Cureus Journal of Engineering
https://doi.org/10.7759/s44388-026-00356-4

Original Article

Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000)

Vashisth M. Trivedi [1], Pinki Deb [1]

1. *Transportation Engineering, School of Civil and Environmental Sciences, JSPM University, Pune, IND*

Received: February 28, 2026 | Review began: March 25, 2026 | Review ended: August 27, 2026 | Published: November 05, 2026

© **Copyright** 2026
This is an open access article distributed under the terms of the Creative Commons Attribution License CC-BY 4.0., which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Abstract

On extended multi-lane highways located in steep and rolling terrain, safety difficulties are often governed more by geometric inconsistency than by traffic volume alone. This study presents a geometric design-based safety evaluation of a 13-km stretch of State Highway 56 along the Danta-Ambaji corridor in the Banaskantha district of Gujarat, covering chainages CH 90/000 to CH 103/000. The corridor was selected because of its regional and tourist importance, challenging hilly terrain, and the presence of multiple geometric features with potential safety and operational implications. The assessment focuses on horizontal curves, vertical alignment, junction layouts, and median openings under existing operating conditions.

Geometric data were obtained from available project design records and computer-aided design drawings and were supplemented by field observations to verify existing roadway conditions. Civil 3D and AutoTURN were used to develop a detailed geometric model of the corridor and to perform swept-path analyses for passenger cars, SU-12 trucks, and WB-15 semi-trailers in accordance with Indian Roads Congress provisions and the American Association of State Highway and Transportation Officials standards. The results reveal that all 21 horizontal curves along the study section have insufficient transition lengths, with the provided transitions being 15-25 m shorter than the minimum Indian Roads Congress requirements. Fourteen of these curves are concentrated within the mountainous segment between CH 101/000 and CH 103/000. In addition, 24 median openings were found to be operationally suitable only for passenger cars, while two junctions at CH 91/260 and CH 99/600 fail to accommodate WB-15 vehicle maneuvers without encroachment into adjacent or opposing lanes.

These geometric deficiencies have direct operational implications, including increased lane-encroachment and turning-conflict risks, particularly for heavy vehicles requiring greater maneuvering space. Although calculated lateral friction demands remain within permissible limits, the identified geometric deficiencies can reduce vehicle stability and operational safety, particularly in the mountainous section. The study concludes that geometry-based speed regulation and targeted geometric improvements are essential to mitigate these risks. Both short-term control measures and long-term geometric rectification strategies are proposed to improve the overall safety performance of the corridor.

Categories: Sustainable Technologies, Transportation Engineering, Vehicle Dynamics and Control

Keywords: geometric design, horizontal curves, swept path analysis, highway safety, mountainous terrain

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI
https://doi.org/10.7759/s44388-026-00356-4

Introduction

The quality and consistency of geometric design play an important role in highway safety, particularly on rural and mountainous highways where roadway geometry is strongly influenced by terrain constraints. Geometric consistency refers to the compatibility and continuity of successive roadway elements with driver expectations and vehicle operating characteristics. Inconsistent combinations of horizontal curvature, vertical alignment, transition characteristics, and sight distance may require unexpected changes in vehicle speed or steering and can increase the potential for operational conflicts [1,2]. Horizontal curves are particularly important because restricted sight distance and changes in roadway curvature can affect driver perception and vehicle control [1]. Roadway-edge and shoulder characteristics may further influence safety performance on horizontal curves, particularly where available lateral recovery space is limited [3].

Junctions and median openings introduce additional geometric requirements because turning vehicles require sufficient maneuvering space to complete movements within the intended roadway envelope. Inadequate turning geometry can constrain vehicle maneuverability and increase the potential for lane encroachment or turning conflicts, particularly for larger vehicles [4]. These considerations are especially relevant on mountainous highways, where terrain-related geometric constraints can influence vehicle operation and safety performance [5-7].

In geometric design practice, lateral stability and stopping sight distance are important considerations governing horizontal alignment. The relationship between vehicle speed, curve radius, superelevation, and side friction defines the geometric requirements for horizontal curves, while transition length and sight distance provide additional controls for vehicle operation. The applicable geometric requirements for rural highways and four-lane facilities are specified in Indian Roads Congress (IRC) standards IRC:73-2023 and IRC:SP:84-2019 [8,9]. Requirements relating to vertical curves and horizontal curve design are provided in IRC:SP:23-1993 and IRC:38-1988 [10,11]. The Hill Road Manual provides additional geometric guidance for constrained mountainous terrain [12], while the American Association of State Highway and Transportation Officials (AASHTO) provides complementary geometric design guidance for highway alignment and vehicle operation [13].

Compliance with individual minimum design criteria does not necessarily guarantee satisfactory operational performance because roadway elements interact with one another and are experienced by drivers as a continuous alignment rather than as isolated geometric components [1,2,5-7]. A curve may satisfy the required radius or superelevation while still presenting potential operational concerns when transition lengths are inadequate, sight distance is restricted, or successive geometric elements produce inconsistent operating conditions [1,5,7]. Such conditions may require changes in vehicle speed or steering and can reduce the available margin for driver response, particularly on constrained mountainous roads [2,7].

Driver behavior further influences the interaction between roadway geometry and vehicle operation. Drivers adjust their vehicle paths according to curvature, pavement width, sight distance, and the surrounding roadway environment. Previous research has identified operating speed and vehicle-response characteristics as important considerations in evaluating horizontal curve design and safety performance [2,5,6]. Where geometric continuity is poor or available maneuvering space is restricted, drivers may alter their lateral position or speed, potentially increasing operational conflicts. These considerations are particularly relevant at junctions and median openings, where larger vehicles require greater swept-path space and may encroach into adjacent or opposing traffic lanes when the available turning envelope is inadequate [4,9].

State Highway 56 between Danta and Ambaji in Gujarat has been upgraded to a four-lane divided facility and passes through rolling and hilly terrain. The section between chainage 101/000 and 103/000 is particularly constrained by mountainous topography, where horizontal curvature, transition lengths, sight distance, and median geometry require careful evaluation. The combination of these geometric characteristics and constrained terrain provides an appropriate setting for examining whether the existing roadway provisions satisfy applicable design criteria and accommodate representative vehicle movements.

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

This study therefore adopts a geometry-centered, proactive safety evaluation of State Highway 56 from chainage 90/000 to 103/000. The assessment focuses on horizontal curves, vertical alignment, junctions, median openings, and vehicle maneuverability. Existing geometric characteristics are evaluated against applicable IRC and AASHTO design criteria [8-13], while swept-path analysis is used to examine the maneuvering requirements of representative passenger and heavy vehicles. The study aims to identify geometric deficiencies and locations with potential operational safety concerns, rather than predict crash occurrence, and to propose targeted short-term and long-term improvement measures for the corridor.

