Lateral Placement Behaviour along Horizontal Curve Sections under Mixed Traffic: Evidence from North Easter Hill range of India

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Abstract
Where a vehicle sits across the carriageway on a curve is closely tied to how safely and how efficiently that curve performs. This paper examines that behaviour on a four-lane median-divided hill highway. Lateral placement was measured at three gates, namely the entry, centre and exit, on ten horizontal curves of the Itanagar–Naharlagun section of NH-415, yielding 26,898 vehicle observations. Each gate was analysed on its own, and the spread of placement at each was fitted to a scaled Beta model built from the measured mean and variance. The section effect was then tested twice. Averaged over the ten curves, the Friedman test returned nothing for any class; such averaging washes out the very within-curve movement that the study set out to capture. The individual vehicles told a different story. With the same vehicle followed through all three gates, a matched Friedman test made the section effect highly significant for every dominant class, namely car, SUV, motorcycle and scooter, with p below 0.001 throughout. Its shape did not change from one class to the next. Vehicles ran widest near the centre and drew closest to the median at the exit, a swing of barely 0.2 to 0.4 m. The section therefore shifts placement in a reliable but small way, and accounts for only a modest part of the overall spread. Valley-side and hill-side curves also differed, most sharply at the entry, although the roadside type here cannot be separated from the direction of travel. Read together, the results make the case for treating the curve section, rather than the whole curve, as the unit of design and maintenance attention on heterogeneous hill corridors.

Keywords: Lateral placement; horizontal curves; heterogeneous traffic; hill highway; Beta distribution; Friedman test

1. Introduction

Lateral position refers to the transverse distance of a vehicle from a fixed reference on the carriageway, usually the median edge or the outer pavement edge. It is seldom recorded, yet it bears directly on capacity, safety and pavement life. Where wheel paths concentrate within a narrow band, the pavement edge deteriorates early and unevenly, and the risk of run-off and side collisions increases.

This matters more under Indian traffic. The stream is strongly heterogeneous: two-wheelers, cars, light commercial vehicles, buses and trucks occupy the same lane, and lane discipline is weak, so the carriageway is loaded unevenly across its width. The effect carries into both operations and pavement wear. Hill roads make it worse. With sharp curves, steep grades, limited sight distance and uneven shoulders, drivers steer almost continuously, and lateral position varies widely from one vehicle to the next. The IRC hill-road provisions recognise the resulting asymmetric distress and safety concerns.

NH-415 connects Itanagar and Naharlagun and forms part of the corridor linking Arunachal Pradesh with Assam and the national network. Running through the eastern Himalayan foothills, it is a busy urban-to-peri-urban route. The carriageway is four-lane and median-divided, its alignment following the terrain through a series of curves, some compound, with shoulders of varying condition. Traffic is mixed, and the spare lateral width is limited. Under these conditions lateral position affects lane discipline, delivered capacity, pavement-edge performance and safety. Edge deterioration and uneven distress are already visible and point to repeated wheel paths. In left-hand traffic, placement is measured as the distance from a reference wheel, usually the one nearest the median, to a fixed roadway mark. It depends on geometry, vehicle size, the roadside, surrounding traffic and driver comfort: heavy vehicles keep more clearance, while smaller vehicles position themselves more freely.

Lateral placement is not always normally distributed. On straight roads with disciplined traffic it can approach normality, but curves, grades and confined surroundings skew it and push it against the lane boundaries. For Indian conditions the Johnson S_B and Beta distributions fit better, as both are bounded and admit asymmetry within a fixed range. Local weather adds variability, with rain, fog and low visibility common on the corridor. Its location, terrain and traffic together make NH-415 a suitable case for an empirical study of lateral placement.

A systematic study of lateral placement is therefore overdue, one that can feed hill-road design, pavement-performance assessment and safety planning alike, and that speaks to the design objectives set out by the IRC and MoRTH.

1.1 Problem Statement

Current IRC and MoRTH design practice leans on macroscopic traffic measures and treats the lateral wheel-path distribution with a few simplifying assumptions. On a straight road carrying uniform traffic those assumptions hold up well enough. On a hill highway carrying everything at once, they do not.NH-415 shows the symptoms plainly enough: damaged pavement edges, distress that falls unevenly, weak lane discipline, recurring safety problems. All of it points the same way, to lateral movement that is anything but uniform and to wheel paths that gather in particular bands of the carriageway. Present design practice has little to say about any of this.

