compute V_{85} for each element, considering curvature, longitudinal grade, and lane width. The module generates the element-based operating speed profile.
- **(iv) Consistency Evaluation Module**
  Computes:
- **(v) Visualisation and Reporting Module**

4 Application

The examined roadway section connects the settlements of Fanari and Arogi and serves as a local connector to the primary national road network (EO2 Komotini–Xanthi). The segment from the national road junction to Fanari has a total length of approximately 5.3 km. Due to construction constraints during its development period, primarily related

to land ownership limitations, the alignment followed restrictive geometric conditions. As a result, the roadway exhibits relatively low geometric standards, including successive horizontal curves, short tangent sections, variable superelevation conditions, and constrained cross-sectional characteristics.

The road traverses areas located both outside and partially within settlement boundaries and is bordered by diverse land uses, including tourism-related facilities, recreational areas, coastal bathing areas, residential properties, and entertainment establishments. A primary functional role of the road is to provide access to these adjacent land uses, operating as a collector facility. Accordingly, the roadway is classified as a Category BIII road under the national road classification system, functioning as a collector arterial with a single carriageway.

From a geometric consistency perspective, the alignment presents a suitable test case due to the presence of successive curves, potentially short tangents between curves, and varying geometric parameters along its length. These characteristics allow for the systematic evaluation of operating speed variation and the identification of locations where speed differentials may indicate reduced geometric consistency.

- Speed profile
- Consistency indicators
- Output plots/tables

5 Discussion

The proposed Python-based framework demonstrates how qualitative road design guideline principles can be translated into a transparent and repeatable computational process for geometric design consistency assessment. By explicitly computing operating speed and systematically evaluating speed differentials between successive alignment elements, the approach enables a level of automation and consistency that is not achievable through manual checks or spreadsheet-based evaluations commonly used in practice. The case study illustrates that the tool can efficiently identify both global design harmony issues and local speed continuity problems along a roadway alignment.

From a computational perspective, the framework offers a modular and extensible structure that facilitates reproducibility and integration into broader design workflows. The explicit treatment of independent and non-independent tangents allows the assessment logic to adapt to different geometric configurations without introducing subjective judgement during analysis. This feature is particularly relevant for computational applications, as it ensures that consistency evaluation rules are applied systematically across all alignment elements.

Despite these advantages, the proposed approach is subject to certain limitations. The current implementation focuses exclusively on horizontal alignment and relies on geometry-based operating speed models, without accounting for driver behaviour, traffic conditions, or vertical alignment effects. While this scope is intentional and aligned with the objectives of the study, future work could extend the framework to incorporate additional design dimensions or to interface with GIS and CAD environments for seamless data exchange.

Overall, the results indicate that the proposed tool effectively bridges the gap between road design guidelines and computational evaluation, providing a practical foundation

for automated geometric consistency assessment and supporting the integration of design rule verification into computational science and engineering applications.

6 Conclusions and Future Work

Despite significant advancements, a standardized and universally adopted procedure for evaluating geometric design consistency in new or existing alignments remains elusive (Hassan et al., 2001). Current design consistency models predominantly focus on two-dimensional horizontal alignments, often neglecting the crucial interaction with vertical alignments and cross-sections in a three-dimensional context (Gibreel et al., 1999). Future research endeavors should prioritize:

- Developing operating speed prediction models based on 3D analysis (Gibreel et al., 1999).
- Establishing novel methodologies for evaluating design consistency that incorporate the effects of 3D sight distance (Gibreel et al., 1999).
- Investigating the impact of design consistency on highway capacity, level of service, and driver comfort (Gibreel et al., 1999).
- Revising and harmonizing existing design guidelines to integrate comprehensive design consistency principles across different countries (Gibreel et al., 1999).

The developed tool will be validated against case studies or existing highway sections with known consistency evaluations. This validation step will ensure the accuracy and reliability of the Python tool. Future enhancements could include incorporating additional consistency criteria (e.g., vehicle stability analysis, alignment indices) (Cefalo et al., 2024), integrating 3D geometric analysis, and linking with crash prediction models to provide a more holistic safety assessment (Chaudhari et al., 2022).

From an engineering perspective, the tool provides a practical and accessible mechanism for evaluating geometric design consistency without requiring advanced programming knowledge. The user supplies standard geometric design parameters for each alignment element, and the tool automatically produces:

- Operating speed estimates per element,
- Speed differential summaries,
- Clear classification of consistency levels (good/acceptable/poor),
- Graphical representation of the longitudinal speed profile,
- Identification of critical geometric transitions.

The automated evaluation reduces reliance on manual spreadsheet calculations and supports objective, repeatable design assessment. Moreover, the tool can be integrated into typical design workflows by importing alignment data exported from CAD environments, thereby enhancing its applicability in practical roadway engineering contexts.

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