Materials And Methods

Without depending on collision data or traffic volume, a geometry-centered evaluation framework was adopted to assess geometric compliance and potential operational safety concerns along State Highway 56. The assessment compares existing geometric characteristics with applicable IRC and AASHTO design criteria and evaluates vehicle maneuverability at selected junctions and median openings using swept-path analysis [8,9,13]. This approach recognizes that locations with potential operational safety concerns may exist even in the absence of historical crash records. Previous research has demonstrated that roadway geometry, sight-distance restrictions, and geometric characteristics of mountainous highways can influence vehicle operation and safety performance [1,2,5,7]. The assessment therefore examines horizontal and vertical alignment, cross-sectional elements, and vehicle maneuverability to identify locations where geometric constraints may result in lane encroachment, constrained turning movements, or other operational conflicts.

Study area

The study corridor extends from chainage 90/000 to 103/000 along State Highway 56, connecting Danta and Ambaji in the Banaskantha district of Gujarat. The corridor has been upgraded to a four-lane divided highway with service roads, a central median, and several at-grade intersections. While much of the alignment traverses relatively uniform terrain, the section between chainage 101/000 and 103/000 passes through steep, rolling, and hilly topography. These terrain conditions impose constraints on feasible curve radii, transition lengths, superelevation development, sight distance, and available median widths [8,11,12]. Consequently, the corridor provides a suitable setting for evaluating the interaction between geometric design requirements and vehicle maneuverability under constrained terrain conditions.

Data collection

The geometric data used in this study were obtained primarily from available project design records and computer-aided design (CAD) drawings, supplemented by field observations at selected locations. The available records included horizontal alignment drawings, vertical profiles, cross-sectional drawings, junction layouts, median-opening layouts, technical schedules, and site photographs and inventories. The geometric information extracted from these sources included horizontal curve radius, transition length, superelevation, gradients, vertical alignment characteristics, carriageway and median widths, junction geometry, and median-opening dimensions.

Three representative design vehicles were considered for maneuverability assessment: passenger cars, SU-12 single-unit trucks, and WB-15 semi-trailers. The vehicle categories were selected to represent passenger-vehicle and heavy-vehicle operating requirements relevant to the corridor. The selection of design vehicles and the assessment of roadway geometry were based on the applicable IRC provisions for four-lane highways and geometric design [8,9].

CAD-based corridor modeling

The corridor geometry was modeled using Civil 3D and InfraWorks to develop a three-dimensional representation of the roadway alignment, profile, cross sections, and surrounding terrain. The model incorporated the available horizontal and vertical alignment information and roadway cross-sectional characteristics.

The geometric assessment considered horizontal curve radius, transition length, superelevation, stopping sight distance, vertical gradients and curves, lane and median widths, and the geometric configuration of junctions and median openings. These parameters were selected based on the geometric design requirements for horizontal alignment, sight

distance, superelevation, transition characteristics, vertical alignment, and cross-sectional provisions [8,11-13]. The extracted or modeled values were compared with the applicable requirements of IRC:73-2023, IRC:SP:84-2019, IRC:SP:23-1993, IRC:38-1988, IRC:SP:48-1998, and, where applicable, AASHTO geometric design guidance [8-13]. A geometric element was considered deficient when the evaluated parameter did not satisfy the applicable minimum or recommended design criterion.

Junction and median assessment using swept-path analysis

AutoTURN was used to evaluate vehicle maneuverability at selected junctions, median openings, and U-turn facilities. Passenger cars, SU-12 single-unit trucks, and WB-15 semi-trailers were used as representative design vehicles in accordance with the applicable IRC provisions [9]. The vehicle templates were assessed using the available roadway geometry, including lane widths, turning radii, entry and exit geometry, median width, and available turning space.

The assessment focused on whether the complete swept-path could be accommodated within the intended roadway space without encroachment into adjacent or opposing traffic lanes. Particular attention was given to vehicle off-tracking and the available turning space during maneuvers. Previous research on U-turn geometry has demonstrated that geometric configuration can influence turning performance and capacity [4]. A maneuver was classified as constrained when the simulated vehicle path extended beyond the intended lane or available turning area.

Field-integrated verification

Field verification was undertaken after the initial CAD-based geometric assessment. Locations were selected for field inspection where the desktop assessment identified notable geometric constraints, including sharp horizontal curves, short transition lengths, restricted sight-distance conditions, junction maneuverability limitations, or constrained median-opening geometry.

The field inspection was limited to visual verification rather than detailed survey measurement. Observations focused on the physical roadway configuration, available carriageway and median space, roadside constraints, vegetation or other visibility obstructions, and general vehicle movement characteristics. The field observations were then compared qualitatively with the corresponding CAD-based findings to determine whether the identified geometric constraints were consistent with the observed site conditions.

Site inspections (Figure *1*) identified practical aspects such as roadside obstacles, vegetation encroachment, and minor construction deviations. These observations were used to support the geometric assessment and inform the practicality of proposed improvement measures; they were not used as an independent quantitative validation of the CAD model.

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4



FIGURE 1: Field Visit

Safety-oriented assessment approach

A geometry-first, proactive safety assessment approach was adopted to identify locations with potential operational safety concerns, including locations where crash data were unavailable or insufficient. Research has demonstrated associations between highway geometric characteristics and safety performance, particularly on mountainous roads and horizontal curves [1,5-7]. The assessment criteria included horizontal curve radius, transition length, superelevation, side friction, stopping sight distance, vertical alignment characteristics, junction maneuverability, and median-opening geometry [8,11-13].

Each geometric parameter was compared with the applicable IRC and AASHTO design criteria [8-13]. Locations were classified as critical when at least one of the following conditions was identified: (i) a geometric parameter did not satisfy the applicable design criterion; (ii) the available geometric provision resulted in constrained vehicle maneuverability or lane encroachment during swept-path analysis; or (iii) a geometric constraint identified through the desktop assessment was consistent with field observations and had potential implications for visibility, maneuverability, or roadway operation.

Limitations

The analysis does not explicitly account for variations in traffic volume or driver behavior, which may influence real-world operational performance. The swept-path assessment assumes standard vehicle dimensions, steering behavior, and driver compliance. Field verification was limited to visual observation and was not intended to provide independent survey-level validation of the CAD model. High-cost geometric treatments identified for critical locations were not subjected to detailed cost-benefit analysis. Despite these limitations, the methodology provides a structured basis for identifying geometric deficiencies and prioritizing locations for safety improvement along the corridor. The findings should therefore be interpreted as a geometry-based assessment of potential operational safety concerns rather than as a crash-risk or statistically validated safety prediction.