The models usually reached for, normal or lognormal, are a poor match for curved and bounded conditions and miss the asymmetry of real lateral behaviour. Empirical, location-specific models for hill roads are scarce. And the levers that matter most in hill terrain, namely curve radius, carriageway width, shoulder width and shoulder condition, have not been pinned down against placement, so their joint bearing on distress and safety stays largely unexamined.

The present study therefore addresses the following gaps:

- The lack of quantitative assessment of lateral placement on hill highways under mixed traffic;
- The need for appropriate bounded statistical models to represent lateral behaviour;
- The limited understanding of the effect of geometric elements on vehicle lateral positioning; and
- The absence of design-oriented guidance for improving the irc hill-road provisions.

The study provides context-specific insight into lateral placement behaviour. The findings support geometric design refinement, pavement maintenance planning, and road safety improvement for hill highways under Indian traffic conditions.

2. Literature Review

Lateral position on curves has occupied traffic engineers for the better part of a century, and for good reason, since it bears directly on safety, on ride comfort and on how the pavement wears. It is, at bottom, a record of how drivers answer the geometry in front of them, and it grows more pronounced wherever geometry tightens, sight lines shorten or shoulders fail. The early work was hands-on, its aim simply to log where vehicles sat under one set of conditions or another. Taragin (1943) was among the first to take up the transverse position of moving vehicles and the part vehicle characteristics play in it; he found heavy vehicles hugging the pavement edge, hastening edge wear and lopsided deterioration. Case et al. (1953) showed that roadside features, kerbs, medians, signs and the like, pull drivers into line as they keep clear of whatever they read as a hazard, the shifts coming out systematic rather than random. Jorol (1962) tied placement on rural highways to perception and sight distance. Gazis et al. (1962) went finer still, treating the stream as something close to a fluid in which each vehicle trims its lateral position against its neighbours. The thread through all of them is the same: placement is not noise, but behaviour with a shape.

As the work moved onto curves and into the mountains, the behaviour turned asymmetric. Felipe and Navin (1998), tracking trajectories on mountain roads, saw vehicles drift inward on left-hand curves and outward on right-hand ones, and tied the pattern to curvature, speed and steering effort; from this came the notion of behavioural asymmetry on horizontal curves. Later studies bore out the familiar habit of cutting a curve to spend less on steering and lateral friction, the sharper the curve the stronger the pull. Field studies in hill terrain keep returning the same three culprits, curvature, gradient and surface. Donnell et al. (2016), weighing lateral friction demand against supply, showed the safety margin thinning as the two closes on each other, worst of all on tight radii and rough surfaces. Ghalehni et al. (2023) looked at vehicles straying into the opposing lane on mountain curves and found the overlap, and the head-on risk that comes with it, climbing where curves are sharp and sight distance short. Read together, these results mark out the boundary of a design that is purely deterministic.

More recent work has turned to reliability-based methods to carry the uncertainty in how drivers behave and choose speed. Al-Sheikh et al. (2024) found that deterministic methods can flatter road safety, especially in mixed traffic on curves. Aminfar et al. (2023) traced the sudden swing in friction demand on compound and reverse curves to a loss of vehicle stability. Chen et al. (2022) linked lateral instability to speed variability, and argued for folding lateral behaviour into speed-management on mountain roads.

Mixed traffic and slack lane discipline are a particular worry in countries like India. Much of the work from the developed world simply assumes orderly lanes, an assumption Indian traffic does not honour. Dey et al. (2006) showed the classes using the carriageway in quite different ways, the small vehicles working the gaps while the large ones hold their distance, and the resulting patchwork weighing on both capacity and flow stability. Munigety and Mathew (2016) put swerving and filtering at the head of the list of causes behind lateral variability in heterogeneous streams.

How placement is defined and measured has shifted over time as well. The standard reading is the perpendicular distance from a reference wheel to a fixed roadway mark, whether the pavement edge or the median (Case et al., 1953). Recent studies favour the median or edge line, the better to keep readings comparable from point to point (Saini and Biswas, 2020), a choice that sits naturally alongside working definitions of lane discipline in mixed traffic. The tools have moved on too. Where wheel paths were once stepped off by hand, coarse and at the mercy of the observer, the work now runs on video tracking, drone survey and image processing. Luo et al. (2016) logged fine-grained tracks on curves with inertial units and three-dimensional profiling. Mauriello et al. (2018) read driver visual attention off trajectory data. Deshmukh et al. (2025) and Sharma et al. (2025) brought roadside and aerial video to mixed traffic on hill roads and broke the behaviour down by class.

For all that progress, the gaps are easy to name. Median-divided hill highways have had little close study, least of all under mixed traffic. How curve radius, carriageway width, median type and shoulder condition act together on placement is still poorly understood. The Johnson Sʙ and Beta distributions look promising for bounded, skewed behaviour (Das et al., 2016), yet no one has tested them across a spread of terrain and layouts. The link between placement patterns and pavement distress has barely been probed. On the design side, the IRC and MoRTH manuals set out lane width, shoulders and sight distance for hill roads (IRC, 2019; IRC, 2023; MoRTH, 2013), but they remain deterministic and make no direct use of observed behaviour in mixed traffic. What is wanted, then, is empirical, correlation-minded research to inform geometric design and maintenance. The present study on NH-415 is a step in that direction, pairing field data with statistical modelling to close some of these gaps on median-divided hill highways, and feeding back into geometric design, pavement-performance analysis and the IRC and MoRTH guidelines.

3. Materials And Methods

3.1 Study Corridor

The study was carried out on the Itanagar–Naharlagun section of National Highway-415 (NH-415) in Arunachal Pradesh. NH-415 is a four-lane median-divided highway. It crosses the Eastern foothills of the Himalayas and serves as an important urban–peri-urban corridor. The highway has the geometric character of hilly terrain, with sharp horizontal curves, variable gradients, and irregular shoulder conditions. The geometric features of the ten study curves, including the left-roadside object, shoulder width, gradient, hand of arc, radius, transition and circular curve lengths, deflection angle, and tangent (straight) distances, are summarised in Table 1.

Table 1. Geometric features of the study curves

SL no.	Curve no.	Left object	Shoulder width (m)	Gradient (%)	Hand of arc	Radius (m)	Transition length (m)	Circular length (m)	Deflection angle (°)	Straight from PC (m)	Straight to SC (m)
1	20	Shoulder + open space	3	3.32	R	55.72	12	39.11	52.55	73.6	13.8
2	19	Railing + open space	1.7	-3.32	L	50.72	17.29	40	64.71	13.8	73.6
3	28	Hill	1.5	4.59	L	40.5	8	57.7	92.94	6	8
4	17	Space + valley	1.3	-3.82	R	28.7	8	70.94	157.81	8	6
5	26	Hill	1.5	3.21	R	20.16	12	38	142.1	4.5	16.8
6	15	Space + valley	3	-6.97	L	21.08	10	32	114.17	4.5	6
7	24	Hill	1.5	5.96	R	35.2	18.36	32.89	83.42	8	12
8	13	Railing + valley	0.5	-9.93	L	26.71	10.54	35.77	99.34	14	12
9	22	Space + hill	2	4.99	R	23.98	9.28	49.85	141.29	6	16.6
10	11	Space + valley	1.5	-4.99	L	28.97	11.67	49.52	121.02	16.6	6

The curves carry their field-survey IDs. Numbers 11, 13, 15, 17 and 19 sit on the Itanagar-to-Naharlagun carriageway, and 20, 22, 24, 26 and 28 on the return carriageway to Itanagar. Gradient is signed by the direction of travel, a minus sign marking a descent. Radii run from roughly 20 m up to 56 m, sharp by any measure. And the inner roadside is never quite the same twice, valley, hill, railing or open space, which is what lets the data speak to roadside-driven asymmetry.

3.2 Selection of Study Locations

The geometric design drawings and alignment data came from the Public Works Department (PWD) at Itanagar, and carried the horizontal radii, superelevation, gradient, chainages and cross-section. Once those records had been checked against what was actually on the ground, the sites were fixed. Fig. 1 places the corridor between Naharlagun and Itanagar.

Fig. 1. Location of the study corridor (Naharlagun–Itanagar)

Reconnaissance surveys and videography were conducted in both directions of travel. Ten horizontal curves were studied, organised as five survey segments. Each segment carries one curve on the Itanagar-to-Naharlagun carriageway and one curve on the Naharlagun-to-Itanagar carriageway, so the ten curves are physically distinct. The five segments pair the curves as (19, 20), (17, 28), (15, 26), (13, 24), and (11, 22), and the mirrored tangent distances in Table 1 reflect this survey pairing. The geometric characteristics of all ten curves are given in Table 1.