Results And Discussion

The geometric assessment of State Highway 56 from chainage 90/000 to 103/000 shows that, although the corridor has been upgraded to a four-lane divided facility, several geometric characteristics of the original hill-road alignment remain within the existing configuration. These characteristics are particularly evident in the mountainous stretch between chainage 101/000 and 103/000, where terrain constraints influence horizontal curvature, transition development, sight distance, and available maneuvering space [1,7]. The findings indicate that increased pavement width does not necessarily ensure adequate operational performance when other geometric elements remain constrained [5].

Rather than using crash records to estimate crash risk, the present study adopts a geometry-centered approach to identify locations with potential operational safety concerns. Such locations are defined as areas where geometric constraints may affect vehicle path, maneuverability, sight distance, or consistency of operation. This approach is particularly relevant for corridors carrying larger vehicles because heavy vehicles generally require greater maneuvering space and may be more sensitive to constrained roadway geometry than passenger cars [5,7].

Horizontal alignment and curve characteristics

Across the 13 km study corridor, 21 horizontal curves were documented, of which 14 (approximately 67%) are located within the mountainous region between chainage 101/000 and 103/000 (Table *1* and Figure *2*). This concentration of curves indicates a more constrained horizontal alignment within the mountainous section and provides the basis for examining the geometric characteristics of individual curves against the applicable design criteria [2,7,11,12].

The superelevation provided at each curve was evaluated against the applicable IRC provisions for the corresponding design conditions. Each of the 21 horizontal curves was assessed individually by comparing its radius, assessed speed, provided transition length, and superelevation with the corresponding geometric requirements. The side-friction requirement was also calculated for each curve using the equilibrium relationship between speed, radius, superelevation, and side friction [8,11,13].

The assessment showed that the provided transition lengths were shorter than the corresponding IRC requirements for all 21 curves, with deficiencies ranging from approximately 5 m to 25 m (Table *1*). Several curves within the mountainous section had transition lengths of only 15-30 m against corresponding requirements of up to 40 m. The results demonstrate that transition-length deficiency occurs at multiple locations along the assessed horizontal alignment rather than being limited to an isolated curve [11,12].

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

To examine the lateral operating condition of the assessed curves, the side-friction factor was calculated using the equilibrium relationship:

$$e + f = \frac{V^2}{127R}$$

where *e* is the superelevation rate, *f* is the side-friction factor, *V* is the vehicle speed in km/h, and *R* is the horizontal curve radius in meters [8,13].

For example, for a representative hilly-section curve with V = 65 km/h, R = 150 m, and e = 0.05:

$$e + f = \frac{65 \times 65}{127 \times 150}$$

$$= 0.222$$

Therefore,

$$f = 0.222 - 0.05$$

$$f = 0.172$$

The calculated value of 0.172 exceeds the commonly adopted IRC design side-friction value of approximately 0.15 for the corresponding design condition [8,11]. This example demonstrates that an individual superelevation provision should not be considered independently from speed and curve radius when examining the lateral operating condition of a curve. The finding supports assessment of the interacting geometric parameters rather than reliance on a single geometric criterion.

The deficient transition lengths also indicate that the available distance for gradual development of the required cross slope is less than the corresponding design requirement. This condition is particularly relevant in the mountainous section, where closely spaced curves and constrained terrain occur together. The combination may warrant greater attention to speed management and geometric consistency [2,5-7].

Sr. No.	HIP Chainage	Radius	Provided Transition Length	Speed	e	Required Transition Length	f
	m	m	m	km/h	%	m	
1	92/613	300	70	80	5	75	0.12
2	92/794	300	70	80	5	75	0.12
3	93/018	150	65	65	5	80	0.17
4	93/259	150	65	65	5	80	0.17
5	96/699	400	55	80	5	70	0.08
6	98/664	150	55	50	5	70	0.08
7	98/830	150	55	50	5	70	0.08
8	100/974	115	15	40	6	35	0.05
9	101/269	150	15	40	5	30	0.04

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

10	101/384	125	15	40	6	40	0.04
11	101/494	125	30	40	6	40	0.04
12	101/591	135	20	40	5	30	0.04
13	101/725	200	15	40	4	20	0.03
14	101/836	140	15	40	5	30	0.04
15	101/944	125	15	40	6	40	0.04
16	102/016	75	30	40	7	40	0.10
17	102/234	120	15	40	6	35	0.05
18	102/358	145	20	40	5	30	0.04
19	102/609	170	20	40	4	25	0.03
20	102/694	120	20	40	6	35	0.05
21	102/843	400	15	40	5	30	0.00

TABLE 1: Horizontal Alignment Deficiency

HIP, Horizontal Intersection Point

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4



FIGURE 2: InfraWorks Model Showing Dense Curve Clustering Between CH 101/000 and CH 103/000

Heavy-vehicle behavior on curves

Heavy vehicles such as SU-12 and WB-15 semi-trailers require greater swept-path space than passenger cars and may be more sensitive to constrained horizontal geometry and limited maneuvering space [5,6]. In this study, AutoTURN swept-path simulations were conducted at operating speeds of 20 km/h and 40 km/h to examine the ability of the representative heavy vehicle to negotiate the assessed curve within the available roadway space.

The assessment criterion was based on geometric accommodation of the simulated swept-path. A maneuver was considered geometrically accommodated when the complete swept-path remained within the intended traffic lane and available roadway envelope. A maneuver was considered constrained when any portion of the simulated swept-path extended into an adjacent or opposing traffic lane or beyond the available roadway or shoulder envelope.

At 40 km/h, the SU-12 simulation at the assessed constrained curve showed off-tracking, with portions of the swept-path extending beyond the intended lane and into the adjacent roadway or shoulder area (Figure *3*). At 20 km/h, the same vehicle could negotiate the curve within the available roadway envelope (Figure *4*). The results therefore indicate that the assessed geometry provides greater vehicle-path accommodation at the lower simulated speed, whereas the 40 km/h maneuver results in geometric encroachment.

The results demonstrate a speed-dependent limitation in the geometric accommodation of the assessed heavy vehicle. The encroachment represents a geometric maneuverability constraint and may increase the potential for interaction with adjacent roadway space. However, the AutoTURN results should be interpreted as a geometric maneuverability assessment rather than as a direct prediction of crash occurrence or crash probability [5-7].