3.3 Data Collection Period and Traffic Characteristics

The video was shot across the last week of January and the first of February 2024. Recording was kept to daylight and dry pavement, to take the weather out of the driver's decisions as far as possible. Conditions stayed kind throughout, visibility and temperature both moderate.

The three gates of the ten curves together yielded 26,898 vehicle observations, near enough 9,000 at each gate, with about 6,300 vehicles caught at all three gates of a curve. Personal vehicles ran the show. SUVs, scooters, cars and motorcycles made up the great bulk of the stream; heavy vehicles, light commercial vehicles and public transport between them accounted for only a sliver. Fig. 2 gives the class breakdown at the study sites.

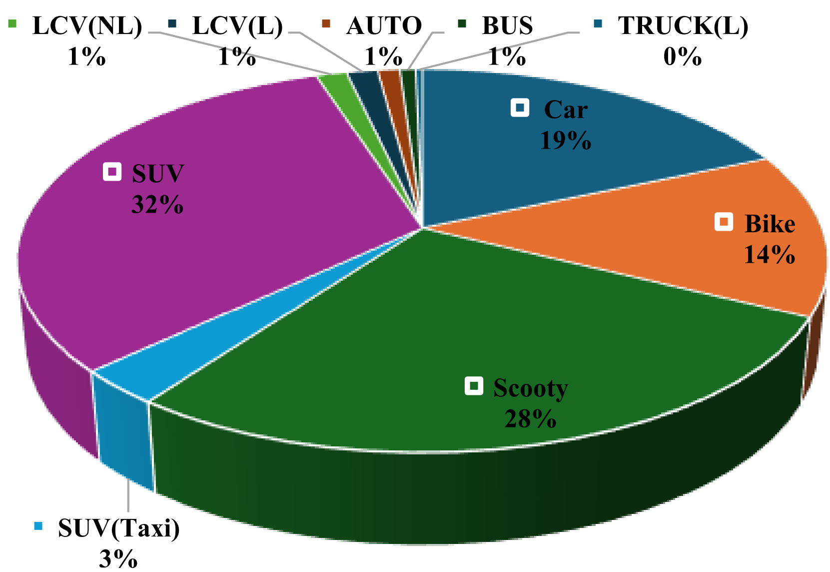

Fig. 2. Vehicle-class composition at the study sites

3.4 Observation Layout and Video Recording

Every curve was split into three segments for observation, the entry at the point of curvature, the middle stretch, and the exit at the point of tangency (Fig. 3, A–C). Two temporary markers, 5 m apart, fixed an observation gate in each.

The cameras went up on the median or shoulder, somewhere between 1.5 and 2.5 m, high enough for a clean view of the whole carriageway and far enough off to leave the drivers none the wiser. Fig. 3 (A–C) sketches the arrangement at each curve.

Fig. 3 A (Entry of Curve 11)

Fig. 3 B (Mid of Curve 11)

Fig. 3 C (Exit of Curve 11)

3.5 Measurement of Lateral Placement

Lateral placement was taken as the perpendicular distance from the vehicle to the median edge at the gate. To make the reading systematic, the carriageway at each site was marked off into 0.5 m lateral bands in durable white paint, and the trajectories were lifted from the video in post-processing. For anything on four wheels or more, the reference was the wheel nearest the median; for two- and three-wheelers, narrow or single-track as they are, the front wheel served instead.

3.6 Computation of Average Lateral Placement

Lateral placement was recorded in 0.5 m lateral segments measured from the median edge, and each reading was converted to metres. For each curve section and vehicle class, the average lateral placement was computed as:

$\bar{x}_i = (1 / n_i) \Sigma_{j=1}^{n_i} x_{ij}$

where, n_i is the number of vehicles observed at the gate; and x_{ij} is the lateral placement of the j-th vehicle. The class-wise and all-vehicle means at the entry, centre, and exit of each curve are presented in Tables 2, 3, and 4.

Table 2. Mean lateral position and average shift of all vehicles at the entry of curves

Curve ID	**R (m)**	**Auto**	**Bus**	**M/Cycle**	**Car**	**LCV (load)**	**LCV (no load)**	**SUV**	**SUV (taxi)**	**Scooter**	**Truck**	**Avg. placement, all veh. (m)**	**Avg. shift /m radius**
Curve 11	28.97	4.92	1.88	3.87	2.39	2.71	1	2.16	3.12	3.79	2.4	2.98	0.103
Curve 13	26.71	4.08	2.9	4.46	2.21	1.62	2.38	1.96	2.56	4.58	3	2.98	0.111
Curve 15	21.08	4.43	2.06	4.34	1.71	1.83	1.69	1.51	2.2	4.6	0.5	2.91	0.138
Curve 17	28.7	4.5	2.83	4.12	2.53	1.91	2.03	2.31	2.89	4.28	0.88	3.17	0.11
Curve 19	50.72	3.16	1	3.64	1.57	1.84	1.81	1.47	1.87	4.01	1.25	2.5	0.049
Curve 20	55.72	4.44	3	4.01	2.68	3.4	2.27	2.42	3.17	4.31	1.5	3.22	0.058
Curve 22	23.98	3.71	0.5	3.16	1.62	1.4	NA	1.55	1.58	3.67	2.5	2.29	0.095
Curve 24	35.2	4.72	2.38	3.06	2.2	1.57	2.58	1.94	2.46	3.23	1	2.53	0.072
Curve 26	20.16	4	3.08	3.79	2.47	1.95	2.14	2.54	2.52	4.03	2.42	3.15	0.156
Curve 28	40.5	4.14	2.38	3.1	1.77	1.95	1.8	1.33	1.32	3.52	0.88	2.27	0.056

Table 3. Mean lateral position and average shift of all vehicles at the centre of curves

Curve ID	**R (m)**	**Auto**	**Bus**	**M/Cycle**	**Car**	**LCV (load)**	**LCV (no load)**	**SUV**	**SUV (taxi)**	**Scooter**	**Truck**	**Avg. placement, all veh. (m)**	**Avg. shift /m radius**
Curve 11	28.97	3.92	1.12	3.19	1.78	2.14	1.1	1.54	2.03	3.04	2.1	2.31	0.08
Curve 13	26.71	3.17	2.4	4.9	2.3	2.27	2.44	2.04	2.35	5.15	3.5	3.21	0.12
Curve 15	21.08	5.07	2.61	4.36	2.37	2.9	2.37	2.3	3.07	4.61	0.88	3.35	0.159
Curve 17	28.7	4.04	2.83	3.35	2.01	2.12	1.61	1.76	2.42	3.84	0.62	2.64	0.092

Curve ID	R (m)	Auto	Bus	M/Cycle	Car	LCV (load)	LCV (no load)	SUV	SUV (taxi)	Scooter	Truck	Avg. placement, all veh. (m)	Avg. shift /m radius
Curve 19	50.72	5.03	2.62	4.83	2.81	2.5	3.07	2.98	3.25	4.93	2.62	3.75	0.074
Curve 20	55.72	2.19	1	2.86	1.75	1.36	1.33	1.75	2.1	3.31	2.5	2.3	0.041
Curve 22	23.98	4.58	1	4.78	2.45	2.24	NA	2.45	2.76	4.92	4	3.36	0.14
Curve 24	35.2	3.86	1.82	2.68	1.47	1	2.08	1.34	1.77	3.1	0.5	2.07	0.059
Curve 26	20.16	3.5	3	3.53	2.33	1.75	1.79	2.16	2.42	3.63	2.42	2.85	0.141
Curve 28	40.5	4.59	3.06	4.17	2.69	2.55	2.62	2.24	2.17	4.32	1.25	3.15	0.078

Table 4. Mean lateral position and average shift of all vehicles at the exit of curves

Curve ID	R (m)	Auto	Bus	M/Cycle	Car	LCV (load)	LCV (no load)	SUV	SUV (taxi)	Scooter	Truck	Avg. placement, all veh. (m)	Avg. shift /m radius
Curve 11	28.97	3.83	1.5	3.68	2.16	2.57	1.6	2.12	2.59	3.46	1.8	2.76	0.095
Curve 13	26.71	4.17	2.33	3.75	1.86	1.47	2	1.68	2.44	4.01	3	2.55	0.095
Curve 15	21.08	3.21	2.22	4.12	1.55	1.7	1.34	1.6	1.91	4.38	0.5	2.78	0.132
Curve 17	28.7	3.64	2.42	4.31	1.91	1.33	2.03	1.87	2.52	4.68	0.83	3.04	0.106
Curve 19	50.72	3.12	1.38	3.63	1.16	1.5	1.29	1.25	1.6	3.92	1.12	2.31	0.046
Curve 20	55.72	3.25	2.75	2.61	2.52	2.93	2.17	2.47	2.55	2.71	4.5	2.57	0.046
Curve 22	23.98	5.08	1.5	4.69	2.83	2.43	NA	2.74	2.54	4.8	4.33	3.49	0.146
Curve 24	35.2	4.08	2.07	2.85	1.65	1.37	2.5	1.57	2.06	3.49	1	2.33	0.066
Curve 26	20.16	2.5	2.33	3.58	1.86	1.45	1.5	1.58	1.62	3.25	1.83	2.42	0.12
Curve 28	40.5	4.27	2.88	3.2	2.31	1.59	2.16	1.82	2.07	3.72	1.38	2.64	0.065