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

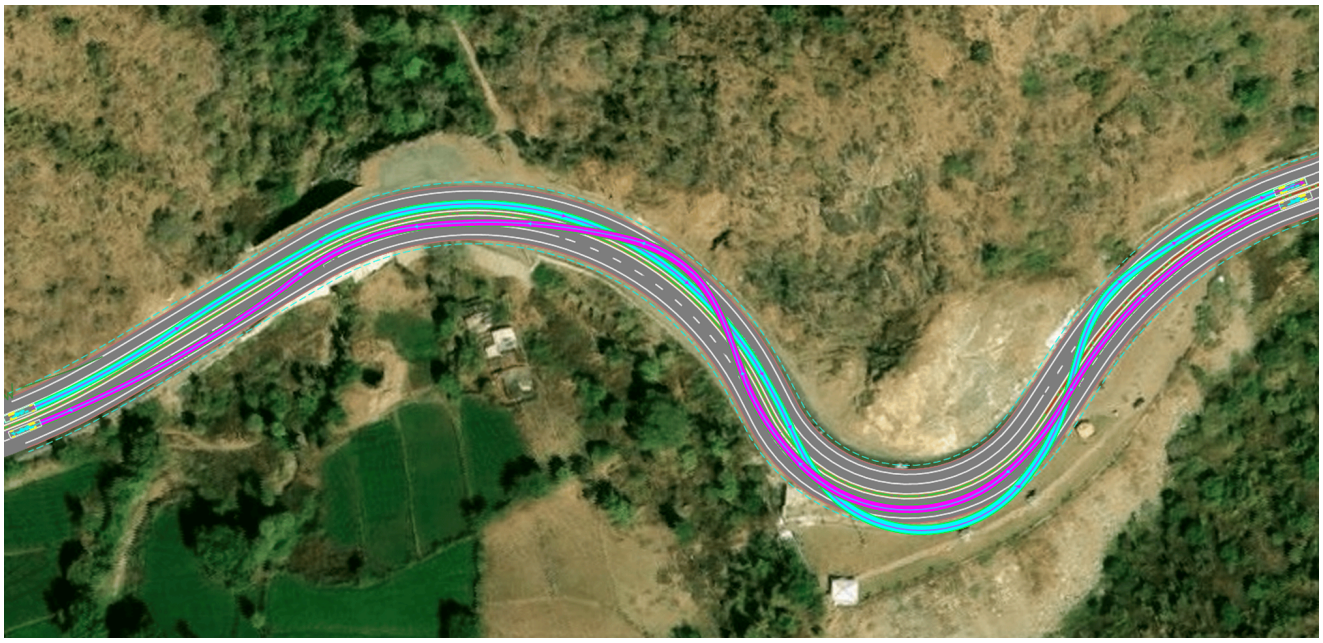


FIGURE 3: SU-12 Swept-Path at 40 km/h Showing Excessive Off-Tracking and Lane Encroachment

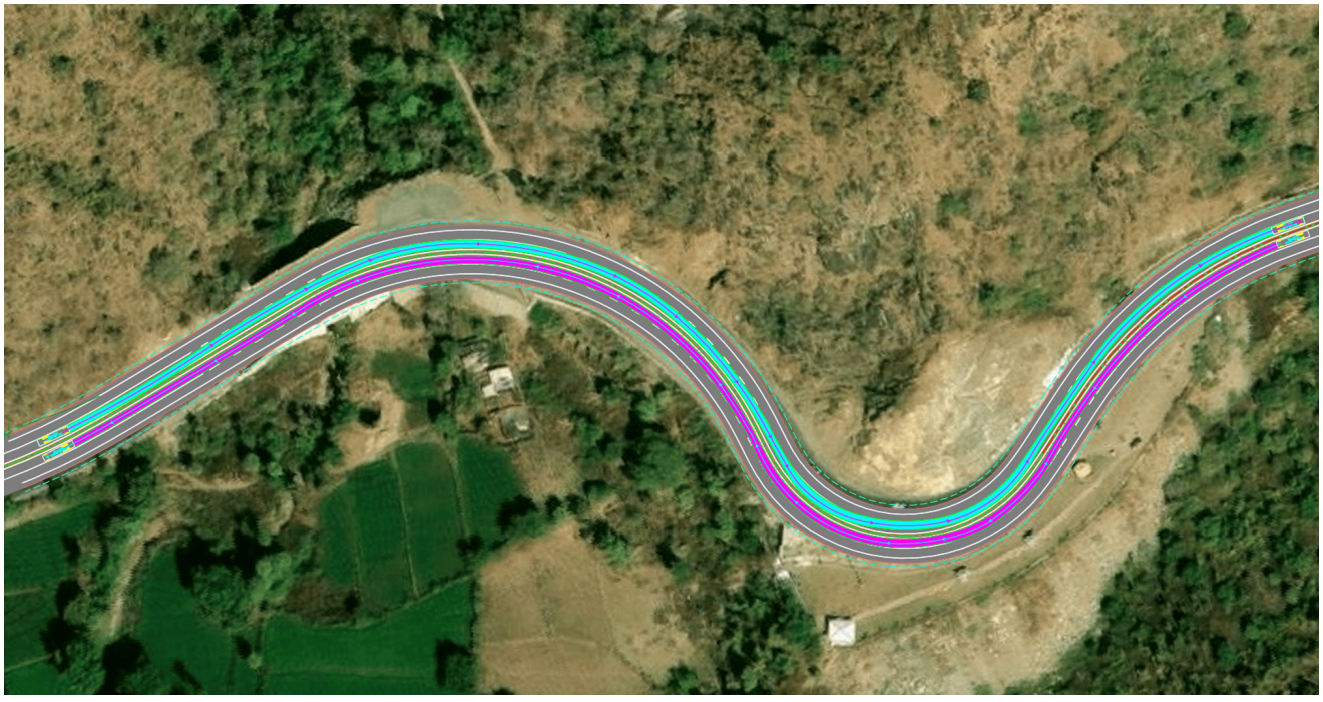


FIGURE 4: SU-12 Swept-Path at 20 km/h on a Hilly Curve Showing Geometrically Feasible but Low-Speed Operation

Junction performance

AutoTURN analysis was undertaken at junctions CH 91/260 and CH 99/600 using SU-12 and WB-15 design vehicles. The assessment examined whether the turning paths could be accommodated within the designated roadway space without encroachment into adjacent or opposing traffic lanes [4,9].

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

At both assessed junctions, the SU-12 vehicle could negotiate the evaluated turning movements within the available roadway geometry, whereas the WB-15 semi-trailer required encroachment into adjacent or opposing roadway space for the assessed movements (Figures *5-8*). The results indicate that the existing junction geometry provides greater maneuvering accommodation for the SU-12 than for the larger WB-15 vehicle.

The observed encroachment represents a geometric maneuverability constraint for the WB-15 design vehicle. Where such heavy-vehicle turning movements occur, the constrained turning envelope may result in operational conflicts with adjacent traffic movements. The findings therefore demonstrate the importance of considering representative heavy-vehicle swept-paths when evaluating junction geometry on a four-lane highway [4,9].