To assess how lateral positioning responds to curvature, a normalised indicator, the shift per metre of curve radius (after Das et al., 2016), was defined as:

$S = \bar{x} / |R|$

where, $\bar{x}$ is the average lateral placement at a location; and R is the curve radius. The shift per metre of radius was used by Das et al. (2016) to set placement on a common footing across curves of different radius, and they reported it falling as the radius grows, that is, as the curve eases. The same indicator is adopted here, computed for each curve section. A larger value of S therefore marks a stronger lateral adjustment, the sharper curves carrying the larger shift. The computed values are reported in Tables 2, 3, and 4.

4. Results And Discussion

4.1 Modelling Methodology for Lateral Placement

Placement is a bounded, continuous quantity; it can only live inside the carriageway width. A scaled Beta distribution suits that, having finite support and room enough to bend into the asymmetric shapes the curves throw up, and bounded forms of this kind have been put to similar use before (Johnson et al., 1995; Das et al., 2016). For every reading in Tables 2, 3 and 4 the measured placement x (m) was divided through by the effective carriageway width W (m):

$u = x / W, \quad 0 \le u \le 1$

Separate datasets were prepared for the entry, centre, and exit sections of each curve. For each dataset and vehicle class, the normalised placement u was assumed to follow a Beta distribution:

$f(u; \alpha, \beta) = [1 / B(\alpha, \beta)] \cdot u^{(\alpha-1)} (1-u)^{(\beta-1)}, \quad 0 \le u \le 1$

where, α and β are the shape parameters; and B(α, β) is the Beta function.

4.2 Parameter Estimation

The method of moments was used for estimation, with both the mean and the variance taken from the individual placement observations in each section. The mean of the Beta distribution is:

$\mu = \alpha / (\alpha + \beta)$

Using the observed mean placement, the normalised mean is:

$\mu = \bar{x} / W$

The measured per-section standard deviation s of placement gives the variance on the unit interval as:

$v = (s / W)^2$

The Beta parameters then follow as:

$t = [\mu(1-\mu) / v] - 1, \quad \alpha = \mu t, \quad \beta = (1-\mu) t$

Here $\alpha + \beta$ carries the concentration, and $\alpha/(\alpha+\beta)$ the skewness and the favoured position. Crucially, the variance is measured and not assumed, so the fitted concentration answers to the real scatter of placement rather than to the mean alone. A single representative width, W = 7.5 m, was used to normalise across the curves.

4.3 Illustrative Calculation

For passenger cars at the entry of Curve 26, the sharpest curve in the set (R = 20.16 m), the measured mean placement was $\bar{x}$ = 2.47 m with a standard deviation s = 1.19 m, and W = 7.5 m:

$\mu = 2.47 / 7.5 = 0.330$

$v = (1.19 / 7.5)^2 = 0.0252$

$t = [0.330\ (1-0.330) / 0.0252] - 1 \approx 7.8$

$\alpha \approx 2.6, \quad \beta \approx 5.2$

Placement for this case is then x = 7.5 u, with u ~ Beta(2.6, 5.2). The modest concentration and the right skew describe a spread that leans towards the median, which is the shape that falls out naturally once the measured variance, rather than an assumed one, drives the fit.

4.4 Section-wise Behaviour

Two clearly separate regimes come out of the fitted parameters. Cars and SUVs ride close to the median, their means sitting around 1.9 to 2.2 m, and their distributions lean right, with skewness from 0.5 to 0.9; most of them stay near the median while a few stray out. Motorcycles and scooters ride far wider, means near 3.6 to 4.1 m, and their distributions lean the other way, skewness running from about minus 0.4 to minus 0.9, which is to say the two-wheelers keep to the outer part of the lane and only a minority cuts back in.

The concentration $\alpha + \beta$ stays between roughly 5.3 and 7.1 across every section and class, a broad and realistic spread rather than a tight cluster. For the two-wheelers it slides down from entry to exit, 7.1 to 5.6 for scooters and 7.0 to 5.3 for motorcycles, so their placement fans out as they leave the curve. Cars and SUVs hold their concentration steadier, but their right skew sharpens at the exit, from 0.56 to 0.81 for cars and 0.74 to 0.94 for SUVs, a sign of more vehicles pulling back towards the median as they pick up the tangent.

4.5 Relationship across Entry, Centre, and Exit

Put the section means and the fitted distributions side by side and a single path-dependent pattern emerges. For every dominant class the placement peaks near the centre, sits in between at the entry, and falls to its lowest at the exit. So the exit is where vehicles run closest to the median, and, for the two-wheelers, where the spread is widest. The sequence reads naturally enough as anticipation at the entry, fullest commitment through the centre, and a pull back inward at the exit as the driver opens up towards the tangent.

4.6 Roadside Environment: Valley-side and Hill-side Curves

What sits on the inner roadside is not the same from curve to curve. Four of them drop into a valley on the inner side, four climb into a hill, and two open onto clear space and are left out of this comparison. On the valley-side curves the mean placement ran 3.00 m at the entry, 2.94 m at the centre and 2.78 m at the exit; on the hill-side curves, 2.56, 2.83 and 2.66 m. The gap is widest, and most clearly significant, at the entry, where valley-side vehicles hold roughly 0.4 m further off the median ($p < 0.001$); it narrows but holds at the centre and exit ($p = 0.02$ and $p = 0.004$). Put plainly, where the inner edge falls away into a valley, drivers keep further from the median and nearer the centre line, and they do it most at the entry.

5. Hypothesis Testing

To settle the question statistically, whether placement really moves between entry, centre and exit, a hypothesis test was run, and run at two levels. The first took the ten curve-average placements, in the manner of earlier curve-based work. The second went down to the individual vehicles, which carry the sample size and the within-section spread that a properly powered test needs. Since the data are bounded and need not be normal, the tests were non-parametric throughout, at the 5% level.

5.1 Hypothesis Formulation

The hypotheses were formulated separately for the dominant vehicle categories: car, SUV, motorcycle, and scooter.

Null hypothesis (H_0): the median lateral placement of a given vehicle category is the same at the entry, centre, and exit sections.

H_0: L_entry = L_centre = L_exit
Alternative hypothesis (H_1): at least one section has a different median lateral placement.
H_1: at least one of L_entry, L_centre, L_exit differs

5.2 Curve-level Test (Friedman)
The Friedman test treats each curve as a block and the entry, centre, and exit sections as the repeated measures, using the mean placement of each section. The test was applied to the ten curve averages for each category. The results are given in Table 5.

Table 5. Friedman test on the ten curve-average placements

Vehicle type	n (curves)	χ^2	df	p-value	Decision (5%)
Car	10	2.6	2	0.273	Not significant
SUV	10	0.2	2	0.905	Not significant
Motorcycle	10	1.4	2	0.497	Not significant
Scooter	10	1.4	2	0.497	Not significant

Not one of the four classes shows a section effect at the curve-average level. That is no surprise: averaging over each curve strips out the within-curve movement and leaves three section means sitting almost on top of one another, and ten paired averages carry little power besides. So the curve-average test misses an effect that, as the next section shows, is plainly there in the individual data.

5.3 Individual-level Test (Matched Friedman)
At the individual level each vehicle is caught at all three gates, so its entry, centre and exit placements make a matched triple. The repeated-measures Friedman test was applied on that basis, each vehicle a block and the three sections the repeated measures, with vehicles matched on the identifier carried in each file. The test runs over the nine curves with a dependable identifier field, 7,079 vehicles in all. Table 6 reports it.

Table 6. Matched Friedman test on individual lateral placement (vehicles tracked through all three gates)

Vehicle type	Matched n	Mean entry (m)	Mean centre (m)	Mean exit (m)	χ^2	p-value	Post-hoc (all pairs)	Decision (5%)
Car	1536	2.09	2.26	1.81	260.8	2.3×10^{-57}	Significant	Significant
SUV	2270	1.88	2.08	1.71	219.1	2.7×10^{-48}	Significant	Significant
Motorcycle	838	3.82	3.95	3.62	59.6	1.1×10^{-13}	Significant	Significant
Scooter	1877	4.05	4.14	3.9	59.9	9.8×10^{-14}	Significant	Significant