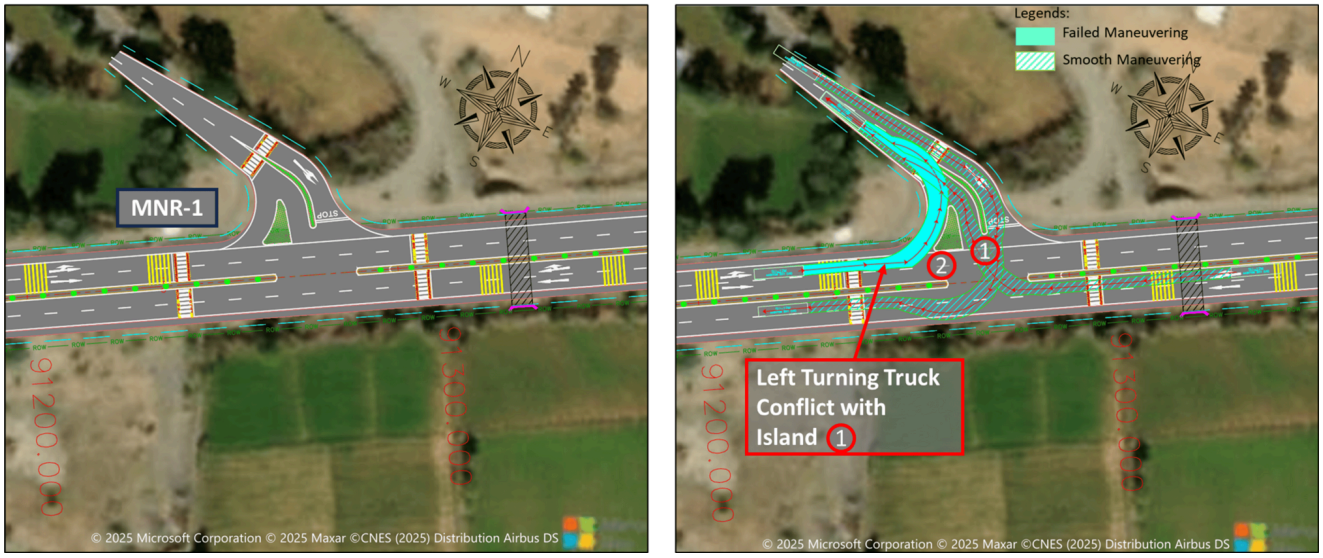


FIGURE 5: AutoTURN Swept-Path Performance of SU-12 Vehicle at Junction CH 91/260

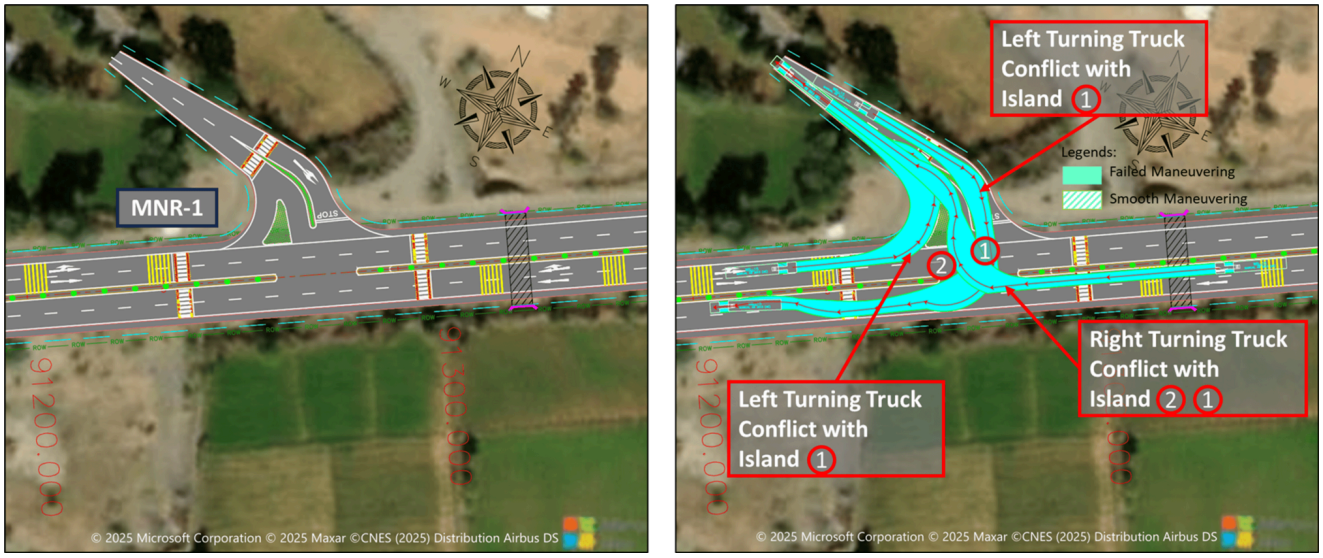


FIGURE 6: AutoTURN Swept-Path Performance of WB-15 Semi-Trailer at Junction CH 91/260