The section effect comes out highly significant for every class, p far under 0.001 in all four. And it takes the same shape each time: placement highest at the centre, in between at the entry, lowest at the exit. Pairwise Wilcoxon signed-rank tests back the ordering. Centre-to-exit and entry-to-exit both clear $p < 0.001$ for every class; the entry-to-centre step clears $p < 0.001$ for cars and SUVs and $p < 0.05$ for the two-wheelers. Vehicles, in other words, swing out as they enter and commit, run widest near the centre, and ease back towards the median on the way out. A Kruskal–Wallis test on all ten curves, independent samples this time, lands in the same place, so the finding owes nothing to the matched subset or the choice of test. Significant though it is, the effect is small: the section moves the mean by only some 0.2 to 0.4 m, and the bulk of the scatter sits between drivers and between curves, not between sections. The null of equal placement across sections is rejected for all four dominant classes.

6. Conclusion and Practical Implications for NH-415

This study set out to read vehicle lateral placement on the horizontal curves of the Itanagar–Naharlagun section of NH-415, a hill corridor carrying heterogeneous traffic. Working from field observation, it paired non-parametric hypothesis testing with bounded probabilistic modelling, the one to test how placement shifts along the curve path, the other to describe the operational pressures the corridor is under.

Averaged over each curve, the Friedman test found no section effect worth the name, for any class; the averaging cancels the within-curve movement and leaves ten near-identical pairs of means. Drop to the individual vehicle, with each tracked vehicle's three placements taken as a matched triple, and the repeated-measures Friedman test turns up a highly significant section effect for all four dominant classes, cars, SUVs, motorcycles and scooters alike. The shape held across the board, widest near the centre and tightest at the exit, with the pairwise gaps confirmed by signed-rank tests. The gap between the two levels is the lesson here: the section effect is real but small, and it shows itself only once the matched individual data are used. Placement on the curve is, in short, path-dependent for every dominant class and not the two-wheelers alone, which is awkward for any design that assumes lane-centred, uniform paths.

The Beta picture fills in the rest. Placement is bounded and lopsided, and its shape depends on both the vehicle and the part of the curve. Cars and SUVs run near the median with a right-skewed spread; motorcycles and scooters run wide with a left-skewed one. Towards the exit the two-wheelers scatter further while the cars and SUVs draw in harder against the median. Valley-side and hill-side curves parted company too, most of all at the entry, though here the roadside cannot be told apart from the direction of travel. Tests and description point the same way: on NH-415, lateral placement is specific to the vehicle and dependent on the path.

6.1 Problem Identified on NH-415

At root, the trouble on NH-415 is a mismatch: real driving behaviour on one side, conventional geometric design assumptions on the other, and the gap widest on the small-radius curves. The lateral scatter seen at entry and exit feeds uneven pavement wear and edge deterioration, thinner lateral safety margins, ragged lane discipline in mixed traffic, and more operational risk through the hill curves. The dominance of two-wheelers and personal vehicles, the patchy shoulders and the tight right-of-way only make it worse.

6.2 Practical Solutions and Recommendations

Based on the combined results, the following measures are recommended for NH-415:

- ➢ Segment-specific curve treatment. Curve design and evaluation should distinguish between entry, centre, and exit sections. The entry and exit, where variability is highest, should be prioritised for safety and pavement work.
- ➢ Targeted widening and shoulder improvement. Selective widening and paved-shoulder treatment should be applied on small-radius curves, particularly at exits, to accommodate the observed dispersion and recovery.
- ➢ Vehicle-class-sensitive design checks. Given the high variability of two-wheelers and light vehicles, design and safety checks should account for their behaviour rather than rely only on heavy-vehicle envelopes.
- ➢ Behaviour-based safety and maintenance planning. The Beta-based placement envelopes can help identify zones of high lateral stress, supporting proactive pavement maintenance and roadside safety work.
- ➢ Refinement of hill-road design guidelines. The findings support the use of probabilistic, behaviour-based lateral placement in place of deterministic lane-centred assumptions, particularly for heterogeneous traffic corridors

6.3 Final Remark

Pairing hypothesis testing with bounded probabilistic modelling gives a clear and workable way to read lateral placement on NH-415. Testing at both levels, curve-average and individual vehicle, shows the section effect to be real for every dominant class yet modest in size, and detectable only once the individual data are brought to bear. The approach ties observed driver behaviour back to geometric design practice, and it should carry over to other hill highways of the same kind in India.

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