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

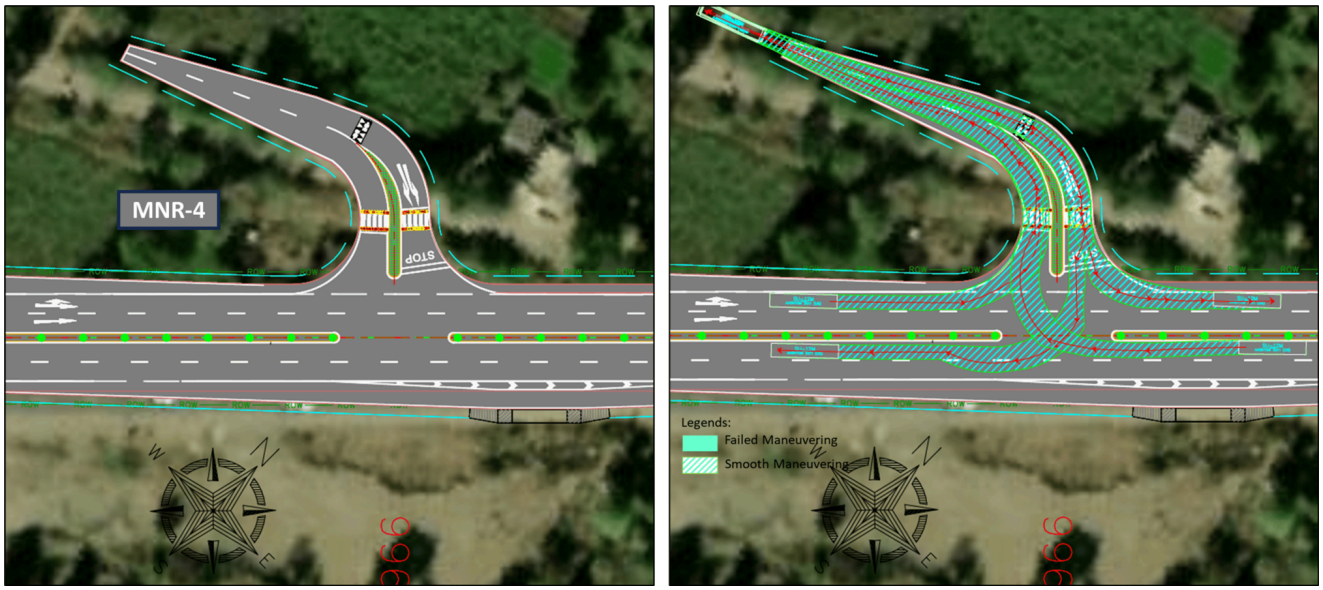


FIGURE 7: AutoTURN Swept-Path Performance of SU-12 Vehicle at Junction CH 99/600

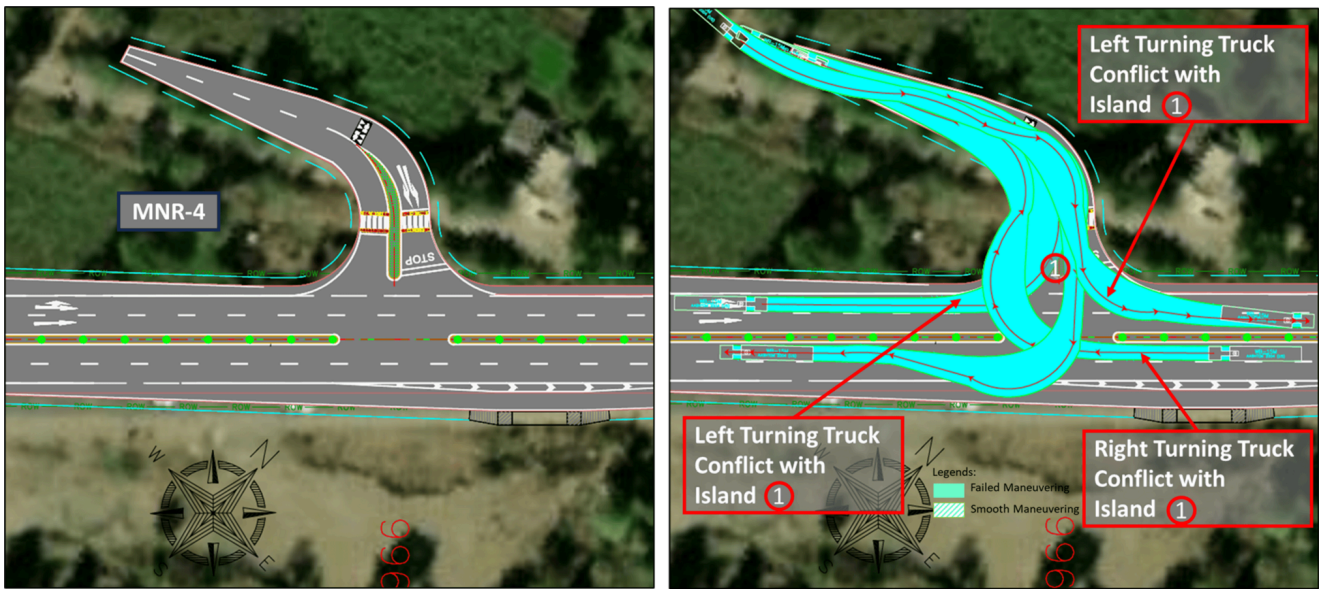


FIGURE 8: AutoTURN Swept-Path Performance of WB-15 Semi-Trailer at Junction CH 99/600

Median opening safety

A total of 24 median openings were evaluated using AutoTURN to examine U-turn maneuverability for passenger cars, SU-12 vehicles, and WB-15 semi-trailers. The assessed median widths ranged from approximately 1.0 to 1.25 m and provided limited space for vehicle maneuvering within the median openings.

The swept-path assessment showed that passenger cars could complete the evaluated U-turn movements without encroachment into opposing traffic lanes (Figure *9*). In contrast, the assessed SU-12 and WB-15 vehicles could not complete the corresponding U-turn maneuvers within the available geometric envelope and required encroachment into

the opposing traffic lane (Figure *10*). These results indicate that the existing median-opening geometry provides greater maneuverability for passenger cars than for the assessed heavy vehicles.

The findings represent a geometric maneuverability constraint rather than direct evidence of crash risk. Where heavy-vehicle U-turn movements are required, the available turning geometry may therefore warrant modification or the provision of an alternative U-turn arrangement.

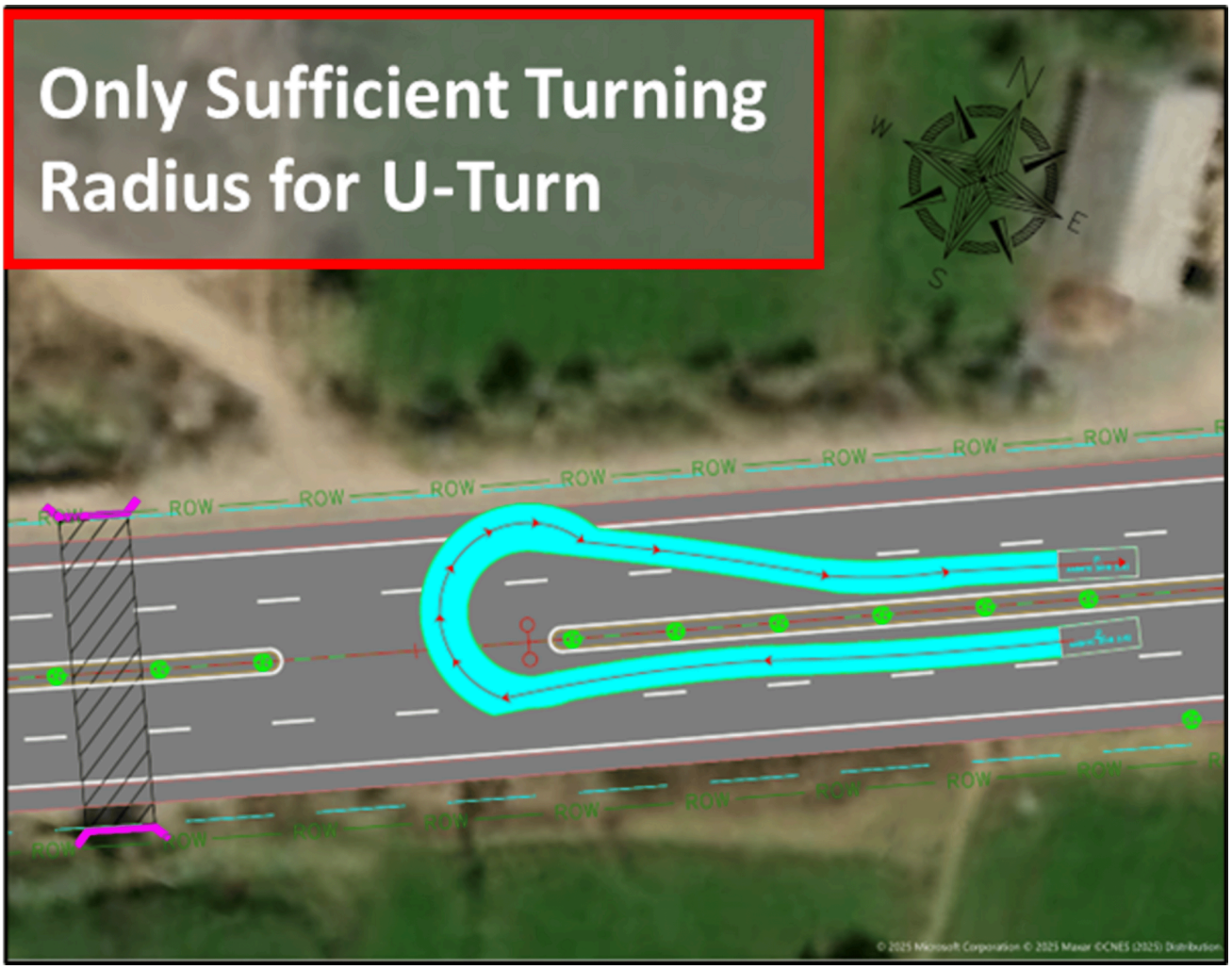


FIGURE 9: AutoTURN Passenger Car U-Turn Performance at Median Openings

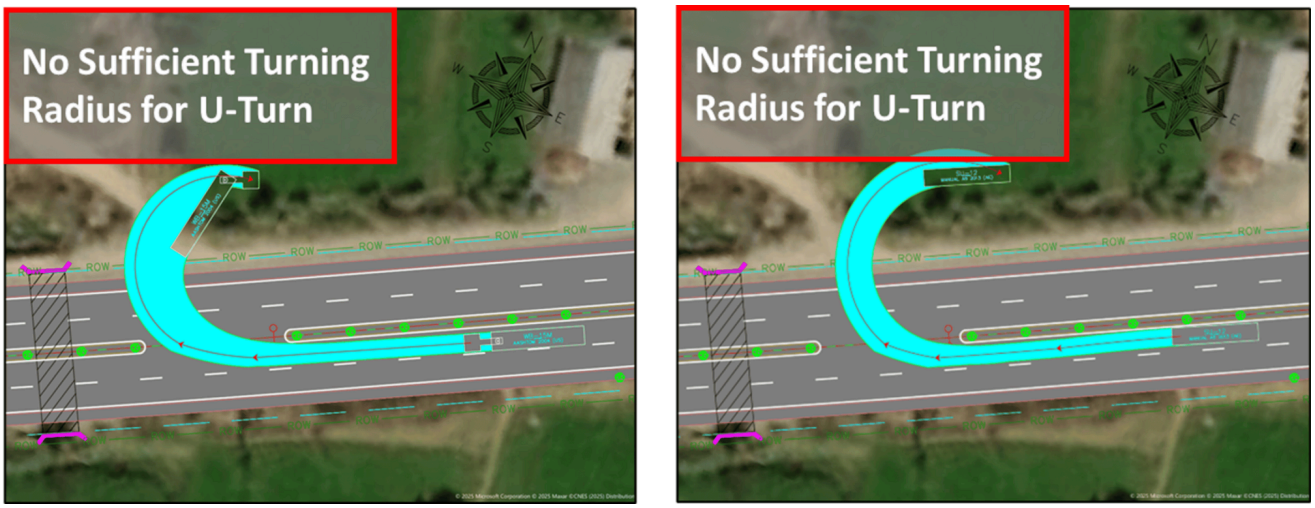


FIGURE 10: AutoTURN U-Turn Failure of WB-15 and SU-12 Vehicles at Median Openings

Vertical alignment and combined effects

The assessed vertical alignment was found to satisfy the applicable minimum requirements considered in the study [8,13]. However, vertical and horizontal alignment should be considered together because vehicle operating conditions are influenced by the combined characteristics of the roadway rather than by individual geometric elements in isolation [2,5,7].

In the mountainous section, steep terrain occurs together with closely spaced horizontal curves and deficient transition lengths. This combination represents a concentration of geometric constraints that may require greater speed control and driver attention. The present analysis identifies these combined geometric characteristics as potential operational safety concerns; it does not quantify vehicle stability or establish a direct relationship between the identified deficiencies and crash occurrences.

Recommendations

The identified geometric deficiencies on State Highway 56 primarily relate to transition-length adequacy, vehicle-path compatibility, junction maneuverability, and median-opening geometry. Accordingly, the recommended measures focus on improving geometric consistency, vehicle maneuverability, and operational control.

Short-Term Measures (Low-Cost, Immediate Safety Gains)

Speed management should be considered in accordance with the geometric characteristics of the corridor, particularly along the mountainous segment between chainage 101/000 and 103/000. The assessed hilly curves may warrant operating speeds in the range of 20-30 km/h, while rolling-terrain curves may warrant speeds of up to 65 km/h based on the geometric assessment [8].

Enhanced curve-warning systems, reflective delineators, advisory speed plates, and chevron boards should be considered at locations where geometric constraints require additional driver guidance [12]. Median openings where heavy-vehicle U-turns cannot be accommodated should be restricted or appropriately channelized. Additional channelization measures should also be considered at junctions CH 91/260 and CH 99/600, where the WB-15 swept-path assessment indicates constrained turning movements [9].

Long-Term Measures (Geometric Corrections Within Existing Alignment)

Transition lengths on deficient horizontal curves, particularly within the hilly section, should be reviewed and upgraded toward the applicable IRC requirements [8,11]. Junctions at CH 91/260 and CH 99/600 should be reviewed for reconstruction to accommodate the WB-15 turning envelope through measures such as increased turning radii,

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

approach flares, and dedicated turning provisions, where feasible [9].

Median openings that cannot accommodate representative heavy vehicles should be reviewed for widening and appropriate turning-bulb arrangements. Where geometric widening is not feasible, closure of unsuitable openings and provision of an appropriately designed alternative U-turn facility should be considered.

Sight-distance constraints should also be reviewed through vegetation removal, cut-slope trimming, and shoulder improvements where required.

Capital-Intensive Measures (Permanent Safety Solutions)

At severely constrained mountainous curves, partial realignment may be considered where the existing right-of-way and terrain conditions prevent achievement of adequate geometric provisions [2,13].

At junctions CH 91/260 and CH 99/600, grade-separated or semi-grade-separated arrangements may be considered where future traffic demand and operational requirements justify such interventions [9].

In locations where satisfactory geometric improvement cannot be achieved within the existing alignment, larger interventions such as hillside bypasses or viaduct solutions may be considered to provide a more consistent roadway geometry (Figure *11*) [2,13].



FIGURE 11: InfraWorks Model for Viaduct Proposal

Conclusions

The geometry-based assessment of the 13-km State Highway 56 corridor identified several geometric deficiencies with potential operational safety implications. Of the 21 horizontal curves identified, 14 (approximately 67%) are concentrated between CH 101/000 and CH 103/000. The provided transition lengths were approximately 5-25 m shorter than the corresponding requirements for all 21 assessed curves. Although the assessed superelevation values were within the applicable design provisions, the calculated side-friction demand reached 0.17 for the representative 150-m-radius curve at 65 km/h, exceeding the adopted design value of approximately 0.15. The swept-path assessment identified vehicle-maneuverability constraints at selected locations. At the assessed curve, the SU-12 vehicle could negotiate the geometry within the available roadway envelope at 20 km/h, whereas the 40 km/h simulation resulted in off-tracking and

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

encroachment beyond the intended roadway space. At junctions CH 91/260 and CH 99/600, the WB-15 semi-trailer required encroachment into adjacent or opposing roadway space to complete the assessed turning movements. Similarly, the assessment of the 24 median openings indicated that the available geometry generally accommodated passenger-car U-turns but did not provide sufficient maneuvering space for the assessed SU-12 and WB-15 vehicles without encroachment into the opposing traffic lane.

Because the study did not incorporate historical crash records, traffic-volume data, measured operating speeds, or quantitative field measurements, the identified conditions are interpreted as geometric deficiencies and vehicle-maneuverability constraints with potential operational safety implications, rather than as direct evidence of crash risk or crash probability. The principal recommended measures are to improve deficient transition lengths where feasible, implement appropriate speed management in constrained mountainous sections, review junction and median-opening geometry for heavy-vehicle maneuverability, and address localized sight-distance and roadside constraints. These measures provide a practical basis for addressing identified geometric deficiencies and improving vehicle accommodation and geometric consistency along the corridor.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Vashisth M. Trivedi

Acquisition, analysis, or interpretation of data: Vashisth M. Trivedi, Pinki Deb

Drafting of the manuscript: Vashisth M. Trivedi, Pinki Deb

Critical review of the manuscript for important intellectual content: Vashisth M. Trivedi

Supervision: Vashisth M. Trivedi, Pinki Deb

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
- **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets supporting the findings of this study, including geometric design drawings, CAD models, swept-path simulation outputs, and field observation records, are not publicly available due to project confidentiality but are available from the corresponding author upon reasonable request for academic and research purposes.

How to cite this article:
Trivedi V M, Deb P (November 05, 2026) Geometric Design and Safety Evaluation of Critical Geometric Elements on State Highway 56 in Gujarat, India (Chainage 90/000–103/000). Cureus J Eng 3 : es44388-026-00356-4. DOI https://doi.org/10.7759/s44388-026-00356-4

Acknowledgements

The author gratefully acknowledges the guidance and support of the academic advisor, Dr. Pinki Deb, whose technical insights and methodological direction were central to this study. Sincere thanks are also extended to Mr. Bhavin Parmar, Principal Designer of the SH 56 project, for providing project data, drawings, and valuable field insight. This work reflects a successful integration of academic research and professional engineering practice made possible through their collaboration.

References

1. Bassan S: Sight distance restriction on highways' horizontal curves: insights and sensitivity analysis. European Transport Research Review. 2016, 8:21. 10.1007/s12544-016-0208-6
2. Xu J, Lin W, Shao Y: New design method for horizontal alignment of complex mountain highways based on “trajectory-speed” collaborative decision. Advances in Mechanical Engineering. 2017, 9:10.1177/1687814017695437
3. Shaik ME, Abid H, Irecho DN, Al-Ahmadi HM: The impact of shoulder characteristics on safety of highway in horizontal curves: a systematic literature review. Discover Civil Engineering. 2025, 2:66. 10.1007/s44290-025-00225-9
4. Muharam FR, Nugroho TS, Weningtyas W: Evaluating U-turn capacity with modified geometry designs and various conflicting traffic flows: a traffic microsimulation approach. Civil Engineering Dimension. 2025, 27:73-84. 10.9744/ced.27.1.73-84
5. Dhahir B, Hassan Y: Framework for reliability-based, safety-explicit horizontal curve design using naturalistic driving data. Transportation Research Record: Journal of the Transportation Research Board. 2019, 2673:605-615. 10.1177/0361198119838853
6. Al-Sheikh O, Ghasemi SH, Jalayer M: Reliability-based analysis of horizontal curve design by evaluating the impact of vehicle automation on roadway departure crashes and safety performance. Heliyon. 2024, 10:e25346. 10.1016/j.heliyon.2024.e25346
7. Choudhary A, Garg RD, Jain SS: Safety impact of highway geometrics and pavement parameters on crashes along mountainous roads. Transportation Engineering. 2024, 15:100224. 10.1016/j.treng.2023.100224
8. Indian Roads Congress: IRC:73-2023 Geometric Design Standards for Non-Urban Roads. Indian Roads Congress, New Delhi, India; 2023.
9. Indian Roads Congress: IRC:SP:84-2019 Manual of Specifications and Standards for Four Laning of Highways. Indian Roads Congress, New Delhi, India; 2019.
10. Indian Roads Congress: IRC:SP:23-1993 Vertical Curves for Highways. Indian Roads Congress, New Delhi, India; 1993.
11. Indian Roads Congress: IRC:38-1988 Guidelines for Design of Horizontal Curves for Highways and Design Tables. Indian Roads Congress, New Delhi, India; 1988.
12. Indian Roads Congress: IRC:SP:48-1998 Hill Road Manual. Indian Roads Congress, New Delhi, India; 1998.
13. American Association of State Highway and Transportation Officials: A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials, Washington, DC; 2